SUPERGEN MARINE ENERGY RESEARCH

October 2007

SUPERGEN MARINE ENERGY RESEARCH

Full Report

Grant GR/S26958/01

Produced by The University of Edinburgh

October 2007

Acknowledgments

The SuperGen Marine Energy Research Consortium acknowledges with gratitude the continuing support of the Engineering and Physical Sciences Research Council.

They also acknowledge the interest and assistance received from the following collaborators: Aberdeen City Council; AEA Energy & Environment; Aquatera Ltd.; Aquamarine Power Ltd; Artemis Intelligent Power Ltd; Black and Veatch; The Carbon Trust; The Crown Estate; Department of Trade & Industry; Entec UK Ltd.; Ecole Centrale de Nantes (Fr); The European Marine Energy Centre Ltd.; The Engineering Business; The University of Exeter; Highlands and Islands Enterprise; Hydraulics and Marine Research Centre (RoI); The Met Office; Marine Current Turbines; The New and Renewable Energy Centre; Newage AvK; Ocean Power Delivery; Orcina Ltd.; Orkney Island Council; Scottish Power; Scottish Enterprise; Scottish and Southern Energy; Scottish Environmental Protection Agency; Scottish Natural Heritage; Teamwork Technologies (NL); TU Delft (NL); Wavegen.

Contents

1 Introduction

The Engineering and Physical Sciences Research Council (EPSRC) Sustainable Power Generation and Supply (SuperGen) programme is the flagship research initiative shaping the future of the United Kingdom's energy landscape. The first of a total of 13 consortia were launched in October 2003. The mission of these consortia is to establish a platform for the development of new and improved devices for efficient and sustainable power generation and supply. The research of the Marine Energy Consortium focuses on the potential for future exploitation of the marine energy resource. SuperGen Marine Phase 1 (October 2003 – September 2007) brought together research staff from the Universities of Edinburgh, Robert Gordon, Lancaster, Heriot-Watt and Strathclyde. Together they undertook generic research with the following long-term objectives. To:

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

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

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

The Marine consortium secured continuation funding for Phase 2, supporting a further four years research from October 2007, and this now brings together staff from the Universities of Edinburgh, Queens Belfast, Lancaster, Heriot-Watt and Strathclyde. There are ten work streams (WSs), all of which are scheduled to be completed by October 2011.

- 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 of devices and network integration
- WS8 Reliability
- WS9 Economic analysis of variability and penetration
- WS10 Dissemination of results

Two additional programmes have been funded in parallel with the core work streams in Phase 2. The first is a Doctoral Training Programme providing for eighteen PhD studentships across the six named universities and at an additional six affiliate universities active in marine renewable research. The second additional programme is the study of the ecological consequences of tidal and wave energy conversion.

The document consists of five sections and contains three appendices. Section 2 contains detailed discussion of Phase 1, spanning the research effort undertaken in the first four years of the programme. The aims of the future research in Phase 2 are presented in section 3. The two additional programmes associated with Phase 2 are summarised in sections 4 and 5. Details of the individuals involved in the programme, abstracts of the research outputs from Phase 1 grouped by work package, and then alphabetically, are contained in the appendices.

2 SuperGen Marine Phase 1

The original SuperGen Marine consortium partners were the Universities of Edinburgh, Robert Gordon, Lancaster, Heriot-Watt and Strathclyde. The research programme consisted of 13 work packages (WPs).

2.1 *Objectives*

The overarching aim of the SuperGen Marine Phase 1 programme was to increase knowledge and understanding of the extraction of energy from the sea in order to reduce investment risk and uncertainty. The support from EPSRC was to pursue generic research benefiting all stakeholders. The aspiration of the consortium was that through its own efforts and collaboration with others it would help to enable marine energy to occupy a significant position in a future energy portfolio. The research had the following objectives. To:

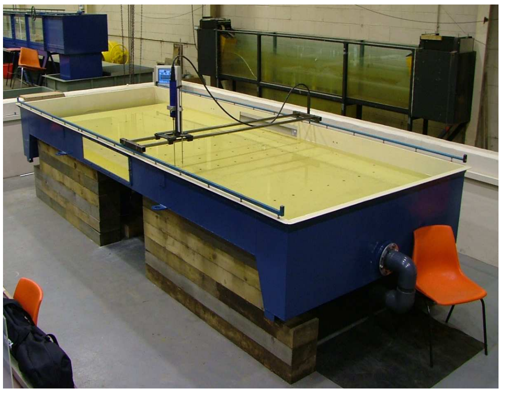
1. Increase knowledge and understanding of the extraction of energy from the sea;
2. Reduce risk and uncertainty for stakeholders in the development and deployment of technology;
3. Enable progression of marine technology and energy into true positions in future energy portfolios

2.2 *Work Packages 1-13*

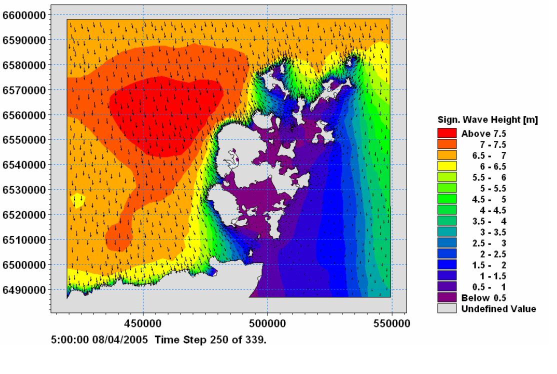
There were twelve research work packages with a thirteenth involving dissemination of results and outreach to the stakeholders and beneficiaries.

WP1 Appraisal of Energy Resource & Converters: Environment Interaction

The aim of WP1 was to establish and calibrate methodologies that allow a greater understanding of the nature and magnitude of the recoverable, sustainable and deliverable marine energy resources, including how they respond to energy extraction; the acceptable limits to exploitation and the importance of extreme conditions upon design.

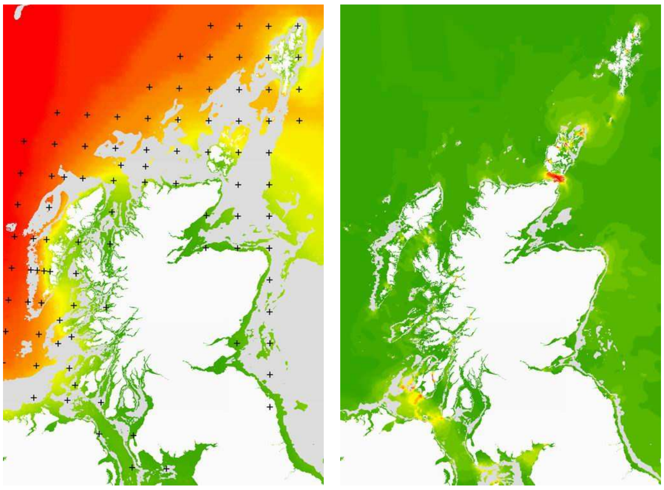


Numerical codes were developed, taking full account of the hydraulic and hydrodynamic natures of a tidal site, to simulate the influence of energy extraction in 1, 2 and 3 dimensions. The codes and their outputs were validated using published peer-reviewed data and by testing in a purpose-built “tidal flow table”. A new fundamental dimensionless parameter was identified which quantifies the sensitivity of tidal sites to energy extraction. This work also now makes it possible to identify the absolute limit to energy extraction for any well defined tidal channel, in terms of the physical parameters that define the physical environment. This enhanced understanding was applied in specific tidal case studies to consider the influence of flow modification on device design. Early principles were used by Black and Veitch in the 2004 Carbon Trust funded tidal current resource assessment of the UK and by Electric Power Research Institute in their assessment of the North American tidal current resource. Recent findings suggest that the findings of the B&V study may be conservative.



A wave prediction model was developed and applied to seas around the EMEC test site. It was calibrated against buoy data and modified to study energy extraction from an array, contributing to work in WP4 and WP3 when applied to long-term extreme wave prediction for a tidal site.

Measurements at three locations in Northern Europe were analysed to show that waves behaved in groups associated with period as well as height. Two new parameters ‘*R*’ and ‘*S*’ were proposed that express the rate of change of the period from one wave to the next. This is a significant finding for the design of control systems of wave energy devices that will have to tune their response for optimum power output from series of individual waves. Real seas were shown to include many small waves with little effect on the available power. Based on these findings, the complexity of the control algorithms and systems may be reduced significantly provided that they can adapt to changing primary energy conditions.



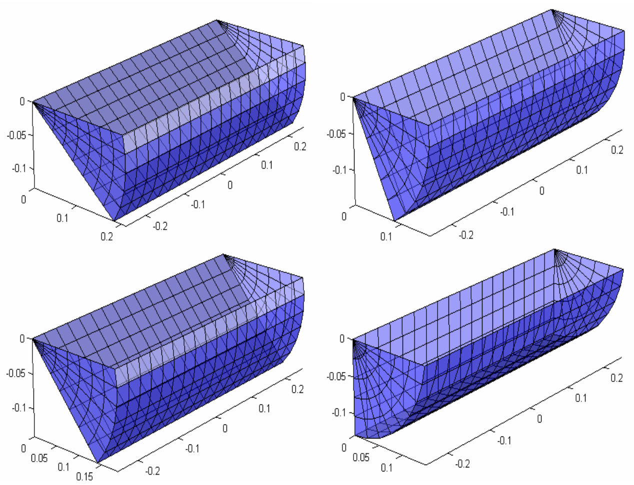
The Scottish Executive funded a parallel and complementary study to determine the extent of the spatial and temporal match between Scotland's renewable resources and demand. Wind, wave and tidal current resources were hindcast at resolutions of 1 km^2. A GIS database was populated with the long-term renewable resources, geographical information, natural and cultural heritage restrictions and restrictions on land, sea and airspace use. For wind, hourly time series over three years were calculated from measurement data using industry-leading software. Wave climates, spectra and directions were calculated as time series from Met Office data. Tidal rates in potential areas were obtained from Admiralty charts, tidal stream atlases and measurements taken within the SuperGen programme. Generic models of wind, wave and tidal current converters were incorporated to quantify the resources and to produce power time series. This has established techniques to derive very comprehensive geographical and temporal description of combined marine and wind renewable resources, and datasets of the Scottish potential.

The physical consequences of energy extraction on marine resources are now much more quantifiable and resource assessment before and after device deployment can now be more effectively conducted, based upon firm scientific principles.

WP2 Development of Methodologies for Device Evaluation and Optimisation

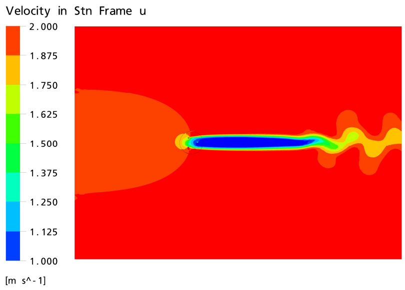
The aim of WP 2 was to develop and advance numerical and physical methodologies used to model wave and tidal-current converters. The numerical models were to be expanded to simulate multi-degree of freedom devices, extended into the time-domain and made more accessible to a wider range of modellers. Tank modelling techniques had to be developed to make the process faster, more accurate and repeatable. There have been several advances as a result of this work.

A new technique was developed using Laplace transforms to formulate time-domain models of the response of floating wave energy converters. This has augmented frequency domains modelling and created the ability to experiment in the time-domain with non-linear control algorithms and device responses.



A sloped wave energy device using a free water-reacting piston within a draft tube as an inertial reference for the power take-off system was examined as a case study. There was good agreement between the large body of results from tank experiments on this device and analysis with those from the WAMIT hydrodynamic analysis suite. WAMIT has now been integrated into a single graphical user interface that combines geometric pre-processing, surface modelling software, numerical analysis and graphics post-processing. Data files describing device shape may now be imported to visualise the device. The device can then be repeatedly reshaped with its description stored and its response predicted at each evolution.

A detailed CFD model of a vertical-axis variable-pitch tidal-current turbine has been developed, meeting the challenge of obtaining high meshing resolution at the surface of the rotating hydrofoils but lower meshing resolution farther from the foil surfaces.

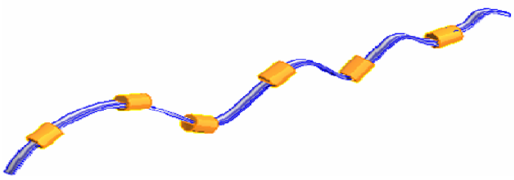


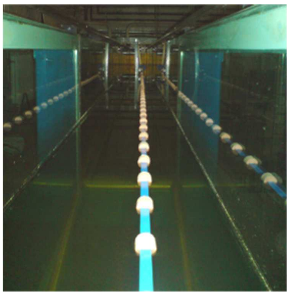
A software package was developed (MarinOPT) for macro-scale modelling of tidal current or wave energy devices. The model enables the assessment of the placement of generic wave or tidal energy converters in different sea environments to compare predicted delivered energy costs.

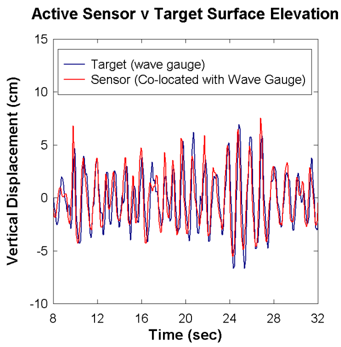
A rapid calibration wave-sensor technique has been developed to avoid the frequent and time consuming calibration that standard conductive probe sensors need to compensate for water temperature and conductivity variation. This combines the use of a video based displacement measuring system and a remote controlled overhead crane, leading to significant time savings with multi-gauge arrays used for directional wave measurements. An extensive toolbox of GUI data acquisition, analysis and display applications was produced.

Modelling the behaviour of wave energy models in tanks requires adaptable variable-constraint support mounts with dynamometer systems to simulate the forces associated with energy extraction. A detailed design study of a six-degree of freedom 'Stewart platform' for use in a multi-directional wave tank has been completed. A surge and heave rig has been refurbished, and its measurements conveyed by D-Space to a dedicated MATLAB control and measurement package.

A novel 'wearable' shape-tape with optical fibre position and shape sensing has been tested in flumes and tanks to demonstrate its ability to measure and report wave profile to data acquisition software, with high correlation between reported and actual wave surface.







There are many new software and hardware prediction and measuring techniques and equipment available for numerical and physical modelling of wave and tidal current energy converters at laboratory and full scale.

WP3 Engineering Guidance

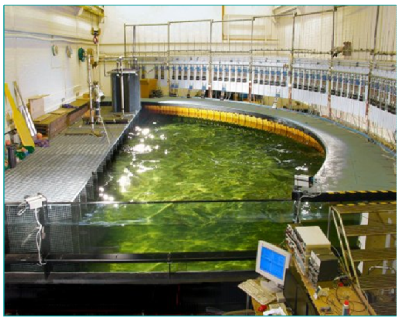
The aims of WP3 were to draw on work from across the Consortium as well as from external sources to establish robust guidance procedures for the design, development and evaluation of marine energy converters; to advance the science of performance measurement; and improve testing protocols to underpin the development of internationally accepted codes and standards.

Based on analysis from WP1, a generic method was developed to relate power capture from a wave device to the statistical properties of the sea. This has shown that conventional time-averaged calculation provides limited information and can underestimate power and energy production. The relation between sea spectral bandwidth and the width of the device power transfer curve has been assessed in terms of spectral shape, device width and ability to tune. Numerical modelling was considered to predict array affects and was applied to a tidal site in order to determine 50 year extreme wave conditions for design purposes. A guideline for the systematic assessment of tidal current resources was established enabling accurate determination of the accessible energy from any suitably defined site.

As part of WP2, a comprehensive written appraisal of fluid modelling for all of the appropriate commercial computational fluid dynamics (CFD) and hydrodynamic software packages was produced to guide understanding of the principles and the comparative advantages of different approaches and packages.

A test rig was designed and constructed to investigate device response in irregular wave fields. Uniquely, the mechanical properties can now be defined to be time-varying, allowing the investigation of a wide-range of 'control' strategies, linking to work in WP7 and WP9. Experimental measurements showed the influence of the wave spectrum bandwidth on the power captured by a flat plate constrained to oscillate in surge. The captured power reduced with increasing bandwidth of the incident wave-field. For a surging flat-plate element, the captured power can vary by up to 15% due to irregularity of the wave-field and up to 50% due to variation of bandwidth of the wave spectrum. Further work has indicated that performance losses are dependent on the form of the collector element and this has provided guidance on the range of validity of the frequency domain numerical models that are typically employed to estimate the performance of oscillating-type wave energy devices.

A comprehensive review of reliability data sources relevant to marine renewable energy led to the production of a database of component failure rates. The use of data from other industries introduces uncertainty into any assessment and the application of Environmental Load Factors was considered. An availability model, incorporating a structural reliability assessment and fault/event tree analysis, has shown that the availability of a generic tidal current turbine could reach 94%. The limited extent and nature of available data were considered and acknowledged. A Monte Carlo based simulation was developed to understand the implication of these uncertainties on the determination of reliability and availability. This information fed into and drew from WP7 and WP12. A functional analysis of wave energy converter types was reported.



In conjunction with work in WP8 and WP10, the tank test facilities in the consortium and the facilities in Orkney were used to review aspects of tank and full-scale testing. A web-based tank test discussion forum was created and used across the participating community.

The Department of Trade and Industry funded complementary research to produce preliminary Device Performance Testing Protocols for full-scale tidal current and wave energy devices. The Protocol documents now form the reporting requirements placed on participants in the £42-million 'Wave and Tidal-stream Energy Demonstration Scheme' component of the government supported 'Marine Renewable Deployment Fund'. Further, the procedures advocated in the Protocol documents are now forming the basis of various draft Standards currently being developed under the auspices of IEC/TC 114 Marine Energy.

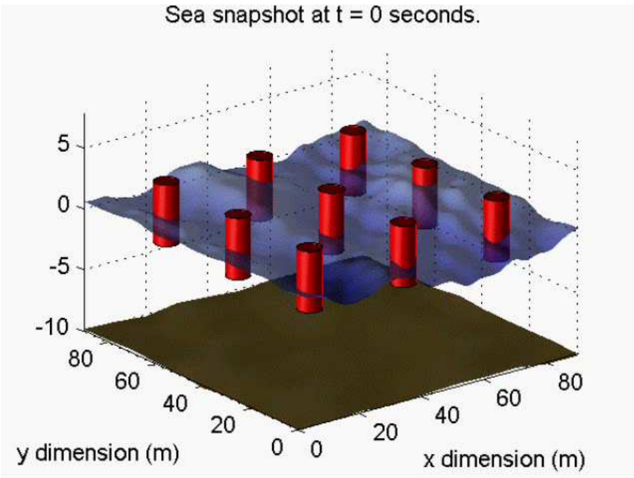
This WP interacted extensively with the landscaping and road-mapping work carried out by the UK Energy Research Centre (UKERC). A description of the technology innovation chain, from the R&D base to developers undertaking or nearing deployment was constructed by paper study and interviews of many participants across the sector. External influences on the progression of the technology and sector were identified and used to establish alignment and disparity between available funding and the forecast direction of the industry. Work on technology learning rates exchanged information and linkages with the R&D road map. This work was heavily consultative and consensus based, with around 50 interviews and several road-mapping workshops well-subscribed by participants across the sector.

A knowledge base was created by secondary research. Consortium staff nominated and summarised the most useful peer-reviewed and accepted journals, texts and standards from current and 1980s research programmes. Collections of seminal reports from the 1980s were turned into ".pdf" files and are being made available on the web-site. All publications by the consortium listed in this report have their abstracts and source indexed on a database on the web-site.

There is now a central resource of documented R&D output including old and new experience, and a R&D Roadmap defining sequential priorities and needs to support the sector from concept to deployment.

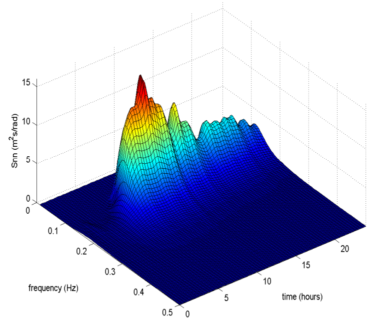
WP4 Offshore Energy Conversion and Power Conditioning

The aim of WP 4 was to explore how the electricity generated by wave and tidal energy converters could be controlled to be of a quality that would allow it to integrate with the electricity supply network without unduly increasing the cost of connection, production or delivery.



A wave-to-wire dynamic model of an array of wave energy converters was constructed, as was a current-to-wire model of a horizontal axis tidal current turbine farm. These models were used as test-beds for mechanical transmission system design and power conditioning algorithms. Each converter within the arrays was individually adjustable and tuneable.

The wave energy field has been modelled as a 2-dimensional sea with multi-directional waves. The effects of differing wave spectra and direction have been tested on the array by adjusting the attack angle of incoming waves and device positioning.



A procedure to synthesise and analyse non-stationary wave time series was developed that allows repeat simulations under the same resource conditions but with different time-series to explore converter designs and control strategies. The model of the wave energy converter is an impulse response driven, time domain implementation that includes the effects of added mass, excitation and radiation forces. The tidal model incorporates variable pitch blade angles and realistic torque characteristics to improve speed control of the rotor.

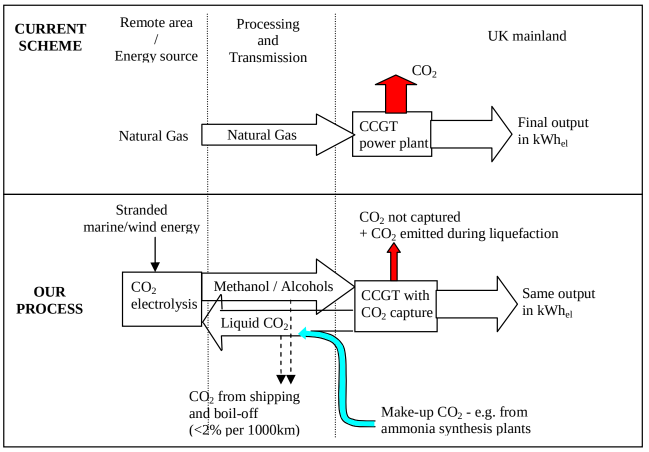
The wave and tidal models both include a mechanical power transmission with a variable speed doubly-fed induction generator and an alternative high-pressure oil hydraulic transmission with an on-board hydraulic accumulator coupled to a constant speed synchronous generator.

The offshore electrical collection system and its connection to a generic distribution network (or specific connection points to the existing Scottish model) have been modelled. Novel network power conditioning techniques, such as control of the oil transmission systems combined with power electronic converter control of doubly fed induction generators, have been evaluated. This has identified that that utilisation of this topology can significantly mitigate impact on voltage quality. Existing intelligent power factor/voltage control algorithms were extended and used to regulate real and reactive power output of the wave and tidal energy converters to reduce adverse impacts of resource variability on voltage quality.

It is now possible to gauge the network impact of individual or aggregate production from marine energy converters and explore control strategies to improve their integration with the electricity network.

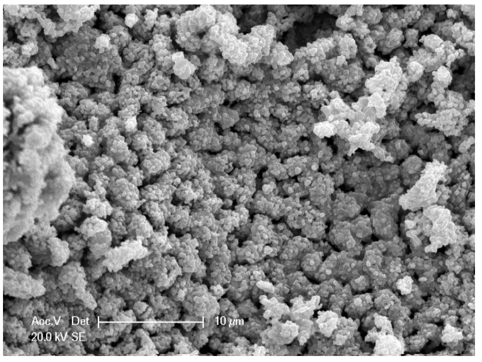
WP5 Chemical Conversion and Storage

The objective of work package 5 was to devise and evaluate processes for the conversion of inherently variable marine energy to a chemical carrier or a fuel, for the storage and/or transmission of energy produced in remote areas. Five processes were considered, four of them utilising hydrogen from the electrolysis of water at variable load. Since the bulk storage of hydrogen is costly and problematic, gaseous hydrogen was excluded. The resulting energy carriers were:



Liquid hydrogen: Storage efficiency was estimated from the literature. Liquefaction of the oxygen by product for transmission was flow-sheeted, taking advantage of pressurisation of the electrolyser.

Carbon-based liquid fuels: Flow-sheets were prepared for methanol; low toxicity mixed alcohols (e.g. ethanol); and gasoline made from methanol. An economic model showed the range of NG prices, electricity prices and CO_2 trading prices for which the methanol process (coupled with CCGT generation and CO_2 capture) would be competitive against CCGT generation from NG without CO_2 capture.

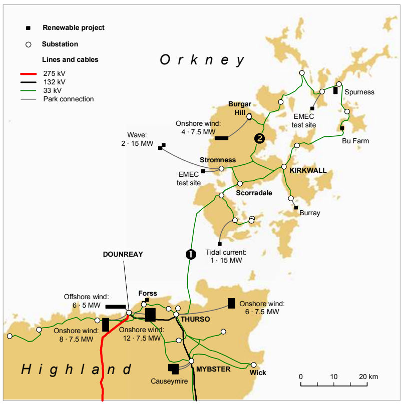


Sponge iron: Although this technology is still at the laboratory scale, it has the potential for greater energy efficiency than the others and is coincident with cheap carrier particles.

Liquid fuels require a source of carbon, which could be carbon dioxide or biomass. CO_2 may be recovered from, for example, power stations or natural gas, shipped to the location of the marine resource, and reacted with H_2. Alternatively, biomass may be gasified using the oxygen by-product from electrolysis; and the resulting syngas supplemented with H_2 from electrolysis, then reacted to alcohols. Certain reactor designs permit operation with variable feed, for which dynamic simulations have been performed in collaboration with WP4. Combining biomass with the products from electrolysis promises improved biomass conversion to methanol, as well as reduced costs and CO_2 emissions. Direct electrochemical reduction of CO_2 in the presence of water also produces alcohols, and should accommodate the variability of marine energy more effectively.

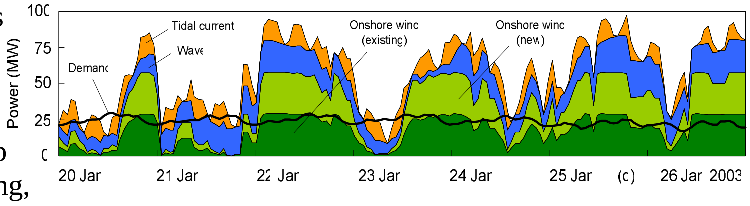
Different chemical media were tested for their capacity to store and return marine energy economically, and the prospects and enabling mechanisms for chemical storage were identified.

WP6 Network Interaction of Marine Energy



The aim of work package 6 was to quantify the interaction of future marine energy converters with the onshore distribution network and to identify means of mitigating their impact to allow greater access to the electricity market.

To carry out network studies, the transmission network across Scotland and the distribution network in resource-rich areas were modelled. The latter included Orkney/Northern Highlands with wind, wave and tidal resources and Lewis/Harris with a strong wind resource and a high potential for wave power developments. With existing and consented renewable projects, these areas offer the prospect of a high penetration of time-varying electricity generation. The traditional static method of checking that network conditions remain acceptable for a maximum demand winter case and a minimum demand summer case does not identify the coincidence of renewable energy production from differing sources or relate that to demand variation. Probabilistic methods contain limited knowledge of correlation between the renewable energy production and demand. A new approach using historic time series was investigated. These power time series were created from measurements and hindcast records (for wind, wave and also demand) or directly calculated (for tidal current) for a period in the past and applied to existing or future generation scenarios. The results of multiple power flow analyses, with hourly time steps over a period of several years, were then analysed statistically, to obtain both typical and extreme values for the network conditions.



Loading duration curves and the benefits and limitations of generator curtailment were produced from the above. This work package has shown that time series analysis has advantages which would help a network operator in generation planning, strategic network reinforcement and improved asset management. The need for balancing generation has been emphasised, and the extent to which this could be done with hydro and diesel capacity has been identified.

A novel means has been developed to explore the synergies between wind, wave and tidal current energy resources and to explore their aggregate network impact over time.

WP7 Lifetime Economics

The aim of work package 7 was to create, test and validate a lifetime model of marine energy converters to provide more reliable predictions for the investment community and to enable fair comparison of the economics of alternative marine energy technologies. Wave energy converters were classified, according to their mode of operation, as Clustered and Independent Oscillating Absorbers or Overtopping and Pneumatic devices. Collated component cost data were used to obtain an indication of how the cost distribution (capital cost, operational cost, etc) differed between classes of marine energy converters and to evaluate a target capital cost for each type of device that would ensure confidence in attaining a target generation cost. The method of calculating present value of the cost of generated electricity estimates the required values when each input or component of expenditure and revenue is described by a probability distribution (e.g. a normal distribution), and financial parameters are risk-adjusted. Multiple calculations, with randomised parameters, produce a statistically valid distribution of the expected costs of electricity, payback period, etc. The variation of unit cost and the variability of financial parameters may be set to model and explore confidence in future trends.

A method has been developed for directly comparing the relative efficiency of a set of wave energy schemes that produce the same electrical output. Based on the Data Envelopment Analysis technique, this provides a means for identifying the production system (e.g. a marine energy conversion scheme) that minimises the use of inputs to attain a target output relative to a peer group of producers. This is a generalisation of the single input-output ratio measure of efficiency, with the specific advantage that it is insensitive to the units that define each parameter, or their relative importance. The resultant efficiency measures are unaffected by variation of the units employed for each parameter providing that the ratio between the inputs into alternative schemes remains constant. This approach is easily extended to assess the economic efficiency of a scheme producing multiple outputs. Additional work has addressed the impact of site accessibility on the cost of offshore operations and reliability, the quantification of the predictable output in the UK market, and the estimation of power output of both wave and tidal devices on the basis of site-specific data and device performance characteristics. In addition, collaboration between WP7 and WP12 has considered the macro-economic impacts of the installation, operation and maintenance of various hypothetical scenarios. This fusion of micro- and macro-economic factors into a single framework offers alternative design criteria in the development of large scale marine power schemes.

It is now possible to compare directly the relative economic efficiency of wave energy schemes of equal capacity independent of 'best guesses' of individual component costs and of variations in market prices.

WP8 Moorings and Foundations

The design and operational requirements of a mooring arrangement for floating wave energy converters are significantly different to those of a typical offshore installation in terms of 'static' and 'dynamic' motions. A motion dependent wave energy converter needs to have a natural response frequency at the dominant wave frequency, and the mooring system needs to be designed around this. In contrast to conventional floating offshore installations, wave devices are installed in shallower water, typically at the 50m contour, for which both tidal changes and currents can have a proportional larger effect on line lifting. When an array of devices is considered, the limitations in sea space may require that the devices be relatively densely packed and, as a consequence, the 'footprint' of the mooring may be constrained to ensure that the moorings from each device do not interfere. This has great significance on possible mooring line length and axial stretching due to mooring line lifting. The design of moorings for a wave device must not only consider reliability and survivability, but also the need to preserve efficient energy conversion.

Tank testing at small-scale was used to investigate the response of a single mooring line for surge motion, with particular emphasis on the effect of axial stretching, and the influence of the top end motion on dynamic response. The laboratory procedures were designed to resemble proposed tests at large scale in 24 m water depth (in WP10), and measurements were compared with output from numerical models.

The work has shown that both the axial stretching and the top end dynamics have an important influence on the station keeping of floating wave energy converters. The relevance of non-linear behaviour of the mooring line was shown to be a major influence on the station keeping of a device, particularly in terms of loading, stiffness and damping characteristics. The strain on the mooring line and components resulting from non-linearities increase both ultimate peak load, and also fatigue damage from higher levels of accumulated cyclic loadings.

This work suggests that compliant chain mooring arrangements relying on the submerged mass of the line to provide the restoring forces are not able to restrict horizontal movements in an efficient manner for arrays of floating wave energy converters. The results highlight the potential for taut-mooring applications where pre-tension provides the restoring forces. This would imply the need for innovative design solutions to allow the required compliance to account for variations in tidal level.

Non-linear effects have been shown to be fundamental to the understanding of device response and must be considered in any detailed design of the station keeping system, and its influence on peak loading and energy conversion efficiency.

WP9 Novel Control Systems for Marine Energy Converters

The aim of work package 9 was to explore adaptive and self-learning neural network-based control systems for generic wave energy converters and contrast performance over a range of changing sea states.

This work package has investigated the efficacy of adaptive control techniques for improving the mean power captured by an oscillating wave energy converter in a range of irregular seas. Different means for controlling the response of the device have been developed and their performance compared over a wide range of sea-states. The power capture performance of each technique has been simulated for the standard case of a heaving buoy using a newly developed SIMULINK^{TM} model, wherein hydrodynamic interactions are modelled using the time-domain model developed in WP2. The control techniques are both passive and active and have been developed for increased power capture. Passive methods can be considered as 'slow-tuning' techniques and differ in terms of how the 'dominant' wave frequency is defined. Two of the active tuning methods aim to maintain quasi-resonance by matching the natural frequency of the device to some measure of the incident wave frequency: both the frequency of the wave-groups and incident wave frequency are considered. These techniques differ in that the group-frequency approach requires future wave prediction, whereas the incident wave model does not. The third active tuning technique is designed to minimise the difference between the period of device velocity and incident wave velocity, by time-variation of the mechanical properties of the device. Uniquely, this approach requires no future wave knowledge or prediction of device response, yet provides an increase of mean power capture. Results show that, relative to a device tuned to the energy frequency of a wave spectrum, the three active control techniques investigated provide a significant increase of power capture in a wide range of sea-states.

This work has identified that the persistence of the radiation force acting on wave energy converters is not adequately modelled in the frequency domain. The resulting control problem is non-causal, especially for large devices with long radiation impulse responses that will experience broad bandwidth seas. In collaboration with Ecole Centrale de Nantes, this work package has attempted to predict parameters and timing data for the next wave, for use with latching control. It has generated a large set of training data describing the waves, developed feature extraction techniques, and trained three different prediction methods - one of which is entirely new. Results have shown that MultiLayer Perceptron neural networks can be trained to provide the information that is required by a control system better than frequency estimation techniques for broad-bandwidth waves. This is significant because the standard control concepts currently being adopted are based on frequency estimation, and most of these devices are large enough to have long natural periods and thus will benefit from knowledge of future waves.

New adaptive control techniques have demonstrated the capability to increase the energy capture from a heaving wave device. Neural-network predictors have been developed to forecast next-wave data for the next generation of control systems.

WP10 Full-scale Field Validation

The aim of work package 10 was to perform full scale assessment of fundamental influences on system performance, such as mooring response, tidal flow turbulence and marine fouling.

The mooring tests were conducted in Scapa Flow at Orkney, including a preliminary test phase using a 22m chain, detailed investigation of mooring characteristics using a 22mm chain and, finally, detailed investigation of three different mooring arrangements including wave and current measurements. The moorings were 22mm chain, 40mm fibre attached to 38mm chain and 40mm fibre rope attached to a floater and sinker buoy. An 82 Tonne vessel was used to conduct all experiments in an average water depth of 23.5m. WP 8 contributed to the design of these large scale experiments.

The top end motion of the vessel and the resulting line tensions were measured as well as the tidal changes and the environmental loadings due to currents and waves. The suitability of chain and/or fibre rope mooring line arrangements for floating wave energy converters were investigated in terms of their effect on "top end" dynamics of the device and the resulting line tension characteristics. A simple catenary chain arrangement, a compliant hybrid mooring arrangement and a taut mooring arrangement in z-configuration were tested to investigate the load, stiffness and damping properties for these slack and taut arrangements. The experimental outcome was also compared by simulating these tests with the commercial software 'OrcaFlex' and demonstrated the capability of a numerical model to simulate the mooring behaviour at large scale. The catenary chain arrangement with large compliancy, where the submerged mass provides the restoring force, was found not to be an efficient means for the station keeping of floating wave energy converters. Significant anchor and fairlead loading was observed in addition to large variation in stiffness and damping behaviour. These criteria were found to be more moderate for the hybrid mooring arrangement, whilst the observation for the taut arrangement provided the best station keeping criteria at low loadings. The test programmes confirmed the conclusions of WP8.

Image courtesy of EMEC

The Robert Gordon Sea Snail tidal test platform was modified for the collection of tidal current data by incorporating transducers and was installed in Burra Sound in 2005. Its deployment and subsequent removal generated important lessons for WP3 about the handling of large scale instrumentation in energetic tidal environments. Adoption of more advanced marine instrumentation during the progress of the project allowed the original sensor array to be replaced by a high frequency Acoustic Doppler Profiler system for the next deployment in Burra Sound in 2006. This generated an enormous amount of high resolution data which, when analysed, identified that turbulence levels cannot be simply expressed in terms of proportions of the ambient flow and that the structure is spatially and temporally complex. The turbulent structure appears to contain "memory" of previous conditions. High and low resolution data was also collected in the deeper Falls of Warness, in association with the European Marine Energy Centre (EMEC) and has given confidence in the findings across different tidal environments. The data is a comprehensive set of tidal current measurements that will enable future determination of temporal and, indirectly, longitudinal statistics through the water column throughout a spring-neap cycle.

The study and data collected has enabled systematic study of full scale mooring and turbulence parameters crucial for assessing the interactions between the technology and the environment.

WP11 Assessment of Testing Procedures for Tidal Current Devices

Forces on objects towed through still water differ from those on objects in moving water, as a result of physical properties such as turbulence and flow shear. The aim of work package 11 was to quantify these differences with respect to tidal current devices and to use this understanding to guide future testing. The work had two parallel modes: numerical and physical. The numerical study has provided understanding of the parameters influencing system performance and has governed the design of the experimental programme. The commercial CFD package, 'Fluent', was used for numerical simulations. A tidal turbine was approximated by a porous disk and the extraction of energy was simulated as a momentum sink. The model was used to generate a sensitivity analysis, demonstrating that turbulence does influence the loading on the energy extraction system, the form of the wake behind the device and pressure/flow distortion around the energy extraction zone. Findings from the numerical programme guided the design of a "flexible" test system, which was used in a moving water environment that formed part of the outflow works of a hydroelectric power station. A series of tests provided results in excellent agreement with those of the numerical studies. The test rig was built and used for a complementary series of tests in a towing tank. This ultimately proved the hypothesis that there are measurable differences between physical tests conducted in moving water and still water resulting from propagation and transmission of the pressure gradient field and turbulence influences. It has now, however, been shown that the influence of flow profile can be effectively handled by data post processing.

This work has demonstrated the difference between measured forces on tidal device components fixed in flowing water compared to being towed in still water, and identified means of resolving that difference.

WP12 Economic, Environmental and Social Impact of New Marine Technologies

WP12 has developed a number of regional, national and interregional Input-Output and Social Accounting Matrix databases for the four regions of the UK (England, Northern Ireland, Wales and Scotland) and established the regional linkages of different electricity generation technologies in the UK.

These databases use a novel disaggregation of the electricity sector as compared to its conventional treatment in economic accounts. Uniquely, they separately identify both generation and non-generation activities, and disaggregate generation activities by type of generation technology.

These extended databases have been used in the application of a number of linkage and attribution studies, using various "fix-price" methodologies of energy issues at both the national and regional level in the UK. This work has examined the backward and forward linkages of marine and other electricity generation technologies. It has also examined the consequences of major changes in the structure of electricity generation on the regional and national economy through a number of "hypothetical extraction" techniques (applied, for example, to the projected closure of nuclear facilities).

WP12 has developed and tested both UK and regional energy-economy-environment CGE models that incorporate separate treatment of renewable and non-renewable energy inputs. These models are calibrated on a subset of the databases generated by this work. CGE analysis has become the most widely adopted modelling approach to addressing the energy-economy-environment nexus, and the work in WP12 is unique in applying these models to the question of new marine renewable technologies for the production of electricity in the UK. With WP7 this study has examined the likely macroeconomic and environmental impacts of the expenditures associated with the development of such a sector in Scotland and the UK.

The results of this work are the first systematic attempt to quantify the potential importance for regional and national economic development of the emergence of an industry based on marine renewable energy.

WP13 Dissemination and Outreach

The consortium has disseminated continuously via peer-reviewed journals, at conferences and at marine-energy related events of others, including

- 5^{th}, 6^{th} & 7^{th} European Wave & Tidal Energy Conferences - Cork 2003, Glasgow 2005, & Porto 2007
- EU Coordinated Action on Ocean Energy Workshops in Aalborg & Uppsala 2005, Amsterdam & Lisbon 2006 and Copenhagen 2007.
- Regional Science Association International – British and Irish Section Conference, 2005, 2006, 2007.
- Scottish Economic Policy Network 2005.
- Royal Society of Edinburgh Inquiry into Energy Issues in Scotland, 2005.
- Intl Conferences on Marine Renewable Energy MAREC – Blyth 2004 & London 2006
- All Energy Conference, Aberdeen 2004, 5, 6 & 7
- World Renewable Energy Congress – Keynotes in Denver 2004 & Florence 2006
- Greenhouse Gas Control Technology Conference – Vancouver 2004 & Trondheim 2006
- DTI Trade Missions to Iberia 2004, France 2006, USA 2006, New Zealand 2006, Korea 2007
- FCO/British Council Renewables Workshops, China 2006/7, Canada 2007
- Intl Symp on Fluid Machinery for Wave & Tidal Energy: State of the Art & New Developments, London, October 2005
- Advances in Reliability Technology Symposium – Keynote in Loughborough, June 2005
- Intl Conference on Offshore Mechanics and Arctic Engineering – Hamburg, June 2006
- Ocean Renewable Energy Group - Nova Scotia, Nov 2006
- Intl Conference Offshore and Polar Engineering Conference – San Francisco, July 2006 and Lisbon 2007.
- International Sustainable Energy Forum, San Francisco, October 2006
- Brazil Wave Power Seminar, Rio de Janeiro, February 2006
- International Conference Ocean Energy, Bremerhaven, 2006
- Centre for Public Policy for Regions-EUREAL workshop, Glasgow 2006.
- IEEE International Conference on Clean Electrical Power Renewable Energy Resources Impact, Capri, May 2007
- IMechE, Fluid Machinery for Developing Engineers, Cranfield, 2007
- ECOMOD Energy and Environment Modelling Conference, Moscow 2007.

The SuperGen workshop programme, organised and run by the consortium, included:

- "SuperGen Marine – Year 1 Progress", October 2004, Edinburgh – 70 delegates
- "From C to sea: modelling and simulation for optimising marine renewable energy extraction"; April 2005, Aberdeen – 50 delegates
- "Learning from Experiences"; Joint workshop with Co-ordinated Action on Ocean Energy at the 6th European Wave Energy Conference, August 2005, Glasgow – 60 delegates
- "Research Route Map for Wave and Tidal Energy Conversion", "Tidal Measurements", Joint workshops with UKERC and EMEC, April and August 2005, Edinburgh – 30 and 30 delegates.
- "Research Route Map for Environmental Impact of Marine Energy", Joint workshop with UKERC, and EMEC, September 2005, Edinburgh - 30 delegates.
- "Making waves: Economic and Social Impact of Marine Renewables", Dec 2005, Glasgow
- "SuperGen Marine Research – Progress and Achievements", Joint invited workshop with UKERC, June 2006, Oxford - 50 delegates.

Several of the research staff and post-graduates have visited European collaborators for extended stays. Some of the partner institutions will operate co-lateral programmes with the Doctoral Training Programme in Phase 2 to adjoin their students to proposed activities.

Dissemination of the activities of the consortium also takes place via the SuperGen Marine web-site http://www.SuperGen-marine.org.uk. It is broadly accessible to all visitors but there are reserved areas with permitted access for members joining via the web-site, collaborators and partners.

Phase 1 of SuperGen enjoyed interest and assistance from collaborating bodies and organisations, including

Aberdeen City Council
AEA Technologies Ltd
Aquatera
Aquamarine Power Ltd
Artemis Intelligent Power Ltd
Black and Veitch
The Carbon Trust
The Crown Estates
DTI
Entec
ECN Nantes (Fr)
EMEC
The Engineering Business
The University of Exeter
HIE
HMRC (RoI)
The Met Office
Marine Current Turbines
NaREC
Newage AvK
Ocean Power Delivery
Orcina
Orkney Island Council
Scottish Power
Scottish Enterprise
Scottish and Southern Energy
SEPA
SNH
Teamwork Technologies (NL)
TU Delft (NL)
Wavegen

3 SuperGen Marine Phase 2

The Consortium now consists of the University of Edinburgh; Heriot-Watt University; the University of Lancaster; the University of Strathclyde and the Queen's University Belfast. The associated research programme consists of nine work streams (WS).

3.1 Aims and Objectives

Work completed in SuperGen Phase 1 has enhanced understanding of the extent and nature of the marine resources, how extraction of energy modifies that resource and its environment, and has pointed to how technology could be developed to enhance the effective exploitation of energy. During the lifetime of Phase 1, a selection of developers has moved from concept to prototype development and this has identified specific needs for further fundamental research. UKERC and SuperGen Marine Phase 1 organised numerous national and international meetings of the stakeholder community to agree an R&D roadmap, and to develop Protocols on behalf of the DTI for open sea testing and performance evaluation. The sector participants in the UKERC Research Roadmap process identified many and varied long term needs. The research priorities proposed in SuperGen Marine Phase 2 build on experiences and questions arising from early device tests, the deployment of prototype devices, the UKERC R&D road-mapping and DTI Protocol processes, and the outcomes of the original work programme. The original overarching aims of the SuperGen Marine programme may be valid for some time, but the work completed and advice absorbed, has resulted in an evolution of the first of the original aims, now:

1. To increase knowledge and understanding of device-sea interactions of energy converters from model-scale in the laboratory to full size in the open sea.

Phase 2 of the programme includes work on: device arrays and how these will influence local and regional environmental conditions; radical design approaches, which take into account new philosophies of design guidance; ensuring that numerical and physical design support is consistent and robust; the challenges posed by design in mixed tidal and wave environments; system control in complex non linear and evolving environments; the complex challenges posed by fixing, mooring and recovery of marine systems; the economic challenges posed by the variable and intermittent nature of the marine resource; the sparse information available to predict and assess the long term reliability of marine energy systems and how an increased understanding of all of these issues can be best disseminated within the stakeholder community.

3.2 Work Streams 1-10

There are now nine research work streams, with an additional tenth work stream associated with the dissemination of results and outreach to the stakeholders and beneficiaries.

WS1 Numerical and physical convergence

Continually increasing computing power has led to the development of new sophisticated numerical models and detailed experimental measurement techniques, making it possible for the first time to examine new generations of wave and tidal technology using a robust combined physical and numerical modelling approach. Modelling tools are required, both at the device and geographic scale, to allow detailed investigation of the design and positioning of single devices and arrays of devices. This work stream will combine new software techniques and experimental hardware and methods to improve convergence between the output of numerical models and measurements made using physical models to quantify and increase confidence in performance predictions of new concepts and designs and how they may be expected to behave in deployment. In addition to being of benefit to the wider community, the modelling tools will be closely integrated with and used by the other work streams throughout Phase 2.

WS2 Optimisation of collector form and response

Effective wave energy extraction requires the conversion of the dynamic internal flux of potential and kinetic energy into differential motion between two, or more, mechanical artefacts that are subsequently used to drive the power take off system. The conversion process begins with the response of the working and other surfaces to forces arising from the wave field. The best form of this working surface and its body has remained a matter of discussion, debate and research since the earliest history of wave power. This work stream will explore whether optimal designs can be evolved for the physical form and response of the collector in a wave energy converter, using a combination of genetic algorithms, numerical modelling and rapid prototyped models tested in tanks.

WS3 Combined wave and tidal effects

Until now tidal current and wave power devices have not been optimised for operation in mixed current/wave environments. Wave devices have tended to be designed to operate with minimal currents and tidal devices designed assuming little or no wave effects. Unfortunately most near coast wave environments are subject to tidal and other current effects and many of the largest tidal sites, such as the Pentland Firth, are exposed to direct wave influence and, crucially, to substantial swell. Extreme long waves modify the fluid motion well down into the water column and could have a significant influence on tidal current devices and their operation.

Experience with devices at sea has now confirmed the need to be able to predict and mitigate the effects of tidal currents on wave devices and waves on tidal current devices. This work stream aims to develop an understanding of the effects of waves on tidal currents and energy conversion devices and the effect of tidal currents on waves and wave devices and how to formulate an integrated design methodology that mitigates counter productive effects. The identification of design practices necessary for mixed environments will considerably extend the exploitation of resources.

WS4 Arrays, wakes and near field effects

As marine renewable energy moves from the deployment of individual prototype devices to the commercial development of arrays, it is vital that array interaction is understood to enable accurate predictions of their individual and combined performance and to enable the prediction of changes in the natural physical processes in coastal waters. This is an essential input to inform accurate environmental impact assessments of the coastal zone and to avoid unnecessary development constraints, resulting from over conservative assessments of hazard. This work stream will explore how array interaction affects the design optimisation and performance of both multiple tidal current and wave energy converters and will enable more accurate quantification of the environmental consequences of large scale energy extraction. It will generate an enhanced understanding of how the presence of multiple wave or tidal current energy extraction systems will result in localised perturbations to the energy and momentum fluxes.

WS5 Power take-off and conditioning

Marine energy converters have working surfaces that either reciprocate or rotate at low speed and operate over a wide range of loadings, making conventional off-the-shelf rotary generators, such as the induction machine, less suitable. Permanent magnet generators exhibit high part load efficiencies and, while they have been demonstrated at sea to a limited extent, designs are not yet fully optimised. Using direct drive generators reduces the number of moving parts but, because of their low speeds and consequent high torques, adopting conventional machine topologies results in large and costly generators. Optimisation of cost and performance requires new iterative integrated structural, electrical and thermal design techniques. This work stream will explore how the design of the prime-mover, drive-train, generator and power electronic converter may be fully integrated to define lighter, cheaper machines that will operating at slow speed with improved efficiency over a wide range of loads. The new analytical tools and concepts developed will be verified using numerical modelling techniques and experimental tests.

WS6 Moorings and positioning

The findings of Phase 1 identified that moorings are still a significant challenge in the design and operation of floating marine energy converters. Their behaviour, when used in arrays of wave energy converters under the joint action of waves, current and wind, has not been fully investigated. This work stream will further develop and validate numerical hydrodynamic and mechanical models of a range of mooring systems to investigate the effects of their passive response within a combined wave and tidal environment.

It will also examine the combined response of taut systems and “deep-moored” tidal devices. Mooring responses will be measured in the field under combined wave and tidal current action and compared with numerical models. The results obtained will be used to predict long-term effects of combined loadings on survival and make an assessment of suitable generic mooring configurations for array deployment.

WS7 Advanced control of devices and network integration

The marine environment and the response characteristics of any engineering system exposed to it are inherently non-linear in form and behaviour. In addition, the traditional analysis of the wave climate uses spectral methods, which implies assumptions of linearity and short-term stationarity. To be able to optimise control for maximum energy capture, cost-efficient design and survival, there is a need to determine the minimum necessary complexity of non-linear modelling of ocean waves to adequately represent the wave climate.

Tidal current energy systems are inherently non-linear. The kinetic component of the energy flux is proportional to the cube of the flow speed. The “total” energy flux contains components of different degrees of non-linearity, such as turbulence, bed friction, pressure head and wave-current interactions. The objective of this work stream is to increase understanding of the effects of non-linearity and non-stationarity of the marine resource on wave and tidal current energy conversion and to satisfactorily mitigate these influences through advanced, evolving and coordinated control of the devices and their power take-off system, when these are installed stand-alone or in arrays. Work in Phase 1 will then be extended to model the interaction of arrays of devices with weak electricity networks.

WS8 Reliability

Work within Phase 1 established, from industry sources, an initial database of details of component parts of marine energy converters that affect reliability and developed methodologies for the reliability analysis of generic marine energy converters. There is a lack of verified failure rate data for many of the critical components that will persist until more devices have been deployed and appropriate data published. The limited or non-existent data sets create uncertainty in prediction of the reliability of marine energy converters and equitable assessment of their economic performance. The aims of this work stream are to assess the effect of uncertainty on the calculations of device reliability and availability. Reliability methodologies from other industries, particularly wind development will be evaluated and adapted for application to marine energy conversion systems.

WS9 Economic analysis of variability and penetration

Wave and tidal resources around the UK display significant seasonal, daily and hourly variability. The extent to which these resources may be developed is frequently assessed in terms of the network impact of their variability and the economic implications for developers and network operators. Ultimately the level of penetration will depend on market conditions, shaped in part by energy policies, and the true costs to consumers taking into account the costs of energy provision and delivery, including balancing and system marginal costs. The work stream will build on the outcomes of Phase 1 to apply optimal portfolio theory to examine potential gains arising from diversification through a portfolio of marine energy sites, and then of marine energy within a broader energy portfolio, using cost and area-specific marine energy attributes. The results of the analysis will provide the cost and other inputs to a computable general equilibrium analysis of the economic, social and environmental impacts of increased penetration of marine and other renewable energies. A range of future electricity generation scenarios will be explored for the UK and its regions against which the impacts of alternative levels of marine penetration will be compared. The policy mechanisms required to achieve desired levels of penetration will be examined.

WS10 Dissemination of Results

Consortium staff and students will continue to collaborate with existing marine energy research being undertaken in the UK/EU and beyond. Workshops, seminars and conferences will be organised to outreach to the beneficiary and research community to bring into context the UK research activities with activities being undertaken elsewhere in Europe. Government, agency and industrial in-reach will be promoted through advisory meetings of collaborators to confirm the scale and impact these research activities will have on the wider marine energy policy objectives. There will be 8 six-monthly workshops to inform and enable the community to provide feedback on the direction of the proposed research.

4 Doctoral Training Programme

The SuperGen Marine Doctoral Training Programme is a new initiative that affiliates and connects other universities including Robert Gordon, Southampton, Exeter, Manchester, Durham and the University of Highlands and Islands Millennium Institute, through the medium of a shared cohort of 24 funded PhD studentships in marine energy and related disciplines such as coastal defence and environmental assessment. It is funded by EPSRC in partnership with Highlands and Islands Enterprise. The Doctoral Training Programme is attracting, sponsoring and training a body of graduates to increase the supply of advanced trained scientists and engineers for the academic, industrial and infrastructure sectors of marine energy. There will be 12-15 students enrolled in year 1, with a further 6-9 in year 2. The students will engage in research complementing the aims of work streams 1-9 above. They will participate in a succession of week-long seasonal schools at venues around the UK, in core disciplines such as: wave and tidal current hydrodynamics; physical test skills; reliability analysis; economic principles; power systems and network integration; environmental impact assessment; regulation and finance; commercialisation, entrepreneurship, IP, patent law; career development, skills marketing and management. The seasonal schools will be open to other participants and advertised in advance. Students in the programme will present from their work at internal seminars and at Phase 2 public events.

5 Ecological Consequences of Tidal & Wave Energy Conversion

It is inevitable that the deployment and operation of marine energy systems will disturb the surrounding environment. With the progressive tightening of statutory marine environmental controls, it is essential to address the issues that are likely to arise as new controls are introduced, especially as the onus will be on the industry to demonstrate minimal environmental disturbance. Heriot-Watt University Orkney Campus and Queens University Belfast Ecology and Evolutionary Biology Group have been funded by EPSRC, within SuperGen Marine Phase 2, to study the Ecological Consequences of Tidal and Wave Energy Conversion. The aim of this programme is to establish the sensitivity of marine environments to the extraction of energy to quantify the risk from device developments and to evaluate subsequent mitigation, monitoring or avoidance strategies. It will carry out observational and experimental studies on the response of benthic and other communities to variations in the ambient flow field and sediment transport effects consequent upon energy extraction. It will also study the impact of related anchoring and mooring systems and the collision risk of large biota such as seals with tidal turbine blades.

As marine renewable energy moves from the prototype to commercial stage of development, it is vital that the environmental impact is accurately assessed; otherwise it is likely that development will be hampered by over conservative assessments of hazard based upon the “precautionary principle”. Preliminary studies, ABPmer (2005), into the likely impact of marine system development have now been conducted and published. No quantification of these impacts has yet been attempted. Accurate knowledge of the likely impacts will reduce uncertainty in both strategic and project specific environmental impact analysis, which will benefit both the development of optimally performing systems and arrays of systems, whilst ensuring that the environment is protected.

Appendices

Appendix 1 Staff and Students of SuperGen Phase 1

Academics and Admin Staff
Prof. A. R. Wallace – UoE
Prof. I.G. Bryden – UoE
Prof. S. H. Salter - UoE
Dr V. Venugopal – HWU/UoE
Dr C. L. Prichard - UOE
Prof J. Wolfram – HWU
Dr G. H. Smith – HWU/Exeter
Dr R. Harris - HWU
Prof. P. McGregor – Strathclyde
Prof. K. Swales - Strathclyde
Prof A. G. Bradshaw – Lanc
Eur. Ing. G. A. Aggidis – Lanc
Prof. R. Rothschild - Lanc
Prof. M. J. French - Lanc
C M Bronsdon - SEEF
Pauline Clark/Kirsten Clarke/Dorothy Shewan – UoE/RGU

Research Staff
Jamie Taylor - UoE
Henry Jeffrey – RGU/UoE
Dr. S. Couch – RGU/UoE
Dr. G. Payne – UoE
Remy Pascal - UoE
Dr. P. Parkin - UoE
Dr. A. Kiprakis - UoE
Dr. D. Mignard – UoE
Dr. T. Boehme - UoE

Research Staff (cont.)
Colin Bullen – HWU
Dr. L. Johanning – HWU/Exeter
Dr. A. Owen - RGU
Dr. A. McCabe – Lanc
Dr. H. Yavus - Lanc
Dr. T. Stallard – Lanc/Manchester
Dr. J. Meadowcroft - Lanc
Grant Allan - Strathclyde
Dr. K. Turner - Strathclyde
Dr. M. Ibrahim - Strathclyde
Dr. N. Kelly - Strathclyde
Dr. C. Johnstone - Strathclyde

Doctoral Students
Alastair Macdonald
Gareth Gretton
Jonathan Shek
Neil Hodgins
John Ruscoe
Jorge Lucas
Alexandra Price
Xaiojing Sun
Tom Davey
Mathew Topper
Michelle Gilmartin
Ben Child
Brian Sellar

Appendix 2 Publications by Work Package

WP 1 Appraisal of Energy Resource & Converters: Environment Interaction

[1] *Child, B.F.M and Venugopal, V. (2007). "Interaction of waves with an array of floating wave energy device." Proc. 7th European Wave and Tidal Energy Conference, paper 1059, Porto, Portugal, 11-13 Sept 2007.*

A method is presented to analyse wave interactions with an array of simplified wave energy devices. The problem is formulated in terms of a group of heaving vertical circular cylinders floating in the ocean, whose motion is damped by their power take-off mechanisms. Under the assumptions of linear wave theory, an exact analytical solution is derived in order to compute wave and body motion amplitudes. From these, the hydrodynamic heave exciting force, the added mass and damping coefficients, and the power extracted by each element of the array are calculated and presented as functions of incident wave number. The numerical implementation proved particularly efficient and the results compare very well with other theoretical and experimental work.

[2] *Chick, J., Bryden, I., and Couch, S.J. (2007). "The influence of Energy Extraction from Tidal Channels and its Impact on System Design." Underwater Technology, International Journal of the Society for Underwater Technology, 27, 2, 49-56, 2007/06, ISSN 0141-0814*

This paper explores the sensitivity of a simple model of open flows, which has been developed to facilitate the preliminary assessment of the suitability of tidal channels for energy exploitation. Using models deliberately simplified for clarity, the sensitivity is show to be dependent primarily upon length, depth and boundary roughness. The model results are then used to support the use of a non-dimensional number which may prove useful in future classification of the sensitivity of tidal channels. Energy extraction from a tidal stream is shown to have the potential for significantly altering the flow through the channel in question and, in so doing, imposes constraints on the design of the extraction system itself. This differs significantly from the practice of resource assessment in the wind energy industry.

[3] *Bryden, I.G. (2007). "Tidal Energy Commentary." World Energy Review 2007, in press.*

This document provides a statement of the state of development of tidal energy in 2007. It covers the technology and principles of tidal energy extraction, including barrage systems, lagoons and tidal currents. It also provides a largely non technical description of issues associated with resource assessment, environmental impact assessment and an informed speculation on future developments.

[4] *Couch S.J. and Bryden I.G. (2004). "The impact of energy extraction on tidal flow development." 3rd IMarEST International Conference on Marine Renewable Energy*

Application of 2-d and 3-d numerical tidal models in the marine renewable energy field has typically been to identify appropriate sites for marine energy extraction and quantify the potential energy available for extraction. Implicit in such an analysis is the assumption that local flow conditions will not be significantly altered by the energy extraction process. Considering the complex hydrodynamic conditions associated with the majority of sites identified as suitable for economic extraction of tidal energy, the general validity of this assumption is questionable. It is therefore necessary to develop modelling techniques which take account of the dynamic 'feedback' of extracting energy from the system. This will enable a more rigorous assessment of suitable sites for development and aid in determining the localised environmental impact of exploitation.

Results from a simplified one-dimensional analysis of the governing equations will be summarised. This analysis demonstrates the significant upstream and downstream effect of energy extraction on velocity and elevation in a simple channel set-up. The energy extraction theory has been extended to a sigma-layer model of the hydrostatic primitive equations. Simulations using idealised domains demonstrate the limits within which the 'blocking' effect of a tidal turbine 'farm' is of significance. This will address concerns that have been raised within the research community regarding the change to the hydrodynamic regime brought about by extensive energy extraction, and potential redistribution of tidal currents away from the installed location.

[5] *Couch S.J., Sun X., Bryden I.G. (2005). "Modelling of Energy Extraction from Tidal Currents." 6th EWTEC European Wave and Tidal Energy Conference.*

Although there are some similarities, the interpretation of energy extraction from tidal currents is substantially different from the wind. This paper outlines recent thinking into the influence of energy extraction of energy from tidal environments, taking particular care to consider the influence of the free surface.

In any environment energy extraction will, inevitably, result in degradation in the resource with possible economic and environmental impact. Reduced overall flow speed will affect resource assessments, whilst simultaneously influencing the transport of nutrients. Localised flow acceleration might, however, accelerate scour effects.

[6] *Couch, S.J. and Bryden, I. (2007). "Large-scale physical response of the tidal system to energy extraction and its significance for informing environmental and ecological impact assessment." IEEE/OES Oceans '07 Marine Challenges: Coastline to Deep Sea, 2007/06/18-21*

The impact of harvesting tidal energy on the underlying tidal hydrodynamics is examined. Understanding of both the near- and far- field physical response of the tidal system is necessary in order to inform environmental and ecological impact assessment. A number of numerical model test cases are presented which provide first stage indications of the potential response of the system.

[7] *Couch, S.J., and Bryden, I. (2006). "Tidal Current Energy Extraction: Hydrodynamic Resource Characteristics," Proceedings of the Institution of Mechanical Engineers, Part M: Engineering for the Maritime Environment, 220, 4, 185-194, 2006, ISSN 1475-0902*

There is an apparent lack of understanding of the tidal resource and its response to harvesting of energy among the principal proponents of the fledgling UK tidal energy industry: the device developers, principally supported by government funding. The authors' intent is to widen understanding of the different hydrodynamic conditions and controls that generate favourable conditions for tidal energy extraction. The paper outlines the generic hydrodynamic conditions that typically provide the most important fundamental requirement for harvesting tidal energy, namely a large tidal current resource. Five generic tidal regimes are presented, and the suitability of each regime for harvesting of energy is considered. Of the five regimes, two cases are identified as being most prevalent, but are generally unsuitable for economic exploitation. Understanding the significant differences between the driving mechanisms of each of the flow regimes is therefore key to effective site selection for large-scale development. Furthermore, the response of the different regimes to energy extraction from the system is not consistent further impacting on site selection. Numerical simulations of idealised examples highlighting the different hydrodynamic conditions in operation will be used to support descriptions of the relevant tidal flow regimes.

[8] *Bryden I.G., Couch S.J., Owen A. and Melville G. (2007). "Tidal Current Resource Assessment." Proc IMechE Journal of Power and Energy, Vol. 221, No. 2, pp. 125-135(11).*

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

[9] *Venugopal, V. and Smith, G.H. (2007). "The effect of wave period filtering on wave power extraction and device tuning." Ocean Engineering, 34, pp. 1120-1137.*

The variations in the quantity of wave power available to a wave energy converter by filtering out short-period waves have been examined in this paper. Ocean wave data recorded at three different locations and water depths around northern Europe are used for this purpose along with numerically synthesized wave time series. A wave power ratio, defined as the ratio between the wave power for the filtered and unfiltered data, is calculated for each data set, and the variation of this quantity with the degree of filtering is investigated. Two new parameters namely, R and S are defined to quantify the effect of this filtering on the variation of wave-to-wave period and height. It is shown that removing the shorter period waves has little effect upon the power available for extraction but may significantly reduce the rate at which the wave energy converter must retune to achieve optimum power conversion.

[10] *Bryden I.G., Couch S.J. and Harrison G. (2006). "Overview of the Issues Associated with Energy Extraction from Tidal Currents." World Renewable Energy Congress IX, Florence, Italy.*

Parallels are frequently drawn between the extraction of energy from the wind and the extraction of energy from tidal currents. At the device scale, this has some appropriateness but, at an environmental scale, the parallels can be misleading. This paper discussed methods of modelling the extraction of energy in one, two and three dimensions and how energy extraction might be expected to modify the flow patterns, including effects in the immediate vicinity of the technology. Such predictions could be used to assess the energy potential of a site. The resulting implications on the design of appropriate tidal technology are briefly discussed.

[11] *Bryden I.G. and Couch S.J. (2005). "ME1 - Marine Energy Extraction: Tidal Resource Analysis." Renewable Energy, RENE2412, paper 10.1016/j.renene.2005.08.012.*

This paper outlines some of the issues which need to be considered when analysing the extraction potential of a tidal current resource. Site selection is not a simple case of identifying an energetic site with an appropriately large peak tidal current. The characteristics of the current throughout the lunar tidal cycle must be considered. Furthermore, implicit in such an analysis is the assumption that the local tidal flow conditions will not be significantly altered by the energy extraction process itself. For high extraction rates, the general validity of this assumption is questionable. The influence of energy extraction upon the underlying hydraulic nature of the tidal environment must be considered. Analysis based upon open channel flow theory demonstrates that energy extraction in a simple channel driven by static head differences can have a significant upstream and downstream effect. This suggests that the environmental impact of energy extraction is not necessarily restricted to the immediate area around the extraction site. It also suggests that there is potential for the process of energy extraction to either diminish or even enhance the available resource at a particular site. Further research is required and is ongoing in this area. In the case examined, the limits to exploitation are shown to be inexact. However, a useful approximate guideline for resource analysis would be that 10% of the raw energy flux produced by the tide can be extracted without causing undue modification to the flow characteristics.

[12] *Bryden I. and Couch S.J. (2004). "Marine Energy Extraction: Tidal Resource Analysis", WREC04, Denver.*

This paper outlines some of the issues which need to be considered when analysing the extraction potential of a tidal current resource. Site selection is not a simple case of identifying an energetic site with an appropriately large peak tidal current. The characteristics of the current throughout the lunar tidal cycle must be considered. Furthermore, implicit in such an analysis is the assumption that the local tidal flow conditions will not be significantly altered by the energy extraction process itself. For high extraction rates, the general validity of this assumption is questionable. The influence of energy extraction upon the underlying hydraulic nature of the tidal environment must be considered. Analysis based upon open channel flow theory demonstrates that energy extraction in a simple channel driven by static head differences can have a significant upstream and downstream effect. This suggests that the environmental impact of energy extraction is not necessarily restricted to the immediate area around the extraction site. It also suggests that there is potential for the process of energy extraction to either diminish or even enhance the available resource at a particular site. Further research is required and is ongoing in this area. In the case examined, the limits to exploitation are shown to be inexact. However, a useful approximate guideline for resource analysis would be that 10% of the raw energy flux produced by the tide can be extracted without causing undue modification to the flow characteristics.

[14] *Bryden I.G. (2006). "The Marine Energy Resource, Constraints and Opportunities." Proceedings of the Institution of Civil Engineers: Maritime Engineering 159, Issue MA2, pp 55-65.*

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

[15] *Bryden, I. and Couch, S.J. (2007). "How much energy can be extracted from moving water with a free surface: a question of importance in the field of tidal current energy?" Journal of Renewable Energy, 32, pp. 1961-1966.*

This short technical note addresses the extraction of energy from a simplified channel in which flow is driven by a head difference between inlet and outlet. This model is used to indicate that there is a maximum rate at which energy can be artificially extracted from the flowing water and that this rate is related to the kinetic energy flux in the unexploited channel but with a multiplying factor which is related to the channel physical properties. Counter intuitively, this multiplier can exceed unity in some circumstances. The simple channel has some similarities to tidal channels but is here presented as an abstraction to allow appreciation of the relationships between energy extraction, flow speed and channel properties.

[16] *Venugopal, V. and Smith, G.H. (2007). "Wave climate investigation for an array of wave power devices." Proc. 7th European Wave and Tidal Energy Conference, paper 1071, Porto, Portugal, 11-13 Sept 2007.*

This paper presents the results of a study carried out to determine the change in wave climate around an array of hypothetical wave devices. The main objective of this work is to investigate the change in wave height in the upstream and downstream of the devices for different levels of wave absorption. This is achieved by modelling the wave devices as porous structures with different porosity levels, with the inclusion of partial reflection and partial transmission. The MIKE 21 suite wave models, (i) Spectral wave and (ii) Boussinesq wave are used for this purpose. The former wave model is employed for the estimation of various phase averaged wave parameters for the Orkney Islands. These wave parameters are then used as input to the Boussinesq model to study wave-device array interactions. The results are presented in the form of wave disturbance coefficients defined as a ratio of the significant wave height at a particular location relative to the incoming or input significant wave height. This study illustrates how the variations in wave absorption by the devices affect the degree of wave reflection and transmission around the devices.

[17] *Couch, S.J. and Bryden, I. (2005). "Numerical Modelling of Energy Extraction from Tidal Flows." Proc WREC 2005 Conference (May 22nd-27th), Aberdeen, Scotland.*

Research into harvesting energy from tidal resources is generally focussed on extraction technology, impact of the fluid environment on the device and grid integration. Of equal fundamental importance is the feedback on the tidal system from energy extraction and potential blocking effects of extraction devices. Development of traditional 2-d and 3-d numerical tidal models to account for the impact of energy extraction in the tidal system is summarised. Using the numerical modelling output produced from simple idealised domains, the physical response of the system to energy extraction is elucidated. Further analysis of the balance of terms in the alongshore momentum equation aids in understanding the underlying dynamical response of the system.

[18] *Harrison, G.P., Couch S.J., Bryden I and Wallace A.R. (2006). "Climate Change Impacts on Marine Energy Resources." European Conference on Impacts of Climate Change on Renewable Energy Sources, 5-9 June 2006, Reykjavik, Iceland.*

Marine energy sources like wave, offshore wind and tidal current could have a significant role to play in lowering carbon emissions within the energy sector, particularly in Western Europe. Ironically, these resources may be susceptible to changes in climate that will result from rising carbon emissions: wind patterns are expected to change and this will alter wave regimes and there appears to be potential for tidal currents to be affected by rising sea levels. Despite a lack of definite proof of a link to global warming, over the past few decades, wind and wave conditions have been changing and sea levels have risen. Here, the potential climate sensitivity of these marine energy technologies is outlined in terms of the changes in the resource, energy capture and the implications for project economics.

[19] *Harrison, G.P. and Wallace, A.R. (2005). "Sensitivity of wave energy to climate change." IEEE Trans. on Energy Conversion, 20 (4), pp. 870-877.*

Wave energy will have a key role in meeting renewable energy targets en route to a low carbon economy. However, in common with other renewables, it may be sensitive to changes in climate resulting from rising carbon emissions. Changes in wind patterns are widely anticipated, and this will ultimately alter wave regimes. Indeed, evidence indicates that wave heights have been changing over the last 40 years, although there is no proven link to global warming. Changes in the wave climate will affect wave energy conversion. Where the resource is restricted, there may be reductions in energy exports and, consequently, negative economic impacts. On the other hand, increased storm activity will increase installation survival risks. Here a study is presented that, for the first time, indicates the sensitivity of wave energy production and economics to changes in climate.

[20] *Harrison, G.P. and Wallace, A.R. (2005). "Climate sensitivity of marine energy." Renewable Energy, 30 (12), pp. 1801-1817.*

Marine energy has a significant role to play in lowering carbon emissions within the energy sector. Paradoxically, it may be susceptible to changes in climate that will result from rising carbon emissions. Wind patterns are expected to change and this will alter wave regimes. Despite a lack of definite proof of a link to global warming, wind and wave conditions have been changing over the past few decades. Changes in the wind and wave climate will affect offshore wind and wave energy conversion: where the resource is constrained, production and economic performance may suffer; alternatively, stormier climates may create survival issues. Here, a relatively simple sensitivity study is used to quantify how changes in mean wind speed—as a proxy for wider climate change—influence wind and wave energy production and economics.

[21] *Smith G. H., Venugopal V. and Wolfram J. (2006). "Wave period statistics for real sea waves and wave energy extraction." Proc I Mech E, Part M, Journal for the Maritime Environment, 220, Special Issue, 1-17.*

The paper describes the analyses of wave data recorded at various locations and water depths around northern Europe to determine the temporal characteristics of individual wave periods and other wave period statistics. These analyses show that, just as there are group characteristics for wave heights, there are similar, but less pronounced, characteristics for wave periods. This is observed in three separate sets of data from different locations in water depths of 18, 50, and 130 m. It is also found in time series simulated using random linear wave theory from a Jonswap spectrum. A simple, new statistic, R, is introduced that measures the rate of change in the wave period from one wave to the next. This is relevant to wave energy devices that may try to tune themselves to obtain optimum power output from each individual wave. The characteristics of this statistic and its variation with significant wave height, mean energy period, and spectral bandwidth have been examined for the three datasets and are discussed. It is found that the R statistic can be fitted quite well by a Gaussian distribution for all the datasets examined. In a real sea there will be many small waves with comparatively very little energy, and the effect of filtering these out upon the R statistic has been examined. It is seen that removing the small waves has very little effect upon the energy available for extraction but significantly reduces the rate at which the wave energy device must retune to obtain optimum power conversion. This is illustrated by considering a hypothetical wave energy device, with a representative power transfer function, that can retune at prescribed rates. It is shown that being able to tune to individual waves can greatly increase power output.

[22] *Sellar, B.G., Bruce, T. and Wallace, A.R. (2007). "Providing Sea Surface Elevations for Marine Energy Converters using a Novel Optical Fibre Sensor: Progress in the Flume." 7th European Wave and Tidal Energy Conference. Porto, Portugal.11-13th September, 2007.*

Marine energy converters will require the implementation of control strategies to achieve viability in some cases and maximise profitability in most. These control strategies may require distributed information on the wave field in which the device resides. A novel method of obtaining this data is investigated using a lattice of treated optical fibres constrained on a flexible substrate and fitted with floatation aids. By measuring the intensity of light lost at bends along its length the patented device, Shape Tape™, can sense its position in three dimensions. Preliminary tests involving JONSWAP spectra, generated in a 20 metre long, 0.7 metre deep two-dimensional wave flume, show the flexible ribbon predicts Hm0 and Tm01 with errors less than 16% and 9% respectively when compared to wave gauge measurements. Repeatability tests using regular wavetrains provide standard deviations away from the results of wave gauges of 5% in wave height and 1% in wave period.

[23] *Lucas, J., Cruz, J., Salter, S., Taylor, J. and Bryden, I. (2007). "Update on the modelling of a 1:33 scale model of a modified Edinburgh duck WEC." Proc. of the 7th European Wave and Tidal Energy Conference, Porto, Portugal, September 2007.*

A modified version of the Edinburgh duck wave energy converter has been studied recently at the University of Edinburgh. From the design point of view the key innovation was a modification of the wetted profile. Wave energy is converted into useful work by the same pitching motion as in the original duck, but by means of a circular cylinder with an off centred axis of rotation. This recent study was focused on a duck version designed for vapour compression desalination rather than electricity production. The duck was partially filled with water and the motion of the water inside provided the necessary pump effect for the vapour compression. The inner water behaves as an inertial reference as well as a double-acting piston. Under the assumptions taken, the results can be applied also to the electricity production version.

WAMIT was used to predict the hydrodynamic coefficients and to select a set of configurations. A 1:33 scale model was tested at the Edinburgh curved tank to validate the numerical predictions.

This paper extends the already published numerical predictions and experimental results obtained with this model, and reports on the new experimental tests and features. The relative capture width of the device that resulted from the measurements is presented, as well as he measured mooring forces in regular waves. Finally, the behaviour of a linear damper used to model the power-take-off mechanism is analysed.

[24] *Quayle, S.D and Aggidis, G.A. (2006). "Preliminary Investigation of Multi-Element Profiles for a High-Lift Variable Pitch Vertical-Axis Tidal Stream Device." (Invited Paper), Fluid Machinery Group of the Institution of Mechanical Engineers, 'CFD for Fluid Machinery', IMechE, London, 24th October 2006, IMechE, Event Publications, v 2006 10, IMechE Conference Transactions.*

Multi-element profiles have been used for decades to assist aircraft during landing and take-off by significantly increasing lift during these vital stages of operation. This paper presents the preliminary CFD results used to validate and optimise the design of a multi-element profile for a vertical axis tidal stream energy device, where the relative velocities, fluid type and Reynolds number differ significantly from that found in the aerospace sector. A vertical axis device has been selected as it offers significant advantages in shallower tidal water, often found near shore thus reducing the required infrastructure and set up costs associated with the deployment of new technologies. The UK is in a prime position to exploit energy capture from Tidal Stream with the advantage over other renewable sources in that it is completely predictable.

[25] *Harrison, G. P. and Wallace, A. R. (2005). "A changing climate for marine energy." Proc. 6th European Wave and Tidal Energy Conference, Glasgow, September 2005.*

Wave energy is critical to the move to a low carbon economy. Unfortunately, like other renewables, it may be sensitive to changes in climate resulting from rising carbon emissions. Changes in wind patterns are forecast and these will alter wave regimes. Evidence indicates that wave heights have been changing over recent decades, although there is no proven link to global warming. Changes in wave climate will impact on wave energy conversion: resource restrictions may lower energy exports with consequent negative economic impacts. Alternatively, increased storm activity will increase survival risks for installations. Here, evidence of recent wave climate change is outlined together with projections of the future. Methodologies for inferring future change are compared and a simple case study is presented.

[26] *Harrison, G. P. and Wallace, A. R. (2005). "Climate change impacts on renewable energy – is it all hot air?" Proc. of World Renewable Energy Congress, 22–27 May 2005, Aberdeen.*

The harnessing of renewable energy sources is vital to constraining the extent of climate change. However, the very fact that such sources are driven by the climate may leave them exposed as climate changes over the coming decades. The impacts will manifest themselves through changes in resource, altered operational capability and impacts on economic performance. With the electricity industry increasingly market-based it is the latter impact that will be of most concern to would-be investors. This paper reviews the current level of understanding of climate change and the potential implications for a range of renewable energy sources including hydropower, wind and wave.

[27] *Taylor, J.R.M. and Motion, A. (2005). "Estimating wave energy in Scottish waters from hindcast data." Proc. 6th European Wave and Tidal Energy Conference, Glasgow, 30th Aug - 1st October 2005.*

Wave hindcasting provides a practical and cost effective alternative to in-situ measurement for the estimation of directional wave climates over a large number of geographically dispersed sites. Hindcasts based on data from the UK Met Office have previously been used to assess the wave resource in UK waters but recent increases in temporal and spatial resolution have improved the quality and quantity of the information that is available. In this paper, the Met Office hindcasting process is described and data from April 2000 to March 2004 is used to calculate average wave power levels and directions for a set of 95 'gridpoints' within Scottish waters. A comparison with concurrent buoy measurements near to one of the grid-points is made.

[28] *Bryden I .G, Grinsted, T. and Melville, G.T. (2005). "Assessing the Potential of a Simple Tidal Channel to Deliver Useful Energy." Applied Ocean Research, Vol. 26/5 pp. 200-206, 10.1016/j.apor.2005.04.001, 2005.*

This paper briefly outlines the principles of energy extraction from tidal currents and develops a simple model, based upon open channel flow, for the assessment of the influence of such extraction upon the underlying hydraulics. It is shown that energy extraction does alter the flow within a simple channel. Extraction of 10% of the energy flux in a natural, undisturbed channel would produce a flow speed reduction of under 3% rising to 6% for the extraction of 20% of the natural flux. The authors suggest that 10% extraction could be considered as a guideline for developers wishing to make a conservative estimate of the extractable resource in a simple channel.

[29] *Gretton, G. I. and Bruce, T. (2005). "Preliminary results from analytical and numerical models of a variable-pitch vertical-axis tidal current turbine." Proceedings of the 6th European Wave and Tidal Energy Conference, Glasgow, UK.*

This paper presents work on the analysis of a variable-pitch vertical-axis tidal current turbine. An analytical Blade Element Momentum (BEM) model has been used to investigate key design parameters such as turbine geometry and tip speed ratio, and also the effect of blade pitch control. In order to better understand the time-varying nature of the problem, a commercial Computational Fluid Dynamics (CFD) package has been used to simulate the flow around the turbine.

Results from the analytical model show that a considerable performance advantage can be gained from the use of variable-pitch blades, especially at the low tip speed ratios which might be necessary to avoid cavitation. Whilst the work on CFD modelling is at an early stage, it highlights the potential for increased understanding of the flow patterns through and around a vertical-axis turbine.

[30] *Gretton, G. I. and Bruce, T. (2006). "Hydrodynamic modelling of a vertical-axis tidal current turbine using a Navier-Stokes solver." Proceedings of the 9th World Renewable Energy Congress, Florence, Italy.*

A commercial Computational Fluid Dynamics (CFD) program, CFX, which solves the Navier-Stokes equations, has been used to simulate the flow through a vertical-axis tidal current turbine. The simulation domain consists of a two-dimensional slice through the turbine in the horizontal plane. The solution is transient and so the angular position of the blades, which are contained within a rotating domain, is time dependent. Results from this numerical simulation are compared with those from an analytical Blade Element Momentum (BEM) model. The cyclical torque signal generated by a single blade on a turbine is used as a comparator. Qualitatively the comparison is good with the salient features of the signal similarly represented. The greatest discrepancy occurs when the analytical model predicts the blades to be in stall when the numerical model does not.

[31] *Smith, G. H., Venugopal, V. and Wolfram, J. (2006). "Wave Period Group Statistics for Real Sea Waves and Wave Energy Extraction." Proc. I Mech. E. Part M: J. Engineering for the Maritime Environment, Vol. 220, No.3, pp. 99-115(17).*

The paper describes the analyses of wave data recorded at various locations and water depths around northern Europe to determine the temporal characteristics of individual wave periods and other wave period statistics. These analyses show that, just as there are group characteristics for wave heights, there are similar, but less pronounced, characteristics for wave periods. This is observed in three separate sets of data from different locations in water depths of 18, 50, and 130 m. It is also found in time series simulated using random linear wave theory from a Jonswap spectrum. A simple, new statistic, R, is introduced that measures the rate of change in the wave period from one wave to the next. This is relevant to wave energy devices that may try to tune themselves to obtain optimum power output from each individual wave. The characteristics of this statistic and its variation with significant wave height, mean energy period, and spectral bandwidth have been examined for the three datasets and are discussed. It is found that the R statistic can be fitted quite well by a Gaussian distribution for all the datasets examined. In a real sea there will be many small waves with comparatively very little energy, and the effect of filtering these out upon the R statistic has been examined. It is seen that removing the small waves has very little effect upon the energy available for extraction but significantly reduces the rate at which the wave energy device must retune to obtain optimum power conversion. This is illustrated by considering a hypothetical wave energy device, with a representative power transfer function, that can retune at prescribed rates. It is shown that being able to tune to individual waves can greatly increase power output.

[32] *Gretton, G. I. and Bruce, T. (2007). "Aspects of mathematical modelling of a prototype scale vertical-axis turbine." Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal.*

Hydrofoil section data, comprising coefficients of lift and drag, are a key input into blade element momentum models of turbines. The aim of this paper is to investigate whether differences in this section data are to account for the predictions from blade element momentum models and Navier-Stokes solutions (using a computational fluid dynamics programme) disagreeing. To this end, a number of sources of hydrofoil section data were researched and compared. It was found that there were notable differences in the coefficients given by the data sets. Two of the data sets, namely the Sheldahl and Klimas data and results produced by the authors with Xfoil, were used as input into the blade element momentum model. When compared with the results from the CFD solution, there is disagreement between all of the results, although the results produced from the blade element momentum model with the Xfoil coefficient data are closer to the CFD results than those produced with the Sheldahl and Klimas data. This shows that whilst uncertainties in the section data may be partially responsible for the disagreement between the two models, other uncertainties must also be significant.

[33] *Ortega, J. and Smith, G.H. (2007). "Spectral Analysis of Storm Waves Using the Hilbert-Huang Transform." Submitted to 16th International Offshore and Polar Engineering Conference (ISOPE) July 2007.*

We use the Hilbert-Huang Transform (HHT) for the spectral analysis of waves during a storm in the North Sea that took place in 1999. We look at the contribution of the different Intrinsic Mode Functions (IMF) obtained by the Empirical Mode Decomposition algorithm and also compare the Hilbert Marginal Spectra and the classical Fourier spectra for the data set and for the corresponding IMFs.

[34] *Smith, G.H. and Venugopal, V. and Fasham, J. (2006). "Wave spectral bandwidth as a measure of available wave power." Proceedings of 25th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2006-92379, 1-9, June 4-9.*

A key requirement in the description of the performance of a wave energy converter is how the efficiency of power capture changes with the properties of the sea. This paper examines the effect of two generic power transfer functions (PTF) on power production from six simulated wave spectra. These were chosen to represent a series of wind, wind-swell mixed and swell dominated seas. The spread in energy within the sea state as defined by a variety of bandwidth parameters were examined to determine if there was a correlation between the width of the transfer function and the sea bandwidth. It was found that, for the 'constant' height PTF, the bandwidth parameter Bb (calculated using zeroth, minus-one and minus-two spectral moments) provided the best performed poorly. When theν and εcorrelation. Customary bandwidths PTF was allowed to vary in height as well as width there was little improvement in correlation from the un-scaled results.

[35] *Vuillemin, J. and Harrison, G. P. (2007). "On wave climate predictability: a mesoscale model to assess future wave energy potential." Waves and operational Oceanography / GLOBWAVE Project Workshop, 19-21 September 2007, Brest, France.*

The growing interest in wave energy together with coordinated actions between ocean energy companies and research organisations should lead in the near future to large scale wave power deployment. However, in developing sustainable wave power facilities, one should carefully consider the availability of wave resources over space and time. Whatever the wave energy conversion (WEC) technology considered and its performance, the location of sites that offer high wave intensity together with reasonable development and operations and maintenance costs is a key asset in assuring appropriate financial return. Importantly, the resource availability over the scheme lifecycle is critical in guaranteeing the technological and economic viability of any WEC project. This is particularly true in the context of climate change which could impact plant operation by changing power generation capability or placing a limit on their structure. In developing sustainable wave power facilities, there is clearly a need for studying climatic variables and anticipating their influence on wave energy resources over the long-term.

The variability of atmospheric circulation is the most important factor determining changes in spatial and seasonal distribution of climatic elements like wind speed which influence wave climate. Various studies report relationships between atmospheric pressure gradients in the North Atlantic (NA) basin and wave heights, frequency or even extreme waves. This fact suggests that if we manage to predict the likely changes in prominent modes of low-frequency variability like the North Atlantic Oscillation (NAO) and the East Atlantic Pattern (EAP), we may provide the ocean energy sector and related industries with capital indications. In this respect a mesoscale wave climate model off the British Isles is being developed. Combining ship, buoy, and satellite data with reconstructed weather information (re-analysis products) and numerical simulations of the climate system (GCMs), this model should improve our knowledge of wave climate over the Atlantic Ocean and contribute to a relevant assessment of potential wave energy farm sites in the context of climate change.

WP2 Development of Methodologies for Device Evaluation and Optimisation

[36] *Cruz, J., Payne, G. (2006). "Preliminary numerical studies on a modified Edinburgh duck using WAMIT." In: Marine Renewable Energy Conference (MAREC), London, U.K.*

A novel offshore wave powered desalination device is currently being studied at the University of Edinburgh using numerical modelling. The device is based on a modified version of the Edinburgh duck. Its hydrodynamic behaviour is investigated using the boundary element method (BEM) package WAMIT. This paper presents the first set of studies related to the numerical modelling of a three degree of freedom version of the desalination device in regular waves. Several configurations are considered and characterized with regard to the hydrodynamic coefficients, the wave exciting force and the response amplitude operator. Future studies based on these results will provide experimental data to benchmark the numerical predictions.

[37] *Owen, A., and Bryden, I.G. (2006). "A novel graphical approach for assessing tidal stream energy flux in the Channel Isles", Proceedings of the IMarEST Part C, Journal of Marine Science and Environment, C4, IMarEST technical proceedings Part C.*

A novel flux methodology approach to modelling the energy available in tidal streams is demonstrated, and compared with an earlier assessment using the farm methodology. Using a combination of existing public domain pictorial data and the graphical capabilities of a readily available BASIC programme it is shown that a realistic quantification of the overall energy flux within a tidal stream can be found, relatively quickly and without the need to employ complex numerical models. The method is applied to the Channel Islands and compared to an earlier study, which used the farm methodology. The results indicate that whilst the resource may not be as large as previous reports suggest, current understanding of tidal stream energy flux is now on firmer ground.

[38] *McCabe, A. P., Bradshaw, A., and Widden, M. B., (2005). "A time-domain model of a floating body using transforms." 6th European Wave and Tidal Energy Conference (6th EWTEC), University of Strathclyde, Glasgow, 30th August – 2nd September 2005.*

This paper presents the use of Laplace transfer functions in the formulation of time-domain models of floating bodies. The transfer functions are Laplace transformations of the 'memory' function convolutions in the generally-accepted form of time-domain models and are derived directly from the hydrodynamic characteristics of the floating body. Consequently, the impulse responses, which form the kernels of the convolution integrals, need not be calculated. In addition, the model may be readily converted into alternative forms, such as state-space models, to facilitate dynamic analysis and control design. A single degree-of-freedom model is used as an example system and its responses to regular and irregular wave inputs are assessed to demonstrate the capabilities of the method.

[39] *Payne, G. (2007). "A modular graphical user interface for WAMIT." 7th European Wave and Tidal Energy Conference, Porto, Portugal.*

The hydrodynamic numerical modelling package WAMIT is a widely used boundary element method code. It is mainly distributed in its PC executable version which does not include any graphical user interface. Instead, input settings are entered into the program by means of text files. Computation results are output in the same way. Preparation of the input files and post-processing of the outputs is often time consuming and repetitive. This paper presents a graphical user interface addressing this task. The interface, programmed in MatLab, is split into pre- and post-processing parts. Its key feature is its modular structure. The programme consists of numerous independent modules that carry out specific and self contained tasks. This makes it easy to customise the interface to suit new requirements.

[40] *McCabe, A. P., Aggidis. G.A. and Stallard, T. J. (2006). " A time-varying parameter model of a body oscillating in pitch." Applied Ocean Research 28 (6): 359-370 Dec 2006, Pergamon-Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, England*

Among the assumptions upon which linear time-invariant models of floating bodies are based is that the body motions are so small that any change in the body's angular position can be disregarded. However, it is often a major design requirement of a wave energy conversion device that the response amplitude is large, thereby invalidating one of the assumptions of the linear model. In particular, the immersed geometry of a body undergoes considerable variation when it is moved in pitch. With regard to this we investigate the difference in performance between a quasi-linear model in which the change of immersed surface is modelled by time-varying parameters and a basic linear model in which the immersed surface is time-invariant. The time-varying parameter model is realized by interpolation between the appropriate parameter values of a set of linear time-invariant (LTI) models derived for the different immersed surfaces that occur at discrete body displacements. It is shown that the responses predicted using the time-varying parameter model are closer to those measured experimentally than those of a standard frequency-domain model. Particular improvement occurs when the responses are large, such as at or near the resonance frequency. A problem which may limit the general use of the model is also discussed.

[41] *McCabe, A.P., Aggidis, G.A., and Stallard, T.J. (2006). "Comparable performance characteristics from different test sites." (Invited Paper), 4th EC Co-ordination Action on Ocean Energy Workshop - Performance Monitoring of Ocean Energy Systems, INETI, Lisbon, Portugal.*

A wide range of technologies have been developed to convert the irregular oscillations of kinetic and potential energy of ocean waves into useful electrical energy. The performance of all devices is dependent on the characteristics of the incident wave-field. Standard testing procedures look to define the performance of a device by its annual power capture. Typically, this is estimated as the overall product of two matrices: a wave-field occurrence matrix and a power capture matrix. The wave field matrix is site-specific and describes the probability that a wave-field with given significant wave height and zero crossing period will occur at a random instant. A power capture matrix is device specific and describes the mean power generated by the device in a wave-field characterised by a given combination of significant wave height and zero crossing period. Draft guidelines for the measurement of wave energy device performance suggest that the power capture stated for a given pair of characteristics should be the mean of that measured in at least six statistically similar wave-fields. Such criteria have been met by few device developers and so
it is important to note that, whilst power capture matrices have been published by several device developers, there is little publicly-available evidence from offshore tests to support the figures stated.

To avoid compromising the intellectual property of companies developing devices, simplified models are used to predict the performance of a device at a number of sites around the UK. Linear mathematical models are used to describe the characteristics of point-absorber wave power device whose performance approaches the theoretical limit of a point absorber in regular waves.

The site-specific wave data was provided by the UK Met-Office (UKMO) numerical weather prediction model, a hindcast wave model which calculates the wave conditions from forecast wind conditions. Seven locations within the UK waters wave model and one taken from the North-Western European waters model provide a wide range of sea states for performance comparison.

[42] *Payne, G., Taylor, J., Parkin, P. and Salter, S. (2006). "Numerical modelling of the Sloped IPS Buoy wave energy converter." 16th International Offshore and Polar Engineering Conference (ISOPE 2006), San Francisco.*

The Sloped IPS Buoy is a deep-water wave-energy converter concept whose power take-off mechanism relies on water inertia for reference. The present work deals with the modelling of this device using the higher order feature of the boundary element method package WAMIT. In a first stage, numerical predictions are compared with experimental data for a configuration where the system motion is constrained to a single degree of freedom. Comparisons are then established, initially for a free-floating configuration with no power take-off system and then with damping applied by a power take-off system.

WP 3 Engineering Guidance

[43] *Aggidis, G.A. Bradshaw, A. French, M.J. McCabe, A.P. Meadowcroft, J. A. C. and Widden, W.B. (2005)."PS Frog MK 5 WEC developments and design progress." World Renewable Energy Congress, Aberdeen.*

This paper describes the latest progress on the development and design of PS Frog Mk 5, one of the most innovative wave energy converters under development by the Lancaster University Renewable Energy Group.

PS Frog Mk 5 is an offshore point-absorber wave energy converter that consists of a large buoyant paddle with an integral ballasted 'handle' hanging below it. The waves act on the blade of the paddle and the ballast beneath provides the necessary reaction. When the WEC is pitching, power is extracted by partially resisting the movement of a power-take-off. The WEC is maintained in a resonant state by the use of special means to maintain a high dynamic magnifier in irregular seas. A robust feedback control system has been developed to ensure stability and maintain efficient power take-off. Totally enclosed in a steel hull, with no external moving parts, PS Frog Mk. 5 is at least as robust as a ship and able to survive storms.

Computer simulation and tank tests suggest that this device can provide a credible and economic method for harnessing more of the world's wave power resource. Promising power output characteristics are obtained and the possibility of significant improvements in performance are anticipated. Such a device could be very economic in terms of power output per unit of capital cost.

[44] *Couch, S.J., Wallace, A.R. and Bryden, I. (2007). "Overview of the SUPERGEN Marine Energy Research Program." IEEE International Conference on Clean Electrical Power 2007, 2007/05/21-23*

An overview of the SUPERGEN Marine Energy research program is presented. The research program is focussed on supporting the development of marine renewable energy exploitation through generic research to reduce investment risk and uncertainty. Background to the research program, progress to date, and future plans are all summarised.

[45] *Couch, S.J., Jeffrey, H.F. (2007). "Tidal current energy: Device Performance Protocol - Response to feedback from 19th July Workshop and consultation." 15, 2007/02. Available from http://www.berr.gov.uk/files/file38991.pdf*

On 2nd August 2004 the Secretary of State for Trade and Industry announced a new 'Marine Renewables Deployment Fund' worth £50 million. At the core of this program is a 'Wave and Tidal Stream Energy Demonstration Scheme' (the Scheme) taking up to £42 million of the total fund. Within the requirements of the Scheme a monitoring and reporting program is mandated. In April 2006 the Department of Trade and Industry (DTI) commissioned the production of a 'Tidal Current Energy Device Performance Assessment Protocol (the Protocol) by the University of Edinburgh to provide a framework within which the monitoring and reporting program would be prescribed.

The approach taken by the University of Edinburgh to producing the Protocol involved the production of a draft Protocol obtaining input from specific key stakeholders where deemed appropriate, holding a Workshop with, and inviting written responses from key stakeholders to discuss the draft Protocol, leading to the production of a preliminary Protocol document to be deliver to the DTI.

A total of 30 stakeholders were consulted during the production of the preliminary Protocol, including 15 participants at the Workshop. The response to the Protocol document elicited thus far has given broad support. In light of discussions during the Workshop, and written responses received a number of amendments have been made to the original draft version of the Protocol. While not changing the fundamental nature of the protocol, these amendments seek to improve the 'fit-for purpose' intent of the Protocol procedure and reporting format. Fit-for-purpose in this context is defined as obtaining an effective balance between quality and quantity of data collection, processing and delivery and operational achievability without being overly burdensome on the Scheme participants.

This document provides an explanation of the changes that have been made to the Protocol, our arguments against some of the suggestions put forward or discussion points that was raised by stakeholders and response to further queries or requests for clarification by the client.
In parallel with this document we have also produced the finalised preliminary version of the Protocol

(version 1.3).

We would like to thank all the participants in the Workshop and written respondents for the feedback we have received. In particular the lively discussion, openness and willingness to share experience observed at the Workshop have been very valuable both in advocating the framework underlying the draft Protocol and in the continued development of the preliminary Protocol.

[46] *Couch, S.J., Jeffrey, H.F. (2007). "Preliminary Tidal Current Energy: Device Performance Protocol." 13, 2007/02. Available from* *http://www.berr.gov.uk/files/file38993.pdf*

The DTI's Wave and Tidal Stream Energy Demonstration Scheme, part of the Marine Renewable Deployment Fund (MRDF) supports the development of full-scale, grid connected, multi-device wave and tidal-current energy demonstration facilities. An important objective of the Scheme is the production of transparent, unambiguous, consistent and meaningful assessments of the performance of tidal devices and arrays of tidal devices. This will enable the performance of devices to be effectively validated and, consequently, enable government, industry and the finance/investment community to form soundly based judgements of the commercial prospects of the technologies being demonstrated. To ensure that the performance of different devices is assessed on a consistent basis, there is a need for an explicit written protocol, which will form part of the contract between MRDF Scheme Participants and the Secretary of State. The protocol sets out in detail how performance assessment should be conducted.

This document proposes a preliminary Protocol for the performance testing of tidal current energy devices/arrays. Feedback on the initial draft Protocol document has been compiled, and where deemed appropriate, incorporated into the finalised preliminary protocol. This exercise is detailed in the accompanying "Response to feedback" document. It is acknowledged at this stage that knowledge gaps exist which impact on the proposed Protocol. These knowledge gaps have been identified in the accompanying documentation. Research to address the key knowledge gaps will inform the content of the final Protocol document adopted by the DTI for the MRDF Scheme.

[47] *Couch, S.J., Jeffrey, H.F. and Bryden, I. (2007). "Tidal Current Energy: Development of a Device Performance Protocol." IEEE International Conference on Clean Electrical Power.*

Development of devices for the exploitation of tidal current energy is reaching the pre-commercialisation phase. In order to equitably test device performance, a standardised procedure for testing is desirable. To meet the remit of the UK government funded Marine Renewable Deployment Fund demonstration scheme, a performance testing protocol was required. This paper discusses the development of, and summarises the requirements of the protocol developed to meet this requirement.

[48] *Mueller, M.A. and Wallace, A.R. (2006). "A road map for marine renewable energy research in the UK." Proceedings of the Institute of Marine Engineering, Science and Technology, Part A8, ISSN 1476-1548.*

The role of the UK Energy Research Centre Marine Energy Research Network in developing a route map for marine renewable energy research is described and put into the context of previous and current marine energy research at a national and EU level. A summary of the route mapping process is given based upon the Batelle approach. Justification is provided for route mapping in terms of encouraging cooperation and collaboration within the community to develop a coherent research, development and demonstration strategy, which will be used to inform policy makers and funding bodies. Some preliminary outputs from the network are presented in the paper to encourage discussion.

[49] *Cruz, J., Pascal, R., and Taylor, J. (2006). "Characterization of the wave profile in the Edinburgh curved tank." Proceedings of OMAE2006 25th International Conference on Offshore Mechanics and Arctic Engineering, Hamburg, Germany.*

A novel wave tank has been in use at the University of Edinburgh since 2003. Its main innovation is in the layout of the absorbing/wave-maker paddles, which are arranged in a 90-degree arc in an attempt to improve the angular spread of the generated three-dimensional sea states, and to minimise cross-tank seiches.

This paper reports on current studies that aim to assess the quality of the waves in the tank. Directional regular and irregular wave analysis is conducted using data from two arrays of wave elevation probes. Comparisons with the expected wave patterns are made. Emphasis is given to the description of the experimental methodology. The study should prove particularly relevant in the design of a future circular combined wave and current tank.

[50] *Bryden I. G. and Melville G. (2004). "Choosing and Evaluating Sites for Tidal Current Development." Proc. IMechE Journal of Power and Energy, Vol. 218, p567-578, London, ISSN 0957-6509.*

Tidal energy has been used since Roman times, although the use of tidal currents as a possible industrial energy source is a more modern concept. Unlike wind power, however, there is still no consensus on the most appropriate technology for resource exploitation. Similarities with wind power can cause errors of interpretation, especially when attempting to assess resource potential. The energy availability estimates that have been produced have, until now, only taken account of the apparent current flow speeds before the extraction of energy. As demonstrated in this paper, this may not be appropriate, especially for large energy extraction rates, which alter the underlying hydraulic nature of the flow environment. In a simple hypothetical channel linking two infinite oceans, a maximum extraction of 10 per cent of the apparent raw kinetic flux would appear to be acceptable. The limitations on sea loch type environments may, however, be less restrictive.

[51] *Douglas, C. A., Harrison G. P. and Chick, J. P. (2007). "Energy and carbon audit of a marine current turbine." Proc. Institution of Mechanical Engineers Part M Engineering for the Maritime Environment, in press.*

The world's first commercial-scale grid-connected tidal current energy installation will feature the Seagen marine current turbine developed by Marine Current Turbines Ltd. With potential for the manufacture of significant numbers of such devices there is a need to assess their environmental impact and, in particular, their life cycle energy and carbon dioxide (CO_2) performance.

This paper presents an analysis of the life cycle energy use and CO_2 emissions associated with the first generation of Seagen turbines. The detailed assessment covers the embodied energy and CO_2 in the materials and manufacturing of components, device installation and operation along with those for decommissioning. With relatively conservative assumptions, the study shows that at 214kJ/kWh and 15gCO_2/kWh, the respective energy and carbon intensities are comparable with large wind turbines and very low relative to the 400 to 1000 gCO_2/kWh typical of fossil-fuelled generation. The energy payback period is approximately 14 months and the CO_2 payback is around 8 months. The embodied energy and carbon show limited sensitivity to assumptions with environmental performance remains excellent even under the most adverse scenarios considered.

[52] *Winskel, M., Mcleod, A. Wallace, A.R. and Williams, R. (2006). "Energy Policy and Institutional Context: Marine Energy Innovation Systems." Science and Public Policy, 33, 5, 365-376, 2006/06, ISSN 0302-3427.*

A process of UK energy policy review in the early 2000s has seen renewable energy technologies moving from the policy margins to centre-stage. The review process drew on international experiences of renewables innovation, including an innovation systems framework that emphasises `social capital' (collaborative learning between distributed agents). However, the UK energy system reflects a longstanding policy commitment to `financial capital' (market competition and avoiding `picking winners'). This paper analyses policy tensions between social and financial capital by focusing on marine energy innovation, especially in the emerging Scottish policy arena. Recent initiatives to promote renewables innovation in the UK, though significant, face continuing challenges.

[53] *Thompson, A. and Aggidis G.A. (2007). "Review and state of the art of wave energy and wave*

energy converters." IMechE, Fluid Machinery for Developing Engineers, Cranfield, (Invited Paper), IMechE, Event Publications, v 2007 1, IMechE Conference Transactions.

There is a worldwide opportunity for both local and distributed clean renewable electrical power, generated from marine energy. Possible applications range from small isolated islands currently relying on diesel generators to large developing countries, with ever increasing energy demands.

The results from the Marine Energy Challenge [1] showed that marine energy has the potential to become competitive with other forms of energy. By 2020, 3% of the UK's energy could be derived from wave or tidal energy, providing up to 1/6 of the UK government aspiration of 20% renewable energy by this time.

This paper reviews the development of wave energy converter systems (WECS) and examines the state of the art, introducing the most promising devices to date and the basic theory behind their operation. This includes an overview of wave energy theory required to appreciate the specific designs discussed. In addition environmental issues and future developments are looked at along with the economic factors affecting the growth of wave energy as a commercial industry.

[54] *Parker, R. P. M., Harrison, G. P. and Chick, J. P. (2007) "Energy and carbon audit of an offshore wave energy converter", Proc. Institution of Mechanical Engineers Part A Journal of Power and Energy, 221 (8), in press.*

The world's first commercial wave farm will feature the 'Pelamis' wave energy converter developed by Ocean Power Delivery. With potential for the manufacture of significant numbers of such devices there is a need to assess their environmental impact and, in particular, their life cycle energy and carbon dioxide (CO_2) performance.

This paper presents an analysis of the life cycle energy use and CO_2 emissions associated with the first generation of Pelamis converters. With relatively conservative assumptions, the study shows that at 293 kJ/kWh and 22.8 gCO_2/kWh the respective energy and carbon intensities are comparable with large wind turbines and very low relative to fossil-fuelled generation. The energy payback period is approximately 20 months and the CO_2 payback is around 13 months.

Material use is identified as the primary contributor to the embodied energy and carbon with shipping (including maintenance) accounting for 42%. Improving the Pelamis' environmental performance could be achieved by increasing structural efficiency, partial replacement of the steel structure with alternative materials, particularly concrete, and the use of fuel-efficient shipping.

[55] *Wolfram J. (2006). "On Assessing the Reliability and Availability of Marine Energy Converters: the Problems of a New Technology." Proc. IMechE Part O: Journal of Risk, 220(1), pp. 55-68.*

There is now considerable interest in marine renewable energy both in the UK and elsewhere in the world with the growing recognition that fossil fuel supplies are finite and further increases in carbon gas emissions will hasten climate change. A major factor in the viability of any potential wave or tidal energy device (marine energy converter (MEC)) is its reliability and availability. However, as for any new technology, this is difficult to predict in advance with confidence. This paper describes the issues that must be addressed to assess the reliability and availability of MECs. It starts with a brief overview of the characteristics of the principal types of wave and tidal energy converters and a review of earlier work on estimating reliability for wave energy converters. It is shown that MECs have many subsystems and components in common with one another and with other existing land-based and marine systems. The ways in which experience with existing systems may be adapted to predict reliability and availability for MECs are discussed and a new embryonic database for MECs is outlined. The choice of distribution for the time to failure of MEC components is discussed and an argument is advanced for the use of the log-normal distribution. The availability of MECs is affected very much by the environment in which they operate and the maintenance strategy adopted. The effects of environment and location upon maintainability and hence availability are described and how availability may be modelled is discussed. Finally the need for a framework for assessing the reliability and availability of MECs and other related issues are discussed.

[56] *Meadowcroft, J.A.C., Stallard, T.J. and Baker, N.J. (2005). "A comparison of power capture in irregular waves and their regular wave components." 6th European Wave and Tidal Energy Conference (6th EWTEC), University of Strathclyde, Glasgow.*

This paper presents preliminary findings from an experimental study of the power capture characteristics of a surging plate with variable spring and damping restraint subjected to loading by both irregular waves and the regular sub-components of each wave. The motive for this work is to investigate how the captured power in irregular waves of different spectral shape but equivalent statistical properties is related to the power captured by the same device in regular waves.

[57] *Johanning, L., Smith, G. H. and Wolfram, J. (2005). "Towards design standards for WEC moorings, 6th European Wave and Tidal Energy Conference, 29.08 – 02.09.2005, Glasgow, UK.*

The demand for environmental friendly energy supply will in part be met through the operation of wave energy converters (WEC). One of the key design considerations will be to maintain the position of the WEC, whilst allowing efficient conversion to be possible. These devices must be installed in wave regimes suitable for the production of exploitable energy. As such they must be capable of withstanding the most extreme loading condition over their design life period. Since the wave energy industry has little practicable long term experience with deployed WEC systems there is no direct evidence for the formulation of appropriate guidelines or standards. At first glance one might wish to employ rules formulated from the nearby oil and gas industry. However these rules would impose a high financial cost on the wave energy where the relative returns are substantially lower than from an oil and gas development. As such the implementation of these standards requires that the many years of experience from the offshore industry be adapted bearing in mind the much lower environmental and health risks and the lower rate of return. More fundamentally there may be issues that are pertinent solely to WECs due to their different operational requirements. This paper discusses how existing standards used in the offshore oil and gas industry might be adapted and raises issues pertinent solely to the station keeping of WECs.

[58] *Meadowcroft, J.A.C., Stallard, T.J., Baker, N.J. and Aggidis, G.A. (2006). "Absorption of energy from irregular waves by a buoyant, surging body." Proceedings of 16th International Offshore and Polar Engineering Conference (ISOPE), San Francisco, USA.*

A series of experimental tests are reported which concern the viability of capturing power from regular and irregular waves by restraint of a wave radiating body oscillating in surge. The effect of hull form and mechanical properties of the restraint on power captured through damping are investigated and the relationship between these parameters and the design requirements of a power take off system are discussed. The results show that an asymmetric plate with one convex and one concave face attains good mean power capture in a range of wave fields.

[59] *Widden, W.B., French, M.J., and Aggidis, G.A. (2005). "The Power Capture of PS Frog Pitching and Surging Point Absorber Wave Energy Converter." International Symposium on Fluid Machinery for Wave and Tidal Energy: State of the Art and New Developments, (Invited Paper), IMechE, London.*

PS Frog is a point-absorber wave energy converter that works in pitch and surge. The power take-off is a mass that can move relative to the body of the device. The combination of gravitational and inertia forces on the PTO mass allows power to be extracted. The paper shows, by a harmonic analysis assuming regular sinusoidal waves, that the path of motion of the PTO mass should be high up in the body of the device to give the greatest effect of the forces, and so allow a smaller PTO mass or a shorter travel to be used.

[60] *Jeffrey, H.F, Mueller M and Smith G.H. (2007). "An investigation of the Knowledge Base of the UK Marine Renewable Sector." 7th European Wave and Tidal Energy Conference, Porto, Portugal.*

This Supergen Marine study highlights the issues facing the UK marine renewables energy industry in conjunction with identifying, investigating and discussing the pertinent issues surrounding this fledgling sector.

A review of technology forecasting methods has identified the "Delphi Interview Method" as providing a suitable mechanism to facilitate the investigation of a forward direction for the sector. The use of this method has provided a robust and auditable set of results from a series of 22 interviews with leading academics in the marine and renewable energy fields. The analysis of the results from the interviewees has facilitated the presentation of the qualitative interview results in quantitative terms, thereby allowing the identification of a unique set of technology trends.

The outcomes of the investigation have in turn been fed into the population of the UK Energy Research Centre (UKERC) Marine Renewables Research Roadmap (where there has been close collaboration) in order to forecast an efficient and effective route forward for the sector. The results from the road-mapping work are discussed in the companion paper presented by Dr Markus Mueller: "UKERC Marine Renewable Energy Technology Roadmap".

[61] *McCabe, A.P., Bradshaw, A., Meadowcroft, J. A. C. and Aggidis, G.A. (2006). "Developments in the design of the PS Frog MK 5 Wave Energy Converter." Renewable Energy Journal, 31(2), pp 141 – 151.*

This paper describes one of the innovative wave energy converters under development by the Lancaster University Renewable Energy Group. An offshore point-absorber wave energy converter, PS Frog Mk 5 consists of a large buoyant paddle with an integral ballasted 'handle' hanging below it. The waves act on the blade of the paddle and the ballast beneath provides the necessary reaction. When the WEC is pitching, power is extracted by partially resisting the sliding of a power-take-off mass, which moves in guides above sea level. Totally enclosed in a steel hull, with no external moving parts, PS Frog Mk. 5 is at least as robust as a ship and the survivability of the device is currently under investigation, though such work is beyond the scope of this paper. Such a device could be very economic in terms of power output per unit of capital cost. New inventive steps with experimental results and computer studies have led to promising improvements to the hull shape. The WEC is maintained in a resonant state by the use of special means to maintain a high dynamic magnifier in irregular seas. A robust feedback control system has been developed to ensure stability and maintain efficient power take-off. Some of these developments are described and illustrated with the results of computer simulations that show power outputs and device motion over a range of conditions. It is shown that useful advances have been made, with the power capture bordering on 2 MW in an increasing proportion of sea states.

[62] *Chaplin, R.V. and Aggidis, G.A. (2007). "An Investigation into Power from Pitch-Surge Point-Absorber Wave Energy Converters", proceedings of IEEE International Conference on Clean Electrical Power Renewable Energy Resources Impact, Capri, Italy. Published by IEEE, Catalogue Number: 07EX1528 – ISBN: 1-4244-0631-5.*

There is a worldwide opportunity for clean renewable power. The results from the UK Governments Marine Energy Challenge showed that marine energy has the potential to become competitive with other forms of energy. The key to success in this lies in a low lifetime-cost of power as delivered to the user. Pitch-surge point-absorber WECs have the potential to do this with average annual powers of around 2MW in North Atlantic conditions from relatively small devices that would be economically competitive with other technologies and would be relatively easy to install and maintain. The paper examines the factors governing the performance of such devices and outlines their underlying theory Preliminary laboratory test results from a 1/100 scale pilot design are presented. It is hoped that more extensive development work will follow these promising early results. Engineering designs for devices based on these findings are outlined.

[63] *Chaplin R.V. and Aggidis G.A. (2007). "WRASPA: Wave Interactions and Control for Pitching-Surge Point-Absorber", Wave Energy Converters, Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal, 11-13 September 2007. ISBN: 978-989-95079-3-7.*

There is a worldwide opportunity for local and distributed clean renewable electrical power from Marine Energy. It has the potential to become competitive with other forms of energy and by 2020, 3% of the UK's energy could be derived from wave and tidal energy, providing up to 1/6 of the UK government's aspiration of 20% renewable energy by this time. The key to success in clean electrical power lies in a low lifetime-cost of power as delivered to the user. For wave power this must start with a compact, powerful and reliable wave energy converter, or WEC. Pitching-surge point-absorber WECs have the potential to generate average annual powers of around 1.5MW in North Atlantic conditions from relatively small devices. The paper reports very early work on one such device – WRASPA (Wave-driven, Resonant, Accurate action, Surging Point-Absorber) - in water depths greater than 20m including the effects of collector geometry on power output, based on both experimental and computational modelling. In particular, the progress towards an optimum collector geometry will be described. Engineering designs for devices based on these findings will be outlined.

[64] *Mueller, M. A. and Wallace, A.R. (2005). "Developing a Research Route Map for Marine Renewable Energy Technology in the UK", invited plenary paper at the 5th European Wave and Tidal Energy Conference, Glasgow.*

The role of the UK Energy Research Centre Marine Energy Research Network in developing a route map for marine renewable energy is described and put into the context of previous and current marine energy at a national and EU level. A summary of the route map process is given based upon the Batelle approach. Justification is provided for route mapping in terms of encouraging cooperation and collaboration within the community to develop a coherent business and technical strategy, which will be used to inform policy makers and funding bodies. Some preliminary output from the network is presented in the paper to encourage discussion.

[65] *Huang, M. and Aggidis, G.A. (2006). "Research on Wave Energy Converters and Mooring Systems in the United Kingdom." Published by the Water Resources and Power Journal in Chinese, in Vol. 24 No. 4, pp 37 – 40, ID: 1000-7709 (2006) 04-0037-04, ISSN: 1000-7709.*

In order to use the renewable wave energy source more efficiently and develop the Wave Energy Converters, the paper introduces the important work of Wave Energy Converters and the mooring system in U K, which is the research of wave energy of the world. The principles and applications of several main Wave Energy Converters have been described, and the construction and recent developments of the mooring system also have been summarized. Otherwise, the current research emphases and suggestions in this field have been discussed for reference.

[66] *Smith, G.H. and Venugopal, V. (2006). "A Generic Method for Determining WEC Power Conversion from a Random Sea." Proceedings of the Sixteenth International Offshore and Polar Engineering Conference, ISOPE 2006, 1, 460-465, May 28 - 2 June.*

This paper examines the calculation of the power delivered from a wave energy converter using a conventional frequency transfer function approach and compares this with an alternative analysis based on a "wave-by-wave" basis. This alternative method goes some way to estimating the power that a resonant device, capable of tuning, might extract from a random sea state. For the purposes of this paper the time series were synthesized from a range of spectra representative of unimodal and bimodal sea states. The calculated power from each method is compared. An initial examination of how the delivered power can be related to the bandwidth of the sea is also presented.

[67] *Widden, W.B. French, M.J. and Aggidis, G.A. (2007). "Analysis of a pitching and surging wave-energy converter that reacts against an internal mass, when operating in regular sinusoidal waves." In review by Proc. of the Institution of Mechanical Engineers, Part M, Journal of Engineering for the Maritime Environment (In review August 2007).*

The paper examines the behaviour of a pitching and surging wave-energy converter driven by unidirectional waves that exert harmonically-varying forces on its hull. The power take-off is by means of an inertia that moves either on a straight horizontal rail, or on an arm that turns about a horizontal axis. Angular displacements are taken to be small, so that linear analysis is appropriate; these are idealised conditions, but any wave-energy converter must be able to operate effectively in ideal conditions. For good power capture with the least engineering difficulties, it is found that the power take-off inertia should be centred as high as possible above the overall centre of mass G. It is shown that power is captured from the waves by motion of the centre of pressure P relative to the overall centre of mass G.

This can only result from motion in pitch, and is dependent on there being a large vertical distance between points P and G. It is found in practical cases that the added mass of water generally brings G closer to P, and this limits the power that can be captured.

[68] *French J. M. (2006). "On the difficulty of inventing an economical sea wave energy converter: a personal view." DOI: 10.1243/14750902 JEME43 © IMechE 2006 Proc. IMechE Vol. 220 Part M: J. Engineering for the Maritime Environment, 3 July 2006.*

Sea waves are a promising potential source of renewable energy, but the technology has not yet settled down to one or two basic forms as has happened with most major inventions. New ideas continue to arise, and no general agreement about how to proceed seems to be emerging. Moreover, although practicable wave energy converters (WECs) have been developed, they are not as economical as might have been hoped. This paper explores a particular aspect of the cost problem. Broadly speaking, the costs of WECs are high because they deal with large forces moving slowly. It is reasonable to expect that where a working surface can be identified, the bigger its area is relative to the overall surface area and the faster the surface moves, the more economical it is likely to be. This suggests two criteria for an economical WEC: a large working area relative to its size and a high ratio of the speed of that surface to the particle speed of the wave. The second criterion indicates a resonant system, and this paper is confined to WECs that have quasi-resonant working surfaces (QR WECs). The quasi- is because the mechanics involved is not quite that of classical resonance. Promising types are listed in four groups according to the source of reaction, because this is generally the most difficult function to provide in QR WECs. Other types of WEC are left out, most often because they do not meet the criteria of a strongly coupled working surface and resonance, and usually require large amounts of material. While size is not uniquely related to cost, WECs using much material are likely to be expensive.

[69] *Norris, J. and Bryden, I. (2007). "The European Marine Energy Centre (EMEC): Facilities and Resources." Proc ICE Energy Journal, in press.*

This paper describes the European Marine Energy Centre (EMEC) wave and tidal test facility, which has been established in Orkney to assist and hasten the development of the wave and tidal stream energy conversion industries. The facilities include both infrastructure and a number of soft provisions, or services, which are described. After a brief overview section on the theory of wave and tidal energy assessment and extraction, the wave and tidal resources available at the EMEC test sites are summarised. Finally, there is an update on the uptake of the facilities by developers, at the time of writing.

WP4 Offshore Energy Conversion and Power Conditioning

[70] *Mueller, M.A., McDonald, A.S. and Macpherson, D.E. (2005). "Structural Analysis of Low Speed Axial Flux Permanent Magnet Machines," IEE Proc B Electrical Power Applications, Vol. 152, pp. 1417 – 1426.*

Analytical expressions obtained from circular plate, elastic beam and cylindrical shell theory are applied to calculate the structural mass of axial-flux permanent-magnet machines for a range of typical wind-turbine ratings. Finite-element models and data from existing low-speed axial-flux machines have been used to gain confidence in the models presented, such that they can be incorporated into design-office programs to rapidly provide a first-order estimate with a reasonable level of accuracy. Results confirm that the inactive mass is greater than 60% of the machine total mass, and at multimegawatt ratings it is almost 90% of the total mass. Optimisation of the machine must therefore include the link between structural and electromagnetic designs. Results presented illustrate the impact of inactive mass on geometrical design parameters and also show that multistage designs can lead to a reduction in mass.

[71] *Kiprakis, A.E. and Wallace, A.R. (2005). "Power Control and Conditioning for Wave Energy Converters", Proc 6th European Wave and Tidal Energy Conference, Glasgow.*

This paper describes a generic wave-to-wire dynamic model of a Wave Energy Converter equipped with hydraulic energy storage and a Doubly-Fed Induction Generator (DFIG). It then discusses the available power control and conditioning strategies for the intermediate (hydraulic) energy stage as well as the generator. The DFIG allows direct voltage regulation using reactive power control. Finally, this paper presents simulation results of the developed WEC model with coordinated hydraulic storage and DFIG control.

[72] *Payne G., Kiprakis A.E., Ehsan M., Rampen W., Chick J. and Wallace A.R. (2007). "Efficiency and dynamic performance of Digital Displacement™ hydraulic transmission in tidal current energy converters", Proc. IMechE Part A, Journal of Power and Energy, Vol. 221, No. 2, pp. 207-218(12).*

Tidal current turbines extract kinetic energy from tidal current in much the same way as wind turbines do with wind. Tidal current velocities are by nature slow and variable, whereas electricity generation typically requires fast and steady rotary motion. This article investigates the performance of a hydraulic transmission system based on Digital Displacement™ technology, which allows variable speed of the tidal current turbine rotor while maintaining constant generator shaft speed. The case study of a generic horizontal axis tidal turbine is considered. Control strategies based on rotor variable speed are derived to optimize yearly power generation and to cope with short-term variations in stream velocity.

[73] *Kiprakis, A.E. and Wallace, A.R. (2005). "Voltage Control in the Distribution Network: Traditional Techniques and New Developments", Invited paper, World Renewable Energy Congress.*

Distributed generators are normally operated in constant power factor control, although this can be more difficult in weak areas of the network. Operating the generator in constant voltage mode is not usually acceptable by distribution network operators, since an unconstrained machine may attempt to define voltages that conflict with the settings of their automatic voltage control equipment. Additionally, active control of the distribution network is only scarcely utilised. The most common means of voltage control in the DN is using transformers with automatic tap changers either for direct voltage control on the transformer bus or for line drop compensation. Novel voltage control techniques include intelligent real and reactive power control of the distributed generator.

This paper will present the traditional techniques and compare them with the novel DN voltage control proposals. Their relative advantages will be quantified through a comparison of the maximum seamless energy dispatch from the connected distributed generators in each case.

[74] *Payne, G., Stein, U.B.P., Ehsan, M., Caldwell, N.J., Rampen, W.H.S. (2005). "Potential of Digital Displacement™ hydraulics for wave energy conversion," In: 6th European Wave and Tidal Energy Conference, Glasgow, UK, pp. 365-371.*

Digital Displacement™ is an innovative technology for hydraulic machines. It offers a high level of control and high efficiency, even at part load. The key features of this technology are presented and its advantages over conventional hydraulic are quantified. The suitability of Digital Displacement™ for wave energy conversion is then investigated and the ongoing project of implementing Digital Displacement™ technology to the Pelamis wave energy converter in collaboration with Ocean Power Delivery Ltd is presented.

[75] *Payne, G. (2005). "Hydrodynamic modelling of a generic power take-off mechanism reacting against water inertia," In: 6th European Wave and Tidal Energy Conference, Glasgow, UK, pp. 359-364.*

The numerical modelling of a generic power take-off (PTO) mechanism reacting against water inertia is presented. The PTO consists of a submerged hollow tube with a piston sliding within. The system is modelled using the boundary element method package WAMIT with the tube and the piston considered as separate bodies. The model is verified against computations involving benchmark formulations.

[76] *Mueller, M.A and Baker, N.J. (2005). "Direct Drive Wave Energy Converters." I Mech E Journal of Power and Energy, Vol. 219, No. A3, pp 223-234.*

This paper investigates the issues associated with converting the energy produced by marine renewable energy converters, namely wave and tidal stream devices, into electricity using direct drive electrical power take-off, without use of complex pneumatic, hydraulic or other mechanical linkages. In order to demonstrate the issues, two alternative topologies of linear electrical machines are investigated: the linear vernier hybrid permanent magnet machine and the air-cored tubular permanent magnet machine. The electrical characteristics of these machines are described and compared in the context of mechanical integration. Potential solutions to the issues of sealing, corrosion and lubrication are discussed taking into account the electrical properties of the two topologies.

WP5 Chemical Conversion and Storage

[77] *Mignard, D., Harrison, G.P., and Pritchard, C.L. (2007). "Contribution of wind power and CHP to exports from Western Denmark during 2000-2004." Renewable Energy.*

The experience of Denmark is used by the United Kingdom's anti-wind lobby to demonstrate that intermittency and inaccuracies in wind forecasting make wind power ineffective and expensive. A further assertion is that most of the power is 'unwanted' since up to 80% of it is exported. Here, available data for Danish energy production for 2000–2004 is used to assess the link between wind generation and exports and test the validity of these claims.

Net exports in Western Denmark showed good correlation with wind production. However, they were more significantly correlated with the production from local combined heat and power (CHP) plants. In order to test the 80% export claim, a simple technique was devised to correlate and rank hourly net exports and generation from wind and local CHP. In the case where net exports were primarily attributed to (or blamed on) wind, 44–84% of annual wind production was deemed to be exported, with wind 'causing' 57–79% of net annual exports. For this extreme scenario, the percentage values are in line with those of critics. However, under the opposite extreme scenario in which exports are attributed to local CHP, 77–94% of exports were caused by CHP and only 4–32% of wind production was exported. Overall, this study shows that there is some degree of correlation between net exports and wind power, but that the claim that 80% is exported is unwarranted since it ignores the demonstrably stronger influence of local CHP.

[78] *Mignard D., Pritchard C.L., Glass D.H. and Bridgwater A.V. (2006). "Simple and Carbon-Efficient Production of Synthetic Fuels by combining Biomass and Marine Energy." Greenhouse Gas Control Technologies 8 (GHGT-8), Trondheim, 18-22 June 2006. Paper posted on http:/www.ghgt8.no, 2006.*

The UK's commitment to a large-scale reduction in CO_2 emissions will necessitate radical changes to the energy supply mix. In particular, replacing hydrocarbon-based transport fuels with carbon-neutral alternatives will require the use of renewable energies and renewable raw materials for the synthesis of fuels. However, the most valuable renewable energy in the UK is the wave, wind and tidal power resource that is located North and West of Scotland, while the electricity transmission grid is poorly developed in the contiguous onshore areas. One possibility for the transmission of such stranded-energy to its point of use would be to use the power for the on-site production of synthetic, liquid carbonaceous fuels.

In the work that we are presenting here, biomass is the CO_2-neutral carbon source for fuel products. Because biomass is deficient in hydrogen for the purpose of fuel synthesis, and because hydrogen can be produced from marine energies via water electrolysis, we propose to enhance both the ability of deriving liquid fuels from marine energy, and the ability to efficiently convert biomass to fuels. Another aspect also concerns the utilisation of the oxygen by-product from electrolysis for more effective biomass utilisation. Design studies are presented for a demonstration project involving the UK's Supergen research consortia on Marine Energy and on Bioenergy.

[79] *Mignard D. and Pritchard C.L. (2006). "Processes for the Synthesis of Liquid Fuels from CO_2 and Marine Energy," Chem. Eng. Research and Design, Special Issue: Carbon Capture and Storage, 84(A9), 828-836*

In Britain, wind and wave power are expected to make a significant contribution to future energy supplies, but the vast majority of the resource is located offshore, away from the mainland electricity grid.

In this context, the chemical storage and transport of this energy appears to be an attractive option for the supply of fuels. On the other hand, it is not unlikely that CO_2 will be recovered on a large scale in the next 10-20 years, thus making it available as a carbon source for liquid fuels. A preliminary analysis indicated that the liquid fuels that could be most readily manufactured from hydrogen (from electrolysis) and recycled CO_2 were: methanol, mixed alcohols, and gasoline (via methanol). Methanol appears to be simplest to manufacture, in the light of developmental work at NEDO, Japan. The Mobil Methanol-to-Gasoline process also enables the manufacture of a very convenient automotive fuel. Mixed alcohols have the advantages both of low toxicity, and efficient Fischer-Tropsch catalysts for their synthesis (the Pearson process and the Ecalene process). This paper compares the energy efficiency of these three processes.

[80] *Mignard D. and Pritchard C.L. (2007). "A review of the sponge iron process for the storage and transmission of remotely generated marine energy." International Journal of Hydrogen Energy, in press.*

The UK's vast marine energy resource is mostly located in remote areas West and North of Scotland, and transmission of this energy to the mainland will be required. This may be achieved by using this stranded-power to generate hydrogen electrolytically, which may in turn be stored or transported using sponge iron technology. This paper reviews the technology and research needed to bring such a process on stream. We propose utilising techniques that have been developed for the oxygen carriers used in chemical looping, and also those used in early processes for hydrogen generation in the chemical industry. We briefly outline the design requirements for an energy efficient sponge iron plant. It is shown that the iron sponge system presents better energy efficiencies than alternative forms of bulk storage such as liquid hydrogen, magnesium hydride slurry, some at least of the metal hydrides, or methylcyclohexane-toluene-hydrogen, provided that requirements can be met for particle durability and reactivity.

WP6 Network Interaction of Marine Energy

[81] *Vovos, P., Kiprakis, A.P., Wallace, A.R., and Harrison, G.P. (2007). "Centralised and Distributed Voltage Control: Impact on Distributed Generation Penetration", IEEE Trans. Power Systems, 22(1), pp. 476-483.*

With the rapid increase in distributed generation (DG), the issue of voltage regulation in the distribution network becomes more significant and centralized voltage control (or active network management) is one of the proposed methods. Alternative work on intelligent distributed voltage and reactive power control of DG has also demonstrated benefits in terms of the minimization of voltage variation and violations as well as the
ability to connect larger generators to the distribution network. This paper uses optimal power flow to compare the two methods and shows that intelligent distributed voltage and reactive power control of the DG gives similar results to those obtained by centralized management in terms of the potential for connecting increased capacities within existing networks.

[82] *Vovos, P., Harrison, G.P., Wallace, A.R., Bialek, J.W. (2005). "Optimal Power Flow as a tool for fault level constrained network capacity analysis", IEEE Transactions on Power Systems, 20, 2, pp. 731 – 741.*

The aim of this paper is to present a new method for the allocation of new generation capacity, which takes into account fault level constraints imposed by protection equipment such as switchgear. It simulates new generation capacities and connections to other networks using generators with quadratic cost functions. The coefficients of the cost functions express allocation preferences over connection points. The relation between capacity and sub-transient reactance of generators is used during the estimation of fault currents. An iterative process allocates new capacity using Optimal Power Flow mechanisms and readjusts capacity to bring fault currents within the specifications of switchgear. The method was tested on a 12-bus LV meshed network with 3 connection points for new capacity and 1 connection to a HV network. It resulted in significantly higher new generation capacity than existing first-come-first-served policies.

[83] *Boehme, T., Harrison, G.P. and Wallace, A.R. (2007). 'Non-firm Renewable Connection Assessment*

using Optimal Power Flow and Time Series', IEEE Trans. Power Systems.

Before new renewable generators can be connected to the electricity network it is necessary to carefully evaluate the impact they will have. Besides worst case scenarios, hourly time series of demand and renewable generation can be applied step-by-step in conventional power flow analysis to determine average and extremes of voltage levels and branch loading. It may sometimes be necessary to curtail the renewable generators' output to ensure that all system parameters stay within statutory limits. Optimal power flow analysis with time series input is a powerful tool for an assessment of the situation. Simulation results give both the network operator and the project developer a good indication of the constraints in the network and the corresponding economic loss the renewable project may experience through curtailment. This method is demonstrated by means of a case study for the Orkney Islands, Scotland.

[84] *Vovos P.N., Kiprakis A.E., Harrison G.P., and Wallace A.R. (2007). "Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration", IEEE Transactions on Power Systems, Vol. 22, Issue 1, pp. 476-483.*

With the rapid increase in distributed generation (DG), the issue of voltage regulation in the distribution network becomes more significant, and centralized voltage control (or active network management) is one of the proposed methods. Alternative work on intelligent distributed voltage and reactive power control of DG has also demonstrated benefits in terms of the minimization of voltage variation and violations as well as the ability to connect larger generators to the distribution network. This paper uses optimal power flow to compare the two methods and shows that intelligent distributed voltage and reactive power control of the DG gives similar results to those obtained by centralized management in terms of the potential for connecting increased capacities within existing networks.

[85] *Boehme, T., Wallace, A.R and Harrison, G.P. (2007). "Applying Time Series to Power Flow Analysis in Networks with High Wind Penetration", IEEE Trans. on Power Systems, vol. 22, no. 3, pp. 951–957.*

With high levels of variable renewable generation in distribution or transmission systems, the application of demand and generation time series to power flow analysis can be advantageous. Demand data are often available from historic measurements, while renewable generation such as wind turbine output may be recorded or can be derived from resource measurements over the corresponding period of time. Power flow solutions with hourly time steps over a year or more can then be used to produce load duration curves for system components. This paper shows, by example, how utilities can use the method to determine overload conditions or to specify non-firm connection agreements for new generators.

[86] *Harrison, G.P. and Wallace, A.R. (2005) "OPF evaluation of distribution network capacity for the connection of distributed generation", IEE Proceedings on Generation, Transmission and Distribution, 152 (1).*

Distributed generation (DG) capacity will increase significantly as a result of UK Government-led targets and incentives. While the technical problems arising from distribution level connections may be mitigated for individual connections, the anticipated connection volumes imply a potential risk of conflict between connections, in that inappropriately sized or located plant could constrain greater development of the network and consequently threaten the achievement of renewable energy targets. One means of addressing this risk is to encourage development at sites that are more suitable whilst discouraging those at inappropriate ones. First network operators must be able to evaluate the available capacity on the system (i.e. the headroom). Here, a technique is presented that facilitates such analysis. Termed 'reverse load-ability', the approach models fixed-power factor DG as negative loads and uses optimal power flow to perform negative load shedding that effectively maximises capacity and identifies available headroom. The technique was applied to an extensive distribution and sub-transmission network. It was found to rapidly identify available headroom within the imposed thermal and voltage constraints. Furthermore, its use is demonstrated in examining the consequences of a sequence of connections in terms of the impact on available headroom and in sterilising the network.

[87] *Boehme, T., Taylor J., Wallace, A. R. and Bialek, J. (2006). "Matching Renewable Energy Generation with Demand", Scottish Executive, ISBN 0-7559-5029-1.*

This study was commissioned to determine whether Scotland could meet 40% of its 2020 demand for electricity from renewable resources. By then annual demand for electrical energy in Scotland could be around 41 TWh with a peak power demand of around 7.3 GW. Supplying 40% (16.4 TWh) of the electricity required over the year from renewable resources suggests the need for around 6 GW of renewable capacity. Generated power must match demand for power on a second-by-second basis. Demand varies with time and with location across Scotland and so does renewable energy. This is particularly true for time-varying resources like wind, wave and tidal-current. Historical time series were analysed to determine the matching between demand and renewable generation on an hour-by-hour and a long-term basis.

[88] *Vovos P., Kiprakis A.E., Harrison G.P., Barrie, J.R. (2005) "Enhancement of Network Capacity by Widespread Intelligent Generator Control", 18th International Conference on Electricity Distribution CIRED.*

Electricity networks are called on to accommodate more and more generation capacity in order to supply the increasing demand. Social, planning and environmental reasons hinder the expansion of the existing infrastructure, whereas lack of investment prohibits its reinforcement. Therefore, the efficient utilisation of the existing network is not only suggested for economy, but also imposed by need. Consequently, the realisation of government targets for renewable energy will depend, in part, on the ability of developers and Distribution Network Operators (DNOs) to maximise generator capacities connected to the network whilst minimising negative impacts.

One means of ensuring maximum capacity with minimal voltage impact is through the use of intelligent power factor and voltage control of generators and other network components. Previously published work demonstrated the benefits in terms of the minimisation of voltage variations and violations as well as the ability of larger generators to connect to the network. While the capacity benefit could be easily quantified for individual dispersed generators, it was more difficult to explore the benefit of widespread usage.

To achieve this it was necessary to draw on earlier work that used Optimal Power Flow (OPF) techniques to evaluate the network capacity available for connecting dispersed generators. The capacity evaluation technique was extended such that it could incorporate the intelligent generator control algorithms and in doing so could find optimal levels of connections. The results of a case study indicate that intelligent power factor and voltage control of generators increases significantly the connecting capacity of existing networks.

[89] *Boehme, T. (2006). "Matching Renewable Electricity Generation with Demand in Scotland." PhD thesis, The University of Edinburgh.*

In this thesis, the location of onshore wind, offshore wind, wave and tidal current resources in Scotland and the physical, environmental and planning constraints for their development were mapped and the lifetime production costs of electricity generation at feasible locations were predicted. For a number of economically ranked renewable generation scenarios, hourly time series of power over a consecutive period of three years were analysed. The study showed that despite their variable nature, renewable sources could be developed so that they supply, on average, 40% of the Scottish demand for electricity by 2020. The study also showed that there will be many hours in a year when renewable generation does not coincide with demand resulting in excess or shortfall. Diversification of sources and their geographical dispersion are measures to achieve better matching. Further mitigation is possible through dedicated dispatching of hydro and pumped storage plant and through management of the power system.

WP7 Lifetime Economics

[90] *Stallard, T.J., Aggidis, G.A., and Rothschild, R. (revision submitted May 2007), "Economic aspects of site selection for large-scale wave power generation," in review by: IMechE part M, Journal of*

engineering for the Maritime Environment (JEME 68).

This paper offers an evaluation of the cost of alternative configurations of a hypothetical wave energy conversion scheme that produces a mean output of 100MW. The principal factors influencing the present value cost of electricity are identified and methods for estimating both the capital expense of several scheme infrastructure items and maintenance expense are discussed. Although several cost studies have been published of marine energy devices, they generally provide a snapshot of the status of prototype design and provide little information on the potential economy of alternative design solutions. Our aim is to evaluate the influence of wave climate characteristics and device performance on the characteristics and potential economy of a wave power plant that would generate a comparable output. Linear mathematical models of the performance of a resonant wave energy device are reviewed and used to identify three classes of device. In conjunction with site-specific wave data, an estimate is obtained of the physical characteristics of wave power plants that would generate a mean output of 100MW from different locations. Subsequently, an estimate is made of the unit installation cost that must be attained for each scheme to generate electricity at an economically viable rate. The approach detailed contrasts with existing published studies of wave power economy in that we investigate whether research and development alone will allow wave power to approach commercial viability. We conclude that, even when optimal performance is approached, the cost of both infrastructure and devices must fall before many UK sites are economically viable.

[91] *Stallard, T.J., Rothschild, R. and Aggidis, G.A. (2007). "A comparative approach to the economic modelling of a large-scale wave power scheme," Article in press, accepted 15 January 2007, by European Journal of Operational Research (EJOR), DOI:10.1016/j.ejor.2007.01.021.*

Conversion of marine energy sources, including ocean waves and tidal currents, into electricity is a rapidly developing industry. Although many technologies have been proposed and some have generated electricity at full scale, it is difficult to predict which technology will be economic at large scales of installation. Several studies have been conducted which estimate the cost of electricity on the basis of schematic designs. However, each study represents a best estimate of the future cost based on current design details and direct comparison between the results of these studies is not straightforward. A methodology for directly comparing different wave energy concepts and potential locations would be beneficial to aid investment decisions. In this study we describe how the established data envelopment analysis technique could be employed for this purpose. The developed model is employed to rank the efficacy with which several types of conceptual and prototype wave energy conversion (WEC) technologies generate electricity from the wave energy resource available at UK and US sites.

[92] *Stallard, T.J., Rothschild, R., Bradshaw, A., and Aggidis, G.A. (2005). "Comparison of Equivalent Capacity Wave Energy Schemes," World Renewable Energy Congress, ISBN 0-080-44671-X.*

A model of the lifetime costs associated with the installation, maintenance, operation and disposal of several generic classes of wave energy conversion (WEC) device is presently being developed as part of the Supergen Marine Energy research project. The effect of uncertainty of
i) the initial capital cost
ii) the continuous investments on device maintenance and operation
iii) the discrete costs associated with installation (e.g. the production of special purpose ships)
on the cost of produced electricity and the internal rate of return are considered over the envisaged lifespan of several generic types of offshore WEC device – e.g. oscillating buoys, overtopping devices, pneumatic devices. The model will facilitate investigation of the scale of production at which a given type of device becomes economically viable.

WP8 Moorings and Foundations

[93] *Harris R.E, Johanning L and Wolfram J. (2004). "Mooring systems for wave energy converters: A review of design issues and choices," 3rd International Conference on Marine Renewable Energy, Blyth, UK.*

An overview of generic types of wave energy converter (WEC) is presented and their mooring requirements discussed. Mooring system configurations and components from the offshore industry suitable for WEC units are identified. Possible mooring configurations for WECs are discussed and it is argued that not only station keeping but also the overall performance characteristics of the WEC mooring should be considered in the design.

[94] *Johanning L, Smith G.H. and Wolfram J. (2007). "Measurements of static and dynamic mooring line damping and their central importance for floating WEC devices." Ocean Engineering, Volume 34, Issues 14-15, pp, 1918-1934.*

The dynamic response of the mooring line will be a dominant factor to consider in their use for the station keeping of a wave energy converter (WEC). Due to the relatively small size of WECs and their being moored in relatively shallow waters the effect of waves, tide and current can be of greater significance than for other floating offshore systems. Axial line stretching and high-frequency 'top-end' dynamics can importantly modify damping and top-end loading.

If a 'farm' of devices is to be considered then limitations in sea space may necessitate that the devices be relatively densely packed. This will mean that the 'footprint' of the mooring should be constrained, to ensure that the moorings from each device do not interfere and this will have great significance for the loading experienced by the line. One must also consider how the mooring system might change the response of the WEC and so alter its ability to extract power from the waves. Unlike a typical offshore system, the design of moorings for a WEC device must consider reliability and survivability, and the need to ensure efficient energy conversion.

The design and operation of a chain mooring for a WEC is considered here. Generic experimental measurements of mooring line damping were conducted in the Heriot-Watt University wave basin at a scale of 1:10. The measurements were conducted on a single mooring line for surge motions and include the study of axial stretching and high top-end dynamics. The laboratory procedures were designed to resemble tests undertaken earlier at 'full' scale in 24 m water depth. The measurements were also compared with numerical studies. The experimental findings for WEC devices, supports the conclusion that dynamic mooring line motion will be an important variable, needing to be considered carefully within the design.

[95] *Johanning L, Wolfram J., Smith G.H and Harris R.E. (2006). "Importance of mooring line damping for WECs," WMTC conference, IMarEST, 06.03 – 10.03.2006, London, UK.*

The work by Huse (1991) [1] indicates that the mooring line damping in surge for a floating oil and gas offshore installation can provide 80% of the total damping. Installation conditions for a wave energy converter (WEC) will be very different to conventional offshore installations, and information about the mooring line damping will be essential for predicting mooring behaviour and power extraction performance. In contrast to conventional offshore installations WECs will be installed in water of shallow or intermediate depths. As a requirement for power extractions this location needs to be unsheltered. Additionally some WECs have to respond to waves for power extraction and a low damping would be seen as desirable in these response modes. The extent of these responses may be directly controlled by damping, making it essential that it is well understood.

The issue of mooring line damping is being studied as part of an EPSRC Supergen Marine Energy Research Programme. This paper reviews mooring line damping in the light of what can usefully be learned from offshore and maritime experience and applied to WECs. The paper describes the experiment programmes underway at laboratory and full scale for WEC mooring systems, and discusses preliminary results from large scale experiments.

[96] *Johanning L. and Wolfram J. (2005). "Challenging tasks on moorings for floating WECs," International Symposium on Fluid Machinery for Wave and Tidal Energy: State of the Art and New Developments, IMechE, London, UK.*

To be effective wave energy converter devices (WECs) must be installed in locations with high energy density. Such regimes are more likely to be at offshore locations and much current interest is focused on offshore floating devices. Since the wave energy industry has little practical long-term experience with deployed WEC systems there is no historical experience upon which to base the formulation of appropriate station-keeping guidelines or standards. The development of standards that will allow the design of reliable, yet cost effective, mooring systems presents a challenging task. This paper raises issues pertinent to the station-keeping of WECs and examines to what extend existing standards used in the offshore oil and gas industry might be adapted.

[97] *Johanning L, Wolfram J., and Smith G.H. (2006). "Interaction between mooring line damping and response frequency as a result of stiffness alteration in surge," 25th Int. Conference on Offshore Mechanics and Arctic Engineering (OMAE), No. OMAE2006-92373, 04.-09.06.2006, Hamburg, Germany.*

The design and operation of a chain mooring for a wave energy converter (WEC) is considered. Experimental measurements of a mooring line were conducted in the Heriot-Watt University wave basin at a scale of 1:10. The laboratory procedures were designed to resemble tests undertaken earlier in the year at 'full' scale in 24 m water depth. This paper describes and compares these measurements and relates the results to earlier work on mooring lines by Webster [1]. Measurements of both the damping and response frequencies of the mooring are described. Although the present results support partly the conclusions of the earlier work, care must be taken in how these are applied when one is considering mooring line design for WECs.

It is concluded that there are significant differences for a WEC for both operational and limit state design in comparison with a more conventional offshore system such as an FPSO or CALM. Although the primary requirement is still one of station-keeping two further considerations may be of great importance. Firstly if a 'farm' of devices is to be considered then limitations in sea space may necessitate that the devices be relatively densely packed. This will mean that the 'footprint' of the mooring should be constrained, to ensure that the moorings from each device do not interfere with one another and this will have great significance for the loading experienced by the line. This can be exacerbated by variations in tidal range which will have a larger effect in comparison with a conventional deepwater mooring. A second factor may arise if the mooring system response is critical to the WEC energy extraction process. If the mooring becomes part of the 'tuned' system then changes in the mooring properties of damping and natural frequency could seriously affect energy conversion efficiencies.

[98] *Smith, G.H. and Johanning, L. (2006). "Mooring research to support Marine Energy Developments," Sea Technology, Offshore Technology Ocean Engineering, 23-26.*

The increasing concerns for the effect of emissions from the fossil fuel production of electricity has seen a renewed interest in developing commercial wave energy 'farms'. Although some devices may be shore based, the majority are likely to operate in deeper waters to take advantage of the better wave climate. Many of these devices will be floating and will need to be moored to the seabed in some manner to restrict their motion in a given sea state. This article explains the authors' beliefs that there are key design differences that must be considered when mooring a floating wave energy converter (WEC) as opposed to the requirements for conventional moorings.

Researchers at Heriot-Watt University, as part of the Supergen Marine consortium, are involved in research to promote the development of renewable wave and tidal energy concepts. The consortium comprising four universities within the UK is investigating a wide variety of issues related to the development of marine energy. Experimental research is being carried out at Heriot-Watt University, Scotland, under the direction of Dr Lars Johanning, to investigate the properties of mooring lines and, importantly, to provide guidelines to designers of wave energy converters.

[99] *Johanning L, Smith G.H and Wolfram J. (2006). "Mooring design approach for Marine Energy Converter," Proceedings of the Institution of Mechanical Engineers, Part M, Journal of Engineering for the Maritime Environment (JEME), Vol. 220, No. 4, pp.159-174(16).*

To be effective, wave energy converter devices (WECs) must be installed in unsheltered locations with high wave energy density. Such regimes are more likely to be at offshore locations and much current interest is focused on offshore floating devices. Since the wave energy industry has little practical long-term experience with deployed WEC systems there is no historical experience upon which to base the formulation of appropriate station-keeping arrangements. The development of generic station-keeping arrangements that will allow reliable, yet cost-effective, mooring systems presents a challenging task. This paper raises issues pertinent to the station-keeping of floating WECs and discusses a preliminary design procedure to identify suitable mooring arrangements.

WP9 Novel Control Systems for Marine Energy Converters

[100] *Mueller M.A., Xiang, J. Shek J. and Macpherson D.E. (2006). "Tuning Point Absorber Wave Energy Devices", Proceedings of the Marine Renewable Energy Conference, IMAREST World Maritime Technology Conference, London.*

The capture bandwidth of wave energy devices can be extended by implementing so-called phase control, also know as reactive power control. Phase control can be implemented by mechanical means, but in this paper the authors propose controlling the force produced by a direct drive electrical generator. An electrical circuit analogue of a wave device is used to describe phase control and the physical parameters used in the control system. The force produced by the linear generator can be resolved into two orthogonal components, one is a damping force and the other is a spring force. The damping force component is used to extract real power and the spring force component is used to control the phase between the wave excitation force on the device and device velocity. This paper shows how the generator current is used to control these two forces in order to modify the frequency characteristics of a simple mass-spring-damper system.

[101] *Yavuz, H., McCabe, A.P. Aggidis, G.A. and Widden, W.B. (2006). "Calculation of the performance of resonant wave energy converters in real seas." Proc. of the Institution of Mechanical Engineers, Part M, Journal of Engineering for the Maritime Environment, Vol. 220, No. 3, pp. 117-128(12).*

It is well known that the performance of point-absorber wave energy converters (WECs) depends upon resonance with the wave frequency. Indeed, the ideal performance of a resonating point-absorber WEC in a regular sea that can be represented by a simple sinusoid is well known, provided all motions are small and remain in the linear region. However, the performance of such a device in a more realistic, irregular sea that is not represented by a simple sinusoid cannot be so readily calculated. The first difficulty lies in modelling the hydrodynamic behaviour of the device. Recent developments in representing the hydrodynamic diffraction and radiation forces have enabled relatively simple simulation models to be developed, such as those presented and used in this paper. The second difficulty lies in the design of the device itself. In a regular sea with a known wave frequency, the settings of the power take-off system can be defined at well-known optimum values. It is shown in the present paper that, even when the wave frequency is not constant, the local wave frequency can be estimated, and this estimate can be used to adjust the power take-off system settings to maintain quasiresonance and, hence, approach the level of performance in a comparable regular sea. In this manner, for irregular seas it is possible to identify a dominant wave frequency over a relatively short time period and to use this frequency continuously to adjust the power take-off system settings, so as to adapt to the current sea conditions. This is likely, in some sea conditions, to involve the power take-off supplying power over part of the cycle, rather than absorbing it. This will increase the demands placed on the power take-off - particularly on its efficiency when the direction of power flow has to be reversible. The relative performance of such a tuneable point-absorber WEC is assessed in the paper. It is shown that the power converted in irregular seas could be as much as 50 per cent of the rated power, where the latter estimate is equivalent to the power converted in a corresponding regular sea.

[102] *McCabe, A. P., Stallard, T. J., Baker, N. J., and Yavuz, H. (2006). "Estimation of the responses of axisymmetric bodies in spread irregular waves," Ocean Engineering, December 2006.*

A method is presented of estimating the responses of axisymmetric bodies floating in spread irregular seas, using a Laplace transfer-function formulation of a floating body time-domain model. A general-case spread-wave model is formulated, using separate wave excitation transfer functions, and a simplification of this approach is proposed, reducing both model complexity and computation time. Responses are computed using both approaches and a comparison made to assess the circumstances in which the simplified approach may be used effectively. The results are also interpreted to highlight the implications of using an equivalent unidirectional wave as an approximation to a spread wave.

[103] *Price, A.A.E. and Wallace, A.R. (2007). Non-linear methods for next wave estimation. Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal.*

The prediction of near future wave excitation force is the fundamental problem associated with optimal control of a wave energy converter. This becomes clear when the latching technique is considered. The central control problem is the choice of the moment at which to release the latched working surface, such that the resulting velocity of the working surface is in phase with the wave exciting force. To calculate the ideal time to unlatch, the time until the next peak or trough in the excitation force would be required. This paper describes the development of various techniques, including neural networks, for estimation of the time until the next peak in excitation force. Two sets of synthetic excitation time series were used: one that was close to sinusoidal, with little variation in period and height, and the other with a high variation in these parameters. Several neural networks were trained and the results compared to alternative methods. It was found that neural networks performed better than the alternative methods for the time series that contained more variation.

[104] *McCabe, A. P., Stallard, T. J., and Aggidis. G.A. (2007). "Comparison of a time-domain model of a surging wave energy collector to experimental measurements." (In review by IMechE part M, (JEME) Journal of engineering for the Maritime Environment, October 2007.*

The ability to predict accurately the time-variation of power capture in irregular waves is an important requirement for developers of wave energy devices. We describe a linear time-domain model that is straightforward to implement in commercially available software. Wave forces and radiation are modelled using a Laplace transfer-function formulation rather than via convolution integrals. Numerical predictions of the time variation of the power captured by a surging collector are compared to experimental measurements of the response of a scale model in a range of regular and irregular wave fields.

When the incident wave-field is regular, the numerical model tends to over-predict the response amplitude particularly when the response is near-resonant. When the incident wave field is irregular, the period of each successive response cycle is in reasonable agreement with measurements, however, the magnitude of both the response and power capture is significantly over-predicted. In the range of sea-states studied, predictions of mean power capture are, on average, a factor of 2.27 greater than measured. It is shown that more accurate prediction of the time-variation of power capture in irregular seas can be obtained by inclusion of a drag coefficient which may be derived from the measured displacement response in regular waves only. In addition, the results suggest that the plan-form of a surging collector significantly influences the magnitude of drag experienced at small-scale.

[105] *Price A., Mundon, T., Murray A. and Wallace A.R. (2005). "A Test-Bed for Advanced Control of Wave Energy Converters," Proc 6th European Wave and Tidal Energy Conference, Glasgow.*

Dependable control systems would make wave energy converters cheaper and less risky. The state of the sea and the device change over time and the power take off settings should be chosen accordingly. Intelligent techniques that learn the relationship between available sensor data and the required power take off settings are considered. Input and target requirements are defined and the need for a training environment identified. A training simulator for a controller is proposed. This would be based on a neural network, which would be trained to identify the system from real sea data. This paper gives a description of the methodology and the steps required to demonstrate and develop this technique.

[106] *Yavuz, H., Stallard, T.J., McCabe, A.P. and Aggidis, G.A. (2007). "Time series analysis of adaptive tuning systems for a heaving wave energy converter in irregular waves." In review by Proc. of IMechE Part A: Journal of Power and Energy, Vol. 221, No. 1, pp. 77-90(14).*

The paper presents a time domain model of a heaving buoy wave-energy converter and investigates the tuning problem in irregular seas. The tuning issue is addressed by employing both fixed (passive) and adaptive (active) power-take-off settings. The fixed power-take-off tuning approach includes models based on tuning the device natural frequency to either the energy frequency or peak frequency of the sea-state or a weighted average of several peak frequencies. The adaptive tuning approaches employ a sliding discrete Fourier transform frequency analysis, or a time-series analysis of the measured wave elevation and device velocity to estimate a localized dominant wave frequency and hence calculate power-take-off settings. The paper presents details of these tuning techniques by discussing issues related to the modelling, simulation, and predicted power captures for each method. A comparative study of each method along with practical implications of the results and recommendations are also presented.

WP10 Full-scale Field Validation

[107] *Johanning L. and Smith G.H (2006). "Comparison of simulation and test results for a generic moored WEC using a catenary mooring arrangement," International conference OCEAN ENERGY, 23.10 – 24.10.2006, Bremerhaven, Germany*

The dynamic response of the mooring line will be a dominant factor to consider in their use for the station keeping of a wave energy converter (WEC). Due to their relatively small size and their being moored in relatively shallow waters the effect of waves, tide and current can be of greater significance. One must also consider how the mooring system might change the response of the WEC and so alter its ability to extract power from the waves. Axial line stretching and high frequency 'top-end' dynamics can importantly modify both damping from the mooring line and the top-end loading, and the way in which the affect the energy production of a device must also be considered. If a 'farm' of devices is to be considered then limitations in sea space may necessitate that the devices be relatively densely packed. This will mean that the 'footprint' of the mooring should be constrained, to ensure that the moorings from each device do not interfere and this will have great significance for the loading experienced by the line. Unlike a typical offshore system, for a wave responding WEC device, the design of its mooring must consider the dynamic response in respect to reliability and survivability, and the need to resume efficient energy conversion.

[108] *Owen A and Bryden I.G. (2005). "Prototype Support Structure for Sea Bed Mounted Tidal Current Turbines." Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, Volume 219, Number 4 / 2005, ISSN: 1475-0902*

This paper introduces the patented concept of the Sea Snail, a pin-jointed tubular steel structure carrying an array of symmetrical section hydrofoils, which is used as a means of fixing a tidal turbine, or other devices, to the seabed. The concept is evaluated as a simple mathematical model, tested as a one-eighth-scale model and subsequently developed into a 21 t model fit for sea trials. Pressure differences created by the flow over the upper and lower surfaces of the hydrofoils generate negative lift, or downforce, which is communicated to the supporting structure. The effects of induced drag on low-aspect-ratio hydrofoils are discussed. This paper gives an overview of the evaluative techniques employed in the Sea Snail's concept and design. The need for the device is outlined and its conceptual basis discussed. In particular, the response of a hydrofoil to increasing angles of attack within a steady flow is examined. Field measurements of the drag and lift forces applied to an NACA0013 section hydrofoil is presented in the context of the Sea Snail. The fundamental design criteria are discussed and the Sea Snail's ability to match these criteria is demonstrated.

[109] *Johanning L, Smith G.H. and Wolfram J. (2007). 'Measurements of static and dynamic mooring line damping and their importance for floating WEC devices,' Ocean Engineering, 34, p.1918–1934.*

The dynamic response of the mooring line will be a dominant factor to consider in their use for the station keeping of a wave energy converter (WEC). Due to the relatively small size of WECs and their being moored in relatively shallow waters the effect of waves, tide and current can be of greater significance than for other floating offshore systems. Axial line stretching and high-frequency 'top-end' dynamics can importantly modify damping and top-end loading.

If a 'farm' of devices is to be considered then limitations in sea space may necessitate that the devices be relatively densely packed. This will mean that the 'footprint' of the mooring should be constrained, to ensure that the moorings from each device do not interfere and this will have great significance for the loading experienced by the line. One must also consider how the mooring system might change the response of the WEC and so alter its ability to extract power from the waves. Unlike a typical offshore system, the design of moorings for a WEC device must consider reliability and survivability, and the need to ensure efficient energy conversion.

The design and operation of a chain mooring for a WEC is considered here. Generic experimental measurements of mooring line damping were conducted in the Heriot-Watt University wave basin at a scale of 1:10. The measurements were conducted on a single mooring line for surge motions and include the study of axial stretching and high top-end dynamics. The laboratory procedures were designed to resemble tests undertaken earlier at ‘full’ scale in 24 m water depth. The measurements were also compared with numerical studies. The experimental findings for WEC devices, supports the conclusion that dynamic mooring line motion will be an important variable, needing to be considered carefully within the design.

[110] *Owen, A. (2007). “The application of low aspect ratio hydrofoils to the secure positioning of static equipment in tidal streams.” PhD thesis, The Robert Gordon University, Aberdeen.*

The costs of installing tidal energy technology are high, requiring expensive vessels to drill sockets in the sea bed or to handle gravity based structures of substantial mass, and this impacts on the commercial viability of any proposed marine renewables development. This thesis offers a viable alternative to socketed or gravity based installations by proposing that the downwards lift force that can be developed from the flow over a hydrofoil can be used to resist the slip and overturning moments applied to a structure by the flow. The fundamental theory of axial and cross flow energy conversion devices is outlined and the current methods of fixing and supporting tidal stream devices are analysed.

The origins of tidal stream flows are discussed and the effects of local topography, bathymetry and system resonance are used to explain the significant differences between real tidal behaviour and the ideal of Newton’s equilibrium theory. The idiosyncratic and localised nature of tidal streams is thereby made clear as well as the need for a solid understanding of the resource prior to device design and installation. The principles of classical hydrodynamics and conformal mapping are used in the context of relating theoretical lift and drag functions to low aspect ratio hydrofoils with endplates, and a numerical model of distributed surface pressures around a hydrofoil is demonstrated. Subsequently, the concept is evaluated using two 1/7th scale test devices, one is field tested in a large stream under real flow conditions, and the second in a tow tank under ideal laboratory conditions. The limitations and challenges of model scaling are shown and the semi-empirical Froude method of scaling using residual forces is applied to the towing model. Analysis of the experimental data shows a correlation with normal distribution and extrapolation of the experimental results shows that the Sea Snail can operate with an average lift coefficient of 0.7 and drag coefficient of 0.18. Application of the experimental data to the full scale device demonstrates that the Sea Snail principle is not only valid, but is a significant advance on existing installation methodologies.

[111] *Johanning, L., Smith, G.H. and Bullen, C. (2007). “Large scale mooring line experiments and comparison with a fully dynamic simulation program with importance to WEC installation,” 17th Int. Offshore (Ocean) and Polar Engineering Conference, ISOPE, Lisbon, Portugal*

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

WP11 Assessment of Testing Procedures for Tidal Current Devices

[112] *Sun, X., Chick, J.P. and Bryden, I.G. (2007). "Laboratory-scale simulation of energy extraction from tidal currents." Renewable Energy, in press.*

The energy available from tidal currents is substantial and considerable work has been conducted into determining the size of the resource and what the large scale consequences of extraction might be. This paper describes work conducted to establish a laboratory-scale model, by using the commercial computational fluid dynamics (CFD) code FLUENTTM, in order to predict local flow consequences resulting from the extraction of energy in 2 and 3 dimensions from within the water column in a tidal flow. As might be expected, a wake is formed but there is considerable localised flow acceleration around and, most especially, under an extraction zone. The wake behind the device is shown to be associated with a drop in the free surface which, in turn, is associated with the decline in the wake itself.

WP12 Economic, Environmental and Social Impact of New Marine Technologies

[113] *McGregor, P.G., Swales, J.K. and Turner, K.R. (2005)."The environmental 'trade balance' between Scotland and the rest of the UK: an inter-regional input-output and SAM analysis", Presented at World Renewable Energy Congress, Aberdeen, Scotland and Regional Science International - British and Irish Section, Stratford-upon-Avon, England, August 2005.*

We use an inter-regional input-output (IO) and social accounting matrix (SAM) pollution attribution framework to serve as a platform for sub-national environmental attribution and trade balance analysis. While the existence of significant data problems mean that the quantitative results of this study should be regarded as provisional, the inter-regional economy-environment IO and SAM framework for Scotland and the rest of the UK (RUK) allows an illustrative analysis of some very important issues.

There are two key findings. The first is that there are large environmental spillovers between the regions of the UK. This has implications in terms of the devolution of responsibility for achieving targets for reductions in emissions levels and the need for policy co-ordination between the UK national and devolved governments. The second finding is that whilst Scotland runs an economic trade deficit with RUK, the environmental trade balance relationship for the main greenhouse gas, CO_2, runs in the opposite direction. In other words, the findings of this study suggest the existence of a CO_2 trade surplus between Scotland and the rest of the UK. This suggests that Scotland is bearing a net loss in terms of pollutants as a result of inter-union trade. However, if Scotland can carry out key activities, such as electricity generation, using less polluting technology, it is better for the UK as a whole if this type of relationship exists. Thus, the environmental trade balance is an important part of the devolution settlement.

[114] *McGregor, P.G., Swales, J.K. and Turner, K.R. (2007). "The CO_2 'trade balance' between Scotland and the rest of the UK: performing a multi-region environmental input-output analysis with limited data", under resubmission to Ecological Economics.*

In this paper we attempt an empirical application of the multi-region input-output (MRIO) method proposed by Turner, Lenzen, Wiedmann and Barrett (2007) in a recent issue of this journal in order to enumerate the CO_2 pollution content of interregional trade flows between Scotland and the rest of the UK (RUK). We extend the analysis to account for direct emissions generation by households, as final consumers, and to a social accounting matrix (SAM), where a more comprehensive account of incomes and expenditures is possible. While the existence of significant data problems mean that the quantitative results of this study should be regarded as provisional, the interregional economy-environment IO and SAM framework for Scotland and RUK allows an illustrative analysis of some very important issues in terms of the nature and significance of interregional environmental spillovers within the UK and the existence of a CO_2 'trade balance' between Scotland and RUK.

[115] *Learmonth, D., McGregor, P.G., Swales, J.K., Turner, K.R. and Yin, Y.P. (2006). "The importance of the regional/local dimension of sustainable development: an illustrative computable general*

equilibrium model of the Jersey economy," Economic Modelling, June 2006.

This paper uses a multi-period economic-environmental Computable General Equilibrium (CGE) modelling framework to analyse local sustainability policy issues. Our focus is the small, open, labour-constrained regional economy of Jersey. The case of Jersey is of particular interest for two main reasons. The first is the unusually low degree of geographical labour market integration for such a small regional economy. This motivates our treatment of labour as a region-specific factor of production. The second is the availability of high quality, Jersey-specific economic-environmental data. We employ CGE model simulations to track the impact of changes in population on a number of energy-consumption and pollution indicators in a recursive dynamic framework under alternative hypotheses regarding economic conditions over the time period under consideration. In the case of Jersey, we find that household consumption is the key factor governing the environmental impact of economic disturbances. Therefore the analysis includes an examination of the sensitivity of the simulation results to different assumptions affecting the wage elasticities of labour demand and supply, and the speed of adjustment to equilibrium on the responsiveness of household income to shifts in labour supply.

[116] *Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006). "The impact of a stimulus to energy efficiency on the economy and the environment: a regional computable general equilibrium analysis", Renewable Energy, p161-171.*

Sustainable development is a key objective of UK national and regional policies. Improvements in resource productivity have been suggested as both a measure of progress towards sustainable development and as a means of achieving sustainability. Making 'more with less' intuitively seems to be good for the environment, and this is the presumption of current UK policy. However, in a system-wide context, improvements in energy efficiency lower the cost of energy in efficiency units and may even stimulate the consumption and production of energy measured in physical units, and increase pollution. Simulations of a computable general equilibrium model of Scotland suggest that an across the board stimulus to energy efficiency there would actually stimulate energy production and consumption and lead to a deterioration in environmental indicators. The implication is that policies directed at stimulating energy efficiency are not, in themselves, sufficient to secure environmental improvements: this may require the use of complementary energy policies designed to moderate incentives to increased energy consumption.

[117] *Turner, K., Allan, G.J., McGregor, P.G. and Swales, J.K. (2005). "The need to establish region-specific economic and environmental data in a consistent and compatible format", Presented at European Wave and Tidal Energy Conference (29th September to 2nd October), University of Strathclyde, Glasgow.*

The Scottish Parliament has expressed a commitment to contributing to the delivery of UK climate change objectives. This paper argues that a consequent policy priority must be to establish useful information on resource use and polluting activities in the Scottish economy. That is, before any analysis of the impact of the Scottish, or any other economy on the local, national or global environment can be carried out, an appropriate accounting framework quantifying economy-environment relationships needs to be established. We argue that such a framework should have two characteristics. First, economic and environmental data should be gathered and reporting using compatible classifications of activities. Second, there should be appropriate disaggregation of economic activity to identify key energy producers, suppliers and users, other polluting activities and environmental protection services.

[118] *Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006), "Augmenting the Input-Output framework for 'common pool' resources: Operationalising the full Leontief environmental model", Economic Systems Research, Vol. 19, No. 1, p. 1-20, ISSN 0953-5314.*

In its initial formulation, the full Leontief (1970) environmental model augments the conventional Input–Output (IO) table by introducing pollution generation and separately identified pollution elimination sectors. Essentially it extends IO analysis to incorporate the use of a 'common pool' resource. Subsequent literature has either been analytical in nature or has concentrated on pollution generation but not cleaning activity. In this paper we generate an empirical full Leontief environmental IO system, based on augmenting the existing Scottish IO tables through endogenising waste generation and waste disposal activity. Due to weaknesses in data, our empirical results need to be treated with some caution. However, the construction of the extended IO system and the interpretation of the output and price multiplier results raise a number of interesting practical and conceptual issues. The analysis undertaken here can be extended to other 'common pool' resources such as the use of highways and irrigation systems.

[119] *Ferguson L., McGregor P.G., Swales J.K., Turner K. and Yin Y.P. (2005). "Incorporating sustainability indicators into a computable general equilibrium model of the Scottish economy", Economic Systems Research, Vol. 17, No. 2, pp 103-140.*

In recent years, the notion of sustainable development has begun to figure prominently in the regional, as well as the national, policy concerns of many industrialized countries. Indicators have typically been used to monitor changes in economic, environmental and social variables to show whether economic development is on a sustainable path. In this paper we endogenise individual and composite environmental indicators within an appropriately specified computable general equilibrium modelling framework for Scotland. In principle, at least, this represents a very powerful modelling tool that can inform the policy making process by identifying the impact of any exogenous policy change on the key endogenous environmental and economic indicators. It can also identify the effects of any binding environmental targets on economic activity.

[120] *Ferguson, L., McGregor, P.G., Swales, J.K., Turner, K.R. and Yin, Y.P (2005). "Incorporating Sustainability Indicators into a Computable General Equilibrium Model of the Scottish Economy", Proc WREC 2005 Conference (May 22nd-27th), Aberdeen, Scotland.*

The notion of sustainable development has begun to figure prominently in regional as well as national policy concerns in many industrialised countries in recent years. Policy proposals have tended to focus on using sustainability indicators to monitor changes in economic, environmental and social variables that show whether economic development is on a sustainable path. In this paper we demonstrate how individual and composite environmental indicators can be endogenised within an appropriately specified computable general equilibrium modelling framework. This implies that the impact of any disturbance to the system on these indicator variables can then be simulated automatically. We argue that, in principle at least, this represents a very powerful additional modelling tool that can inform the policy making process, by identifying the impact of any policy changes on the key environmental and economic indicators. It can also identify the effects of any binding environmental targets on economic activity.

[121] *Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006). "The Macroeconomic Rebound effect and the UK economy", Final report to the Department of Environment, Food and Rural Affairs, available online at http://www.defra.gov.uk/science/project_data/DocumentLibrary/EE01015/EE01015_3553_FRP.pdf*

Would a more efficient use of energy resources reduce the environmental burden of economic activity? This question has become prominent in recent years as governments across the world have implemented energy efficiency programs.
Improvements in resource productivity have been suggested as both a measure of progress towards sustainable development and as a means of achieving sustainability (Cabinet Office, 2001). The popular interpretation of resource productivity is "doing more with less": that is, of reducing the material or energy requirements of economic activity. However, the presumption of the "conventional wisdom" that underlies current policy initiatives is that improving resource productivity will lower the burdens on the environment.

In fact, there has been an extensive debate in the energy economics/ policy literature on the impact of improvements in energy efficiency in particular. This focuses on the notion of "rebound" effects, according to which the expected beneficial impacts on energy intensities are partially, or possibly even more than wholly in the case of "backfire", offset as a consequence of the economic system's responses to energy efficiency stimuli. The "Khazzoom-Brookes postulate" (Saunders, 1992) asserts that improvements in energy efficiency can actually stimulate the demand for energy, thereby nullifying the anticipated environmental benefits of such changes. Jevons (1865) was the first to argue for such an effect, in the context of improvements in the efficiency of coal use. Very recently the House of Lords have acknowledged that energy efficiency improvements alone might not deliver the expected environmental benefits.

In this report we explore the conditions under which the notion that energy efficiency is environment-enhancing would be expected to hold theoretically, and present some empirical evidence from an energy-economy-environment computable general equilibrium (CGE) model of the UK economy.

[122] *Turner, K., Lenzen, M, Wiedmann, T. and Barrett, J. (2007). "Examining the global environmental impact of regional consumption activities - Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade", Ecological Economics, Vol. 61, No. 1, p. 15-26, ISSN 0921-8009*

This paper offers a detailed review of recently described single- and multi-region input–output models used to assess environmental impacts of internationally traded goods and services. It is the second part of a two-part contribution. In Part 1 [Turner, K., Lenzen, M., Wiedmann, T. and Barrett, J. in press. Examining the Global Environmental Impact of Regional Consumption Activities — Part 1: A Technical Note on Combining Input–Output and Ecological Footprint Analysis; Ecological Economics.] we describe how to enumerate the resource and pollution content of inter-regional and inter-national trade flows with the aim to illustrate an ideal accounting and modelling framework for the estimation of Ecological Footprints. A large number of such environment-economic models have been described but only in the last few years models have emerged that use a more sophisticated multi-region, multi-sector input–output framework. This has been made possible through improvements in data availability and quality as well as computability. We identify six major models that employ multi-sector, multi-region input–output analysis in order to calculate environmental impacts embodied in international trade. Results from the reviewed studies demonstrate that it is important to explicitly consider the production recipe, land and energy use as well as emissions in a multi-region, multi-sector and multi-directional trade model with global coverage and detailed sector disaggregation. Only then reliable figures for indicators of impacts embodied in trade, such as the Ecological Footprint, can be derived.

[123] *Allan, G.J., McGregor, P.G., Stallard, T., Swales, J.K. and Turner, K.R. (2007), "Concurrent and legacy economic impacts from establishing a marine energy sector in Scotland", under review for resubmission to Energy Policy, October 2007.*

We examine the economic impact that the installation of 3GW of marine energy capacity would have on Scotland. This is done by estimating construction, installation and operating expenditures and the duration of these expenditures on a generic wave energy device. Earlier studies of the economic impacts of such expenditures have used Input-Output models; however, these assume that the supply-side of the economy is entirely passive. Using a regional computable general equilibrium (CGE) model of Scotland, AMOSENVI, we show that this assumption is quantitatively important for the economic impact of these expenditures. Such expenditure injections will produce supply-side effects, through increased net migration and capital stock adjustment, which affect the timing and scale of the resulting economic impacts. The scale of the impacts on GDP and employment over the lifetime of the devices is significant, and there are also substantial "legacy" effects that persist beyond the design life of the devices. These results show the importance of considering supply-side consequences of demand injections for estimating the economic impact of the expansion of renewable energy on a regional economy.

[124] *Allan, G.J., McGregor, P.G., Stallard, T., Swales, J.K. and Turner, K.R. (2006). "Concurrent and legacy impacts from the expenditures required to establish a marine energy industry in Scotland: a computable general equilibrium analysis", Proc World Renewable Energy Congress IX, Florence, Italy.*

In Scotland, significant reductions in electricity generation capacity are expected as coal- and nuclear power stations close. Although the UK Parliament makes decisions on energy supply, the Scottish executive has responsibility for encouraging renewable technology development and has set ambitious targets for renewable generation. Allowing for constraints imposed by resource availability, economic viability and technological feasibility wave power alone could generate capacity in excess of 3GW.

In this paper, we examine the economic impact that the installation of 3GW wave energy capacity would have on Scotland. We estimate the costs that may be incurred to construct and install this level of capacity between now and 2020 and the subsequent expenditures required to operate and refit the generators during their 20-year life. A regional computable general equilibrium (CGE) of Scotland, AMOSENVI, is then used to estimate the scale of the economic impact, in terms of GDP and employment, of these expenditures. The scale of these economic impacts over the lifetime of the devices is significant, and there are also substantial "legacy" effects that persist beyond the design life of the devices. These results illustrate both the importance of looking beyond the duration of direct expenditures when considering the scale of economic impacts, and also the potential economic benefits to Scotland from the development of an indigenous marine energy industry.

[125] *Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), "The impact of increased efficiency on industrial use of energy: a computable general equilibrium analysis for the United Kingdom", Energy Economics, Vol. 29, No. 4, pp. 779-798, ISSN 0140-9883*

The conventional wisdom is that improving energy efficiency will lower energy use. However, there is an extensive debate in the energy economics/policy literature concerning "rebound" effects. These occur because an improvement in energy efficiency produces a fall in the effective price of energy services. The response of the economic system to this price fall at least partially offsets the expected beneficial impact of the energy efficiency gain. In this paper we use an economy–energy–environment computable general equilibrium (CGE) model for the UK to measure the impact of a 5% across the board improvement in the efficiency of energy use in all production sectors. We identify rebound effects of the order of 30–50%, but no backfire (no increase in energy use). However, these results are sensitive to the assumed structure of the labour market, key production elasticities, the time period under consideration and the mechanism through which increased government revenues are recycled back to the economy.

[126] *Turner, K., Lenzen, M, Wiedmann, T. and Barrett, J. (2007), "Examining the global environmental impact of regional consumption activities – Part 1: A technical note on combining input-output and ecological footprint analysis", by K. Turner, M. Lenzen, T. Wiedmann and J. Barrett, Ecological Economics, Vol. 62, No. 1, p. 37-44, ISSN 0921-8009*

In recent years there have been a number of attempts to develop a more comprehensive approach to the issue of measuring resource use and/or pollution generation embodied in trade flows, including contributions that combine input–output techniques and Ecological Footprint analysis. In this two-part paper we describe how to enumerate the resource and/or pollution content of inter-regional and international trade flows (Part 1) and we present a literature review of recent methodological and empirical developments (Part 2). It is straightforward in principle to extend the basic input–output approach to capture international trade flows. However, in practice, problems of data availability and compatibility, and of computability of extended input–output matrices, mean that simplifying assumptions are generally applied, but with the implications of these assumptions often not made fully explicit. What appears to be absent from previous applications is an account of the analytical method by which Ecological Footprints should ideally be estimated in an international input–output accounting analysis. This allows an explicit analysis of the problems that prevent the application of the full method and identification of the most appropriate short-cut methods in a transparent way. The objective of this paper is to provide such an account.

[127] *Gilmartin, M., Learmonth, D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), "The national impact of regional policy: demand-side policy simulation with labour market constraints in a two-region computable general equilibrium framework", Strathclyde Discussion Paper in Economics, No. 07-04.*

UK governments generally advocate regional policy as a means of reducing regional disparities and stimulating national growth. However, there is limited comprehension of the effects of regional policy on non-target economies. This paper examines the system-wide effects on the Scottish and rest of UK (RUK) economies of an increase in Scottish traded sector exports to the rest of the world. The research is carried out in an inter-regional Computable General Equilibrium framework of the Scottish and RUK economies, under alternative hypotheses regarding wage determination and inter-regional migratory behaviour. The findings suggest that regional policy can have significant national spillover effects, even when the target region is small relative to the RUK. Furthermore, the configuration of the labour market is important in determining the post-shock adjustment path of both economies. In particular, while Scottish economy results are sensitive to alternative versions of how regional labour markets function, RUK region effects prove to be even more so.

[128] *Gilmartin, M., McGregor, P.G., and Swales, J.K. (2007), "The national impact of regional policy: supply-side policy simulation with labour market constraints in a two-region computable general equilibrium framework", Strathclyde Discussion Paper in Economics, No. 07-05.*

In a UK context, research into regional policy impacts has focused largely on the effects of a policy on the target region, with any consequences for other regions being largely ignored. This study aims to address this issue by providing a comprehensive evaluation of regional policy, focusing on both the regional and national implications of a policy shock. The paper examines the system-wide effects on the Scottish and rest of UK (RUK) economies of an increase in labour efficiency in the Scottish traded sectors. The research is carried out in an inter-regional computable general equilibrium framework of the Scottish and RUK economies, under alternative hypotheses regarding wage determination and inter-regional migratory behaviour. The findings suggest that regional policy can have significant national spillover effects, even when the target region is small relative to the RUK. Furthermore, the configuration of the labour market is important in determining the post-shock adjustment path of both economies. In particular, while Scottish economy results are sensitive to alternative versions of how regional labour markets function, RUK region effects prove to be even more so.

[129] *Allan, G.J., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007). "The impact of alternative electricity generation technologies on the Scottish economy: an illustrative input-output analysis", Proceedings of the Institute of Mechanical Engineering (Part A): Journal of Power and Energy, Vol. 221, No. 2, pp. 243-254(12).*

UK energy policy is at a critical juncture, with major changes in the electricity generation mix in prospect. In Scotland, significant reductions in electricity-generating capacity are expected as coal- and nuclear-powered stations close, and renewable technologies provide a growing share of total electricity. Despite these radical changes, there has as yet been no assessment of the likely implications for the Scottish economy. This paper explores the likely system wide impact of these changes on aggregate and sectoral outputs and employment levels using an input-output analysis that separately identifies eight generating technologies. The results suggest the need for careful disaggregation of the electricity generation sector and emphasize the economic distinctiveness of individual generation technologies.

[130] *Hanley, N.D., McGregor, P.G., Turner, K.R. and Swales, J.K. (2007). "Do increases in resource productivity improve environmental quality? Theory and evidence on 'rebound' and 'backfire' effects from an energy-economy-environment computable general equilibrium model of Scotland" submitted to Ecological Economics, September 2007.*

Resource Productivity is increasingly seen as an important aspect of sustainability by governments world-wide. Making more with less seems to be intuitive in terms of reducing the burden on the environment while allowing for economic development. In the UK policy context there appears to be an acceptance that enhanced resource productivity is "good for the environment". However, there is a debate in the literature
concerning the possibility that any beneficial impact on the environment may be partially ("rebound") or even more than wholly ("backfire") offset. This paper clarifies the theoretical conditions under which such effects would occur and explores their likely significance using a CGE model of the Scottish economy. We find that an improvement in energy efficiency ultimately increases energy use and results in a worsening of the GDP to CO_2 emissions ratio. The time interval of analysis proves
significant, with rebound effects eventually growing into backfire. The reason is simple: energy efficiency improvements result in an effective cut in energy prices, which produces output and substitution effects that stimulate energy demands. However, the presence of backfire effects does not imply irrelevance of efficiency-enhancing policies: rather it implies that such policies alone are insufficient to improve the environment. The implication is that energy policies need to be

co-ordinated.

[131] *Allan, G.J., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006). "The impact of alternative electricity generation technologies on the Scottish economy: an illustrative input-output analysis", Strathclyde Discussion Paper in Economics, No. 06-02, available from http://www.strath.ac.uk/media/media_34009_en.pdf.*

UK Energy policy is at a critical juncture, with major changes in the electricity generation mix in prospect. In Scotland significant reductions in electricity generating capacity are expected as coal- and nuclear-powered stations close, and although rapid growth of renewable capacity continues, it does so from a very small base. There is no doubt that Scotland faces very substantial shifts in the composition of its electricity generating capacity, and very probably also a major contraction in the level of that capacity in the absence of further changes in UK energy policy (such as a move to commission new nuclear generating stations). The choices made will have important economic, as well as environmental, consequences.

[132] *Graham, J., McGregor, P.G., Swales, J.K. and Turner, K. (2007), "Additional measures of progress for Scotland: an analysis of the issues and problems associated with aggregate/composite measures of sustainability", Paper for the Scottish Executive Additional Measures of Progress Steering Group, August 2007, online at http://www.scotland.gov.uk/Resource/Doc/147491/0052143.pdf*

A central part of the sustainability question is the argument that National Income as currently measured is not sustainable income, as it does not aim to capture well-being or quality of life issues, and does not account for environmental assets or the impacts of environmental degradation. This has led to efforts to find ways of adjusting or supplementing conventional measures of national income, in particular GDP, to capture a wider range of issues. However, due to problems of aggregation and valuation of components where markets do not exist, or are imperfect or incomplete, the idea of replacing the conventional system of national accounting with a 'Green GDP' or 'sustainable income' is problematic and controversial and no consensus has emerged on accepted measures of progress in this broad sense.

To deal with this, many countries have introduced systems of satellite accounts, which exist alongside conventional national income accounts, providing information to help manage economic activity in a way that is sustainable. A key element of satellite accounting has been the adoption and use of 'baskets' of individual sustainability indicators, which involves systematic and regular reporting of movements in a number of economic, environmental and social indicators. Where valuation is difficult, as in the case of environmental factors, in contrast to the concept of a fully integrated Green GDP or sustainable income, satellite accounts allow measurement in physical units, with no necessity that these be converted to monetary units.

However, the practice of monitoring and reporting on sometimes very large sets of individual indicators is a complex one and, despite the reservations noted above, the issue remains as to whether it is reasonable to attempt to measure sustainability in a single or composite measure. In the case of Scotland, the question arises in Section 14 of 'Choosing Our Future: Scotland's Sustainable Development Strategy' where the Executive states a commitment to "review the evidence on the options for additional and improved ways of measuring progress, and report by the end of 2006".

As a first step in this process, the purpose of this paper is to consider the broad set of issues and problems associated with adopting aggregate measures of sustainability. We do this by first considering what we mean when we talk about 'sustainable development' in a policy context and the role that we want sustainability indicators to play. Two broad types of sustainability are identified and we argue that the role of sustainability indicators depends on which type we are concerned with. This also proves to have a bearing on many of the problems and issues commonly associated with composite or aggregate indicators. In order to consider these problems and issues systematically we initially abstract from examination of any specific candidate indicators. However, in the latter stages of the paper we illustrate our analysis with a number of candidate measures of sustainability.

[133] *Allan, G.J., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), "Economic linkages and*

impacts of alternative electricity generation technologies on a regional economy: an input-output analysis for Scotland", under revision for submission to Energy Policy, September 2007.

A recent paper in Energy Policy (Han et al., 2004) uses Input-Output (IO) analysis to examine the economic linkages and the other characteristics of electricity generation sectors. In this paper, standard techniques from Han et al., (2004) are applied to the regional economy of Scotland and extensions to the use of IO modelling are presented for future scenarios of electricity generation. Scotland offers an interesting case study as the pattern of electricity generation is expected to alter significantly over the next twenty years. Existing fossil-fuel and nuclear facilities are projected to close down whilst there are also significant resources for the generation of electricity from renewable resources, including off-shore wind, wave and tidal technologies. Linkage and multiplier analyses show the extent to which existing generation technologies are embedded into the regional economy, while extending the Leontief price model allows a first assessment of the impact that significant changes in the pattern of electricity generation might have on regional prices.

Appendix 3 Publications in Alphabetical Order

Aggidis, G.A. Bradshaw, A. French, M.J. McCabe, A.P. Meadowcroft, J. A. C. and Widden, W.B. (2005). “PS Frog MK 5 WEC developments and design progress,” World Renewable Energy Congress, Aberdeen, May 2005. (WP 3, [43]).

Allan, G.J., Gilmartin, M., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), “Assessment of evidence for rebound effects from computable general equilibrium modelling studies”, Report for the UKERC Technology and Policy Assessment on the Rebound Effect, expected publication Autumn 2007.

Allan, G.J., Gilmartin, M., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), “Lessons learned from recent CGE analyses of energy efficiency improvements: rebound and backfire effects”, Expert Commentary chapter in Energy Efficiency Research Trends, expected publication late-2007.

Allan, G.J., Gilmartin, M., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), “Modelling the economy-wide rebound effect”, book chapter for Energy efficiency and sustainable consumption: dealing with the rebound effect, edited by Steve Sorrell and Horace Herring, expected publication early-2008.

Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006), “Augmenting the Input-Output framework for ‘common pool’ resources: Operationalising the full Leontief environmental model”, Economic Systems Research, Vol. 19, No. 1, p. 1-20, ISSN 0953-5314 (WP 12, [118]).

Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006), “The Macroeconomic Rebound effect and the UK economy”, Final report to the Department of Environment, Food and Rural Affairs, available online at http://www.defra.gov.uk/science/project_data/DocumentLibrary/EE01015/EE01015_3553_FRP.pdf (WP 12, [121]).

Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), “The impact of increased efficiency on industrial use of energy: a computable general equilibrium analysis for the United Kingdom”, Energy Economics, Vol. 29, No. 4, July 2007, pp. 779-798, ISSN 0140-9883 (WP 12, [125]).

Allan, G.J., McGregor, P.G., Stallard, T., Swales, J.K. and Turner, K.R. (2007), “Concurrent and legacy economic impacts from establishing a marine energy sector in Scotland”, under review for resubmission to Energy Policy, October 2007 (WP 12, [123]).

Allan, G.J., McGregor, P.G., Stallard, T., Swales, J.K. and Turner, K.R. (2006). “Concurrent and legacy impacts from the expenditures required to establish a marine energy industry in Scotland: a computable general equilibrium analysis”, Proc World Renewable Energy Congress IX, Florence, August 2006 (WP 12, [124]).

Allan, G.J., McGregor, P.G., Stallard, T., Swales, J.K. and Turner, K.R. (2006), “Concurrent and legacy impacts from establishing a marine energy sector in Scotland: a computable general equilibrium analysis”, Strathclyde Discussion Paper in Economics, No. 06-04, August 2006.

Allan, G.J., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), “Economic linkages and impacts of alternative electricity generation technologies on a regional economy: an input-output analysis for Scotland”, under revision for submission to Energy Policy, September 2007 (WP 12, [133]).

Allan, G.J., McGregor, P.G., Swales, J.K. and Turner, K.R., (2007). “The impact of alternative electricity generation technologies on the Scottish economy: an illustrative input-output analysis”, Proceedings of the Institute of Mechanical Engineering (Part A): Journal of Power and Energy, Vol. 221, No. 2, pp. 243-254(12), (2007). (WP 12, [129]).

Allan, G.J., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006). “The impact of alternative electricity generation technologies on the Scottish economy: an illustrative input-output analysis”, Strathclyde

Discussion Paper in Economics, No. 06-02, March 2006 available from http://www.strath.ac.uk/media/media_34009_en.pdf. (WP 12, [131]).

Allan, G.J., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006), "The impact of Scotland's economy on the environment: a response", Fraser of Allander Institute Quarterly Economic Commentary, 30(5), p. 45-46.

Baker N.J., Mueller M.A., Tavner P.J., Li Ran (2005). "Prototype Development of Direct-Drive Linear Electrical Machines for Marine Energy Converters", World Renewable Energy Congress, Aberdeen, UK, May 2005.

Boehme, T., Harrison, G.P. and Wallace, A.R., (2007). "Non-firm Renewable Connection Assessment using Optimal Power Flow and Time Series", IEEE Trans. Power Systems. (WP 6, [83]).

Boehme, T., Taylor J., Wallace, A. R. and Bialek, J. (2006). "Matching Renewable Energy Generation with Demand", Scottish Executive, February 2006, ISBN 0-7559-5029-1. (WP 6, [87]).

Boehme, T., Wallace, A.R and Harrison, G.P. (2007). "Applying Time Series to Power Flow Analysis in Networks with High Wind Penetration", IEEE Trans. on Power Systems, vol. 22, no. 3, August 2007, pp. 951–957. (WP 6, [85]).

Boehme, T., (2006). "Matching Renewable Electricity Generation with Demand in Scotland." PhD thesis, The University of Edinburgh, April 2006. (WP 6, [89]).

Bryden I .G, Grinsted T. and Melville G.T. (2005). "Assessing the Potential of a Simple Tidal Channel to Deliver Useful Energy", Applied Ocean Research, Vol 26/5 pp. 200-206, 10.1016/j.apor.2005.04.001, 2005. (WP 1, [28]).

Bryden I, Couch S.J., (2004). "Marine Energy Extraction: Tidal Resource Analysis", WREC04, Denver, 2004 (WP 1, [12]).

Bryden I. G. and Melville G., (2004). "Choosing and Evaluating Sites for Tidal Current Development", Proc. IMechE Journal of Power and Energy, Vol 218, p567-578, London, ISSN 0957-6509, 2004. (WP 3, [50]).

Bryden I.G. and Couch S.J., (2005). "ME1 - Marine Energy Extraction: Tidal Resource Analysis", Renewable Energy, RENE2412, paper 10.1016/j.renene.2005.08.012, 2005. (WP 1, [11]).

Bryden I.G., Couch S.J. and Harrison G., (2006). "Overview of the Issues Associated with Energy Extraction from Tidal Currents", World Renewable Energy Congress IX, Florence, August 2006 (WP 1, [10]).

Bryden I.G., Couch S.J., Owen A. and Melville G. (2007). "Tidal Current Resource Assessment", Proc IMechE Journal of Power and Energy, Vol. 221, No. 2, pp. 125-135(11), (2007). (WP 1, [8]).

Bryden I.G., (2006). "The Marine Energy Resource, Constraints and Opportunities", Proceedings of the Institution of Civil Engineers: Maritime Engineering 159, June 2006, Issue MA2, pp 55-65 (WP 1, [14]).

Bryden, I. and Couch, S.J.; (2007). "How much energy can be extracted from moving water with a free surface: a question of importance in the field of tidal current energy?", Journal of Renewable Energy, 32, pp. 1961-1966. (WP 1, [15]).

Bryden, I.G., (2007). "Tidal Energy Commentary." World Energy Review 2007, in press. (WP 1, [3]).

Chaplin R.V. and Aggidis G.A. (2007), "An Investigation into Power from Pitch-Surge Point-Absorber Wave Energy Converters", proceedings of IEEE International Conference on Clean Electrical Power Renewable Energy Resources Impact, Capri, Italy, 21-23 May 2007, published by IEEE, Catalog

Number: 07EX1528 – ISBN: 1-4244-0631-5, Library of Congress: 2006932315 - @ 2007 IEEE, 23 May 2007. (WP 3, [62]).

Chaplin R.V. and Aggidis G.A., (2007). “WRASPA: Wave Interactions and Control for Pitching-Surge Point-Absorber”, Wave Energy Converters, Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal, 11-13 September 2007. ISBN: 978-989-95079-3-7 (2007). (WP 3, [63]).

Chick, J., Bryden, I., and Couch, S.J. (2007); "The influence of Energy Extraction from Tidal Channels and its Impact on System Design", Underwater Technology, International Journal of the Society for Underwater Technology, 27, 2, 49-56, 2007/06, ISSN 0141-0814 (WP 1, [2]).

Child, B.F.M and Venugopal, V. (2007). “Interaction of waves with an array of floating wave energy devices,” Proc. 7th European Wave and Tidal Energy Conference, paper 1059, Porto, Portugal, 11-13 Sept 2007. (WP 1, [1]).

Couch S.J., Bryden I.G. (2004); "The impact of energy extraction on tidal flow development", 3rd IMarEST International Conference on Marine Renewable Energy (WP 1, [4]).

Couch S.J., Sun X., Bryden I.G.; (2005). "Modelling of Energy Extraction from Tidal Currents", 6th EWTEC European Wave and Tidal Energy Conference, 2005 (WP 1, [5]).

Couch, S.J, and Bryden, I.; (2006). "Tidal Current Energy Extraction: Hydrodynamic Resource Characteristics", Proceedings of the Institution of Mechanical Engineers, Part M: Engineering for the Maritime Environment, 220, 4, 185-194, 2006, ISSN 1475-0902 (WP 1, [7]).

Couch, S.J. and Bryden, I.; (2007). "Large-scale physical response of the tidal system to energy extraction and its significance for informing environmental and ecological impact assessment", IEEE/OES Oceans '07 Marine Challenges: Coastline to Deep Sea, 2007/06/18-21 (WP 1, [6]).

Couch, S.J. and Bryden, I.; (2005). "Numerical Modelling of Energy Extraction from Tidal Flows", WREC'05, 2005 (WP 1, [17]).

Couch, S.J., Jeffrey, H.F. and Bryden, I.; (2007). "Tidal Current Energy: Development of a Device Performance Protocol", IEEE International Conference on Clean Electrical Power 2007 (WP 3, [47]).

Couch, S.J., Jeffrey, H.F.; "Preliminary Tidal Current Energy: Device Performance Protocol", 13, 2007/02. Available from http://www.berr.gov.uk/files/file38991.pdf (WP 3, [46]).

Couch, S.J., Jeffrey, H.F.; "Tidal current energy: Device Performance Protocol - Response to feedback from 19th July Workshop and consultation", 15, 2007/02. Available from http://www.berr.gov.uk/files/file38993.pdf (WP 3, [45]).

Couch, S.J., Wallace, A.R. and Bryden, I; (2007). "Overview of the SUPERGEN Marine Energy Research Program", IEEE International Conference on Clean Electrical Power 2007, 2007/05/21-23 (WP 3, [44]).

Cruz, J, Pascal, R, Taylor, J (2006), “Characterization of the wave profile in the Edinburgh curved tank ”, Proceedings of OMAE2006 25th International Conference on Offshore Mechanics and Arctic Engineering, Hamburg, Germany, June 2006 (WP 3, [49]).

Cruz, J., Payne, G. (2006), “Preliminary numerical studies on a modified Edinburgh duck using WAMIT,” In: Marine Renewable Energy Conference (MAREC), London, U.K. (WP 2, [36]).

Cruz J, Salter S, & Payne G, (2006) “Wave powered desalination: Hydrodynamic studies”, World Maritime Technology Conference (MAREC 2006), London March 2006.

Douglas, C. A., Harrison G. P. and Chick, J. P. “Energy and carbon audit of a marine current turbine”, Proc. Institution of Mechanical Engineers Part M Engineering for the Maritime Environment, in press. (WP 3, [51]).

Ferguson L., McGregor P.G., Swales J.K., Turner K. and Yin Y.P.; (2005). “Incorporating sustainability indicators into a computable general equilibrium model of the Scottish economy”, Economic Systems Research, Vol. 17, No. 2, pp 103-140, June 2005. (WP 12, [119]).

Ferguson, L., McGregor, P.G., Swales, J.K., Turner, K.R. and Yin, Y.P.; (2005). “Incorporating Sustainability Indicators into a Computable General Equilibrium Model of the Scottish Economy”, Proc WREC 2005 Conference (May 22nd-27th), Aberdeen, Scotland, 2005. (WP 12, [120]).

French J. M., (2006). “On the difficulty of inventing an economical sea wave energy converter: a personal view”, DOI: 10.1243/14750902 JEME43 © IMechE 2006 Proc. IMechE Vol. 220 Part M: J. Engineering for the Maritime Environment, 3 July 2006. (WP 3, [68]).

Gilmartin, M., Learmonth, D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), “The national impact of regional policy: demand-side policy simulation with labour market constraints in a two-region computable general equilibrium framework”, Strathclyde Discussion Paper in Economics, No. 07-04, July 2007 (WP 12, [127]).

Gilmartin, M., McGregor, P.G., and Swales, J.K. (2007), “The national impact of regional policy: supply-side policy simulation with labour market constraints in a two-region computable general equilibrium framework”, Strathclyde Discussion Paper in Economics, No. 07-05, July 2007 (WP 12, [128]).

Graham, J., McGregor, P.G., Swales, J.K. and Turner, K. (2007), “Additional measures of progress for Scotland: an analysis of the issues and problems associated with aggregate/composite measures of sustainability”, Paper for the Scottish Executive Additional Measures of Progress Steering Group, August 2007, online at http://www.scotland.gov.uk/Resource/Doc/147491/0052143.pdf (WP 12, [132]).

Gretton, G. I. and Bruce, T (2005), “Preliminary results from analytical and numerical models of a variable-pitch vertical-axis tidal current turbine”, Proceedings of the 6th European Wave and Tidal Energy Conference, Glasgow, UK. (WP 1, [29]).

Gretton, G. I. and Bruce, T (2006), “Hydrodynamic modelling of a vertical-axis tidal current turbine using a Navier-Stokes solver”, Proceedings of the 9th World Renewable Energy Congress, Florence, Italy. (WP 1, [30]).

Gretton, G. I. and Bruce, T (2007), “Aspects of mathematical modelling of a prototype scale vertical-axis turbine”, Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal. (WP 1, [32]).

Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2006). “The impact of a stimulus to energy efficiency on the economy and the environment: a regional computable general equilibrium analysis”, Renewable Energy, February, p161-171, 2006 (WP 12, [116]).

Hanley, N.D., McGregor, P.G., Turner, K.R. and Swales, J.K. (2007). "Do increases in resource productivity improve environmental quality? Theory and evidence on 'rebound' and 'backfire' effects from an energy-economy-environment computable general equilibrium model of Scotland" submitted to Ecological Economics, September 2007 (WP 12, [130]).

Hanley, N.D., McGregor, P.G., Swales, J.K. and Turner, K.R. (2004). “Do increases in resource productivity improve environmental quality? Theory and evidence on ‘rebound’ and ‘backfire’ effects from an energy-economy-environmental regional computable general equilibrium model of Scotland”, Presented at World Renewable Energy Congress VIII, August, Denver, August 2004

Harris R.E, Johanning L and Wolfram J., (2004). “Mooring systems for wave energy converters: A review of design issues and choices,” 3rd International Conference on Marine Renewable Energy, 2004, Blyth, UK. (WP 8, [93]).

Harrison, G. P. and Wallace, A. R. (2005). “Climate change impacts on renewable energy – is it all hot air?” World Renewable Energy Congress, 22–27 May 2005, Aberdeen. (WP 1, [26]).

Harrison, G. P. and Wallace, A. R., (2005). “A changing climate for marine energy”, Proc. 6th European Wave and Tidal Energy Conference, Glasgow, September 2005. (WP 1, [25]).

Harrison, G.P. Wallace; A.R. (2005). "OPF evaluation of distribution network capacity for the connection of distributed generation", IEE Proceedings on Generation, Transmission and Distribution, 152 (1). (WP 6, [86]).

Harrison, G.P. and Wallace, A.R., (2005). ‘Climate sensitivity of marine energy’, Renewable Energy, 30 (12), pp. 1801-1817. (WP 1, [20]).

Harrison, G.P. and Wallace, A.R., (2005). ‘Sensitivity of wave energy to climate change’, IEEE Trans. on Energy Conversion, 20 (4), pp. 870-877. (WP 1, [19]).

Harrison, G.P., Couch S.J., Bryden I, Wallace A.R.; (2006). "Climate Change Impacts on Marine Energy Resources", European Conference on Impacts of Climate Change on Renewable Energy Sources, 5-9 June 2006, Reykjavik, Iceland. (WP 1, [18]).

Huang, M. and Aggidis, G.A., (2006). “Research on Wave Energy Converters and Mooring Systems in the United Kingdom”. Published by the Water Resources and Power Journal in Chinese, in Vol. 24 No. 4, 25 Aug. 2006, pp 37 – 40, ID: 1000-7709 (2006) 04-0037-04, ISSN: 1000-7709. (WP 3, [65]).

Jeffrey, H.F, Mueller M and Smith G.H. (2007). “An investigation of the Knowledge Base of the UK Marine Renewable Sector”, 7th European Wave and Tidal Energy Conference, Porto, September 2007. (WP 3, [60]).

Johanning L, Smith G.H and Wolfram J., (2006). “Mooring design approach for Marine Energy Converter,” Proceedings of the Institution of Mechanical Engineers, Part M, Journal of Engineering for the Maritime Environment (JEME), Vol. 220, No. 4, pp.159-174(16), (2006). (WP 8, [99]).

Johanning L, Smith G.H. & Wolfram J.; (2007). “Measurements of static and dynamic mooring line damping and their importance for floating WEC devices”, Ocean Engineering, 34, p.1918–1934. (WP 10, [109]).

Johanning L, Smith G.H; (2006). “Comparison of simulation and test results for a generic moored WEC using a catenary mooring arrangement,” International conference OCEAN ENERGY, 23.10 – 24.10.2006, Bremerhaven, Germany (WP 10, [107]).

Johanning L, Wolfram J., And Smith G.H, (2006). “Interaction between mooring line damping and response frequency as a result of stiffness alteration in surge,” 25th Int. Conference on Offshore Mechanics and Arctic Engineering (OMAE), No. OMAE2006-92373, 04.-09.06.2006, Hamburg, Germany (WP 8, [97]).

Johanning L, Wolfram J., Smith G.H And Harris R.E., (2006). “Importance of mooring line damping for WECs,” WMTC conference, IMarEST, 06.03 – 10.03.2006, London, UK (WP 8, [95]).

Johanning L. & Wolfram J., (2005). “Challenging tasks on moorings for floating WECs,” International Symposium on Fluid Machinery for Wave and Tidal Energy: State of the Art and New Developments, IMechE 2005, 19 Oct. 2005, London, UK, 2005. (WP 8, [96]).

Johanning L., Smith G. H. and Wolfram J.(2005). “Towards design standards for WEC moorings, 6th European Wave and Tidal Energy Conference, 29.08 – 02.09.2005, Glasgow, UK. 2005. (WP 3, [57]).

Johanning, L., Smith, G.H. and Bullen, C.; (2007). “Large scale mooring line experiments and comparison with a fully dynamic simulation program with importance to WEC installation,” 17th Int. Offshore (Ocean) and Polar Engineering Conference, ISOPE 2007, 01. - 06.07.2007, Lisbon, Portugal (WP 10, [111]).

Kiprakis A.E. and Wallace A.R.; (2005). “Voltage Control in the Distribution Network: Traditional Techniques and New Developments”, Invited paper, World Renewable Energy Congress, 22-27 May 2005. (WP 4, [73]).

Kiprakis A.E. Wallace A.R.; (2005). "Power Control and Conditioning for Wave Energy Converters", Proc 6th European Wave and Tidal Energy Conference, Glasgow, 30th Aug - 1st October 2005. (WP 4, [71]).

Learmonth, D., McGregor, P.G., Swales, J.K., Turner, K. and Yin, Y.P. (2007), “The importance of the local and regional dimension of sustainable development: a computable general equilibrium analysis”, Economic Modelling, Vol. 24, No. 1, p. 15-41, ISSN 0264-9993. (WP 12, [115]).

Lucas, J., Cruz, J., Salter, S., Taylor, J. and Bryden, I., (2007). “Update on the modelling of a 1 :33 scale model of a modified Edinburgh duck WEC.” Proc. of the 7th European Wave and Tidal Energy Conference, Porto, Portugal, September 2007. (WP 1, [23]).

McCabe, A. P., Aggidis. G.A., and Stallard, T. J. (2006). “A time-varying parameter model of a body oscillating in pitch”, Applied Ocean Research 28 (6): pp. 359-370, Pergamon-Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, England (WP 2, [40]).

McCabe, A. P., Bradshaw, A., and Widden, M. B., (2005), “A time-domain model of a floating body using transforms,” 6th European Wave and Tidal Energy Conference (6th EWTEC), University of Strathclyde, Glasgow, 30th August – 2nd September 2005. (WP 2, [38]).

McCabe, A. P., Stallard, T. J., Baker, N. J., & Yavuz, H., (2006). “Estimation of the responses of axisymmetric bodies in spread irregular waves,” Ocean Engineering, December 2006. (WP 9, [102]).

McCabe, A. P., Stallard, T. J., and Aggidis. G.A., (2007) “Comparison of a time-domain model of a surging wave energy collector to experimental measurements”. (In review by IMechE part M, (JEME) Journal of engineering for the Maritime Environment, October 2007). (WP 9, [104]).

McCabe, A.P. Bradshaw, A. Meadowcroft, J. A. C. and Aggidis, G.A., (2006). “Developments in the design of the PS Frog MK 5 Wave Energy Converter”. Published by Renewable Energy Journal, 31(2), pp 141 – 151. (WP 3, [61]).

McCabe, A.P., Aggidis, G.A., and Stallard, T.J., (2006). “Comparable performance characteristics from different test sites”, 4th EC Co-ordination Action on Ocean Energy Workshop - Performance Monitoring of Ocean Energy Systems, INETI, Lisbon, Portugal, Thursday 16th November 2006,. (WP 2, [41]).

McGregor, P.G., Swales, J.K. and Turner, K.R. (2007), “The CO2 ‘trade balance’ between Scotland and the rest of the UK: performing a multi-region environmental input-output analysis with limited data”, under resubmission to Ecological Economics, October 2007 (WP 12, [114]).

McGregor, P.G., Swales, J.K. and Turner, K.R. (2005). “The environmental ‘trade balance’ between Scotland and the rest of the UK: an inter-regional input-output and SAM analysis”, Presented at World Renewable Energy Congress 2005, Aberdeen, Scotland and Regional Science International - British and Irish Section, Stratford-upon-Avon, England, August 2005 (WP 12, [113]).

McGregor, P.G. (2005). “Some economic aspects of energy issues in Scotland”, presentation to the Royal Society of Edinburgh Inquiry into Energy Issues in Scotland, October 2005.

Meadowcroft, J.A.C., Stallard, T.J. and Baker, N.J. (2005) “A comparison of power capture in irregular waves and their regular wave components," 6th European Wave and Tidal Energy Conference (6th EWTEC), University of Strathclyde, Glasgow, 30th August – 2nd September 2005. (WP 3, [56]).

Meadowcroft, J.A.C., Stallard, T.J., Baker, N.J. and Aggidis, G.A. (2006) "Absorption of energy from irregular waves by a buoyant, surging body," Proceedings of 16th International Offshore and Polar Engineering Conference (ISOPE), San Francisco, USA, May 28th – Jun 2nd, 2006. (WP 3, [58]).

Mignard D. and Pritchard C.L., 2006. "Processes for the Synthesis of Liquid Fuels from CO2 and Marine Energy," Chem. Eng. Research and Design, Special Issue: Carbon Capture and Storage, 84(A9), 828-836 (WP 5, [79]).

Mignard D. and Pritchard C.L., 2007. "A review of the sponge iron process for the storage and transmission of remotely generated marine energy." International Journal of Hydrogen Energy, in press. (WP 5, [80]).

Mignard D., Pritchard C.L., Glass D.H. and Bridgwater A.V., (2006). "Simple and Carbon-Efficient Production of Synthetic Fuels by combining Biomass and Marine Energy," 2006. Greenhouse Gas Control Technologies 8 (GHGT-8), Trondheim, 18-22 June 2006. Paper posted on http:/www.ghgt8.no, 2006. (WP 5, [78]).

Mignard, D., Harrison, G.P., and Pritchard, C.L., (2007). "Contribution of wind power and CHP to exports from Western Denmark during 2000-2004." Renewable Energy, Feb. 2007. (WP 5, [77]).

Mueller M. A. & Wallace A.R. (2005). "Developing a Research Route Map for Marine Renewable Energy Technology in the UK", invited plenary paper at the 5th European Wave and Tidal Energy Conference, Glasgow, Sept. 2005. (WP 3, [64]).

Mueller M.A, & Baker N.J. (2005). "Direct Drive Wave Energy Converters"; IMech.E Journal of Power and Energy, Vol. 219, No. A3, pp 223-234, March 2005. (WP 4, [76]).

Mueller M.A. & Wallace A.R., (2006). "A road map for marine renewable energy research in the UK.' Proceedings of the Institute of Marine Engineering, Science and Technology, Part A8, 2006, ISSN 1476-1548. (WP 3, [48]).

Mueller M.A., McDonald A.S. & Macpherson D.E. (2005). "Structural Analysis of Low Speed Axial Flux Permanent Magnet Machines," IEE Proc B Electrical Power Applications, Vol. 152, pp. 1417 – 1426, Nov. 2005. (WP 4, [70]).

Mueller M.A., Xiang, J. Shek J. & Macpherson D.E. (2006), "Tuning Point Absorber Wave Energy Devices", Proceedings of the Marine Renewable Energy Conference, IMAREST World Maritime Technology Conference, London, March 2006. (WP 9, [100]).

Norris, J. and Bryden, I. (2007). "The European Marine Energy Centre (EMEC) : Facilities and Resources." Proc ICE Energy Journal, in press. (WP 3, [69]).

Ortega J and Smith G H, (2007). "Spectral Analysis of Storm Waves Using the Hilbert-Huang Transform." , submitted to 16th International Offshore and Polar Engineering Conference (ISOPE) July, 2007. (WP 1, [33]).

Owen A and Bryden I.G., (2005). "Prototype Support Structure for Sea Bed Mounted Tidal Current Turbines", Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, Volume 219, Number 4 / 2005, ISSN: 1475-0902 (WP 10, [108]).

Owen A, and Bryden IG, (2006). "A novel graphical approach for assessing tidal stream energy flux in the Channel Isles", Proceedings of the IMarEST Part C, Journal of Marine Science and Environment, C4, 2006 IMarEST technical proceedings Part C. (WP 2, [37]).

Owen, A., (2007). “The application of low aspect ratio hydrofoils to the secure positioning of static equipment in tidal streams.” PhD thesis, The Robert Gordon University, Aberdeen, May 2007. (WP 10, [110]).

Parker, R. P. M., Harrison, G. P. and Chick, J. P. (2007). “Energy and carbon audit of an offshore wave energy converter”, Proc. Institution of Mechanical Engineers Part A Journal of Power and Energy, 221 (8), December 2007. (WP 3, [54]).

Payne G, Taylor J, Parkin P, & Salter S, (2006) “Numerical modelling of the Sloped IPS Buoy wave energy converter”, 16th International Offshore and Polar Engineering Conference (ISOPE 2006), San Francisco, 28th May – 2nd June 2006 (WP 2, [42]).

Payne G., Kiprakis A.E., Ehsan M., Rampen W., Chick J., Wallace A.R.; (2007). “Efficiency and dynamic performance of Digital DisplacementTM hydraulic transmission in tidal current energy converters”, Proc. IMechE Part A, Journal of Power and Energy, Vol. 221, No. 2, pp. 207-218(12), (2007). (WP 4, [72]).

Payne, G. (2007), “A modular graphical user interface for WAMIT,” In: 7th European Wave and Tidal Energy Conference, Porto, Portugal. (WP 2, [39]).

Payne, G., (2005), “Hydrodynamic modelling of a generic power take-off mechanism reacting against water inertia,” In: 6th European Wave and Tidal Energy Conference, Glasgow, UK, pp. 359-364. (WP 4, [75]).

Payne, G., Stein, U.B.P., Ehsan, M., Caldwell, N.J., Rampen, W.H.S. (2005), “Potential of Digital DisplacementTM hydraulics for wave energy conversion,” In: 6th European Wave and Tidal Energy Conference, Glasgow, UK, pp. 365-371. (WP 4, [74]).

Price A., Mundon T. Murray A., Wallace A.R. (2005). “A Test-Bed for Advanced Control of Wave Energy Converters,” Proc 6th European Wave and Tidal Energy Conference, Glasgow 30th Aug - 1st October 2005. (WP 9, [105]).

Price, A.A.E. and Wallace, A.R.. (2007). “Non-linear methods for next wave estimation”. Proceedings of the 7th European Wave and Tidal Energy Conference, Porto, Portugal, 2007 (WP 9, [103]).

Quayle, S.D and Aggidis G.A., (2006). “Preliminary Investigation of Multi-Element Profiles for a High-Lift Variable Pitch Vertical-Axis Tidal Stream Device”, (Invited Paper), Fluid Machinery Group of the Institution of Mechanical Engineers, ‘CFD for Fluid Machinery’, IMechE, London, 24th October 2006, IMechE, Event Publications, v 2006 10, IMechE Conference Transactions, 2006. (WP 1, [24]).

Sellar, B.G., Bruce, T. and Wallace, A.R., (2007). “Providing Sea Surface Elevations for Marine Energy Converters using a Novel Optical Fibre Sensor: Progress in the Flume”, EWTEC, 7th European Wave and Tidal Energy Conference. Porto, Portugal.11-13th September, 2007. (WP 1, [22]).

Smith G. H., Venugopal V. and Wolfram J. (2006). "Wave period statistics for real sea waves and wave energy extraction", Proc Instn Mech Engrs, Part M, Journal for the Maritime Environment, 220, Special Issue,1-17. (WP 1, [21]).

Smith G. H., Venugopal V. and Wolfram J. (2006). ‘Wave Period Group Statistics for Real Sea Waves and Wave Energy Extraction’. Proc. I Mech. E. Part M: J. Engineering for the Maritime Environment, Vol. 220, No.3, pp. 99-115(17), (2006). (WP 1, [31]).

Smith G.H., Venugopal V. &Wolfram J. (2007). “Measurements of static and dynamic mooring line damping and their central importance for floating WEC devices” Ocean Engineering, Volume 34, Issues 14-15, pp, 1918-1934. (WP 8, [94]).

Smith, G.H. and Johanning, L., (2006). “Mooring research to support Marine Energy Developments,” Sea

Technology, Offshore Technology Ocean Engineering, April 2006, 23-26. (WP 8, [98]).

Smith, G.H. and Venugopal, V. (2006). "A Generic Method for Determining WEC Power Conversion from a Random Sea", Proceedings of the Sixteenth International Offshore and Polar Engineering Conference, ISOPE 2006,, 1, 460-465, May 28 - 2 June. (WP 3, [66]).

Smith, G.H. and Venugopal, V. and Fasham, J. (2006). "Wave spectral bandwidth as a measure of available wave power", Proceedings of 25th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2006-92379, 1-9, June 4-9. (WP 1, [34]).

Stallard, T.J., Aggidis, G.A., and Rothschild, R., (revision submitted May 2007), “Economic aspects of site selection for large-scale wave power generation,” in review by: IMechE part M, Journal of engineering for the Maritime Environment (JEME 68). (WP 7, [90]).

Stallard, T.J., Rothschild, R. and Aggidis, G.A., (2007). “A comparative approach to the economic modelling of a large-scale wave power scheme,” Article in press, accepted 15 January 2007, by European Journal of Operational Research (EJOR), DOI:10.1016/j.ejor.2007.01.021. (WP 7, [91]).

Stallard, T.J., Rothschild, R., Bradshaw, A., and Aggidis, G.A., (2005). “Comparison of Equivalent Capacity Wave Energy Schemes,” World Renewable Energy Congress, ISBN 0-080-44671-X, May 2005. (WP 7, [92]).

Sun, X., Chick, J.P. and Bryden, I.G. (2007). “Laboratory-scale simulation of energy extraction from tidal currents.” Renewable Energy, in press. (WP 11, [112]).

Taylor J.R.M. & Motion A. (2005). “Estimating wave energy in Scottish waters from hindcast data”, Proc 6th European Wave and Tidal Energy Conference, Glasgow, 30th Aug - 1st October 2005. (WP 1, [27]).

Thompson, A. and Aggidis G.A., (2007). “Review and state of the art of wave energy and wave energy converters”, IMechE, Fluid Machinery for Developing Engineers, Cranfield, (Invited Paper), IMechE, Event Publications, v 2007 1, IMechE Conference Transactions, 2007. (WP 3, [53]).

Turner, K., Allan, G.J., McGregor, P.G. and Swales, J.K. (2005), “The need to establish region-specific economic and environmental data in a consistent and compatible format”, Presented at European Wave and Tidal Energy Conference (29th September to 2nd October), University of Strathclyde, Glasgow (WP 12, [117]).

Turner, K., Lenzen, M, Wiedmann, T. and Barrett, J. (2007), “Examining the global environmental impact of regional consumption activities - Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade”, Ecological Economics, Vol. 61, No. 1, p. 15-26, ISSN 0921-8009 (WP 12, [122]).

Turner, K., Lenzen, M, Wiedmann, T. and Barrett, J. (2007), “Examining the global environmental impact of regional consumption activities – Part 1: A technical note on combining input-output and ecological footprint analysis”, by K. Turner, M. Lenzen, T. Wiedmann and J. Barrett, Ecological Economics, Vol. 62, No. 1, p. 37-44, ISSN 0921-8009 (WP 12, [126]).

Venugopal, V. and Smith, G.H. (2007). “The effect of wave period filtering on wave power extraction and device tuning,” Ocean Engineering, 34, pp. 1120-1137. (WP 1, [9]).

Venugopal, V. and Smith, G.H. (2007). “Wave climate investigation for an array of wave power devices,” Proc. 7th European Wave and Tidal Energy Conference, paper 1071, Porto, Portugal, 11-13 Sept 2007. (WP 1, [16]).

Vovos P., Kiprakis A.E., Harrison G.P., Barrie, J.R.; (2005). 'Enhancement of Network Capacity by Widespread Intelligent Generator Control', 18th International Conference on Electricity Distribution CIRED 2005, 6-9 June 2005. (WP 6, [88]).

Vovos P.N., Kiprakis A.E., Harrison G.P., and Wallace A.R., (2007). 'Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration', IEEE Transactions on Power Systems, Vol. 22, Issue 1, pp. 476-483 (Feb. 2007). (WP 6, [84]).

Vovos, P., Harrison, G.P., Wallace, A.R., Bialek; J.W. (2005). "Optimal Power Flow as a tool for fault level constrained network capacity analysis", IEEE Transactions on Power Systems, 20, 2, pp. 731 – 741. (WP 6, [82]).

Vovos, P., Kiprakis, A.P., Wallace, A.R., and Harrison,G.P. (2007). "Centralised and Distributed Voltage Control: Impact on Distributed Generation Penetration", IEEE Trans. Power Systems, 22(1), pp. 476-483. (WP 6, [81]).

Vuillemin, J. and Harrison, G. P. (2007). "On wave climate predictability: a mesoscale model to assess future wave energy potential", Waves and operational Oceanography / GLOBWAVE Project Workshop, 19-21 September 2007, Brest, France. (WP 1, [35]).

Widden, W.B. French, M.J. and Aggidis, G.A., (2007). "Analysis of a pitching and surging wave-energy converter that reacts against an internal mass, when operating in regular sinusoidal waves", In review by Proc. of the Institution of Mechanical Engineers, Part M, Journal of Engineering for the Maritime Environment (In review August 2007). (WP 3, [67]).

Widden, W.B., French, M.J., and Aggidis, G.A., (2005). "The Power Capture of PS Frog Pitching and Surging Point Absorber Wave Energy Converter," International Symposium on Fluid Machinery for Wave and Tidal Energy: State of the Art and New Developments, (Invited Paper), IMechE, London, 19th October 2005. (WP 3, [59]).

Winskel, M., Mcleod, A. Wallace, A.R., Williams, R.; (2006). "Energy Policy and Institutional Context: Marine Energy Innovation Systems", Science and Public Policy, 33, 5, 365-376, 2006/06, ISSN 0302-3427. (WP 3, [52]).

Wolfram J. (2006). "On Assessing the Reliability and Availability of Marine Energy Converters: the Problems of a New Technology" Proc. IMechE Part O: Journal of Risk, 220(1), pp. 55-68. (WP 3, [55]).

Yavuz, H., McCabe, A.P. Aggidis, G.A. and Widden, W.B., (2006). "Calculation of the performance of resonant wave energy converters in real seas," Proc. of the Institution of Mechanical Engineers, Part M, Journal of Engineering for the Maritime Environment, Vol. 220, No. 3, pp. 117-128(12), (2006). (WP 9, [101]).

Yavuz, H., Stallard, T.J., McCabe, A.P. and Aggidis, G.A., (2007). "Time series analysis of adaptive tuning systems for a heaving wave energy converter in irregular waves". In review by Proc. of IMechE Part A: Journal of Power and Energy, Vol. 221, No. 1, pp. 77-90(14), (2007). (WP 9, [106]).

The SuperGen Marine Energy Research Consortium is funded by the
UK Engineering and Physical Sciences Research Council.

EPSRC
Engineering and Physical Sciences
Research Council