Research within the EPSRC SuperGen Marine Energy Consortium and the UKERC R&D Roadmap for Wave and Tidal Current Energy

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Abstract— **The United Kingdom leads the world in the development and deployment of wave and tidal current energy technology. It has some of the best wave and tidal energy resources in the world. The UK university R&D base is well-supported through initiatives like the EPSRC SuperGen Consortium. This paper outlines the work of the consortium, summarises highlights and achievements of its research programme and describes progress in a second phase. It includes an overview of industrial engagement, capacity building in a novel Doctoral Training Programme. It also describes the production, findings and recommendations of the UKERC marine technology R&D roadmap. It concludes by identifying opportunities for research collaboration.**

I. Introduction

There are examples of far-shore, near-shore and shoreline wave energy converters and single-, double-rotor and open-flow tidal current converters operating in UK waters, connected to and supplying electricity to the national grid. However fundamental to applied research and development is still necessary to support and learn from demonstration and deployment. The UK Engineering and Physical Sciences Research Council flagship programme in Sustainable Power Generation and Supply (SuperGen) has supported fourteen research consortia. It is in its sixth year of operation and is shaping the future of the United Kingdom's energy landscape. These consortia have established platforms for the development of new and improved devices for efficient and sustainable power generation and supply. SuperGen Marine is now in year two of its second phase of funding. In any new technology vital feedback mechanisms define new R&D needs and influence the journey to maturity of the technology. R&D and technology road-mapping is a well-proven planning process by which has established many new technologies. The UKERC marine energy roadmap is the result of widespread structured consultation across the sector. It influenced the programme of Phase 2 of SuperGen Marine.

II. The SuperGen Marine Energy Research Consortium

SuperGen Marine Phase 1 (Oct 2003 – Sept 2007) brought together research staff from the Universities of Edinburgh, Robert Gordon, Lancaster, Heriot-Watt and Strathclyde. Working together they delivered generic research with the overarching objective *to increase knowledge and understanding of the extraction of energy from the sea*.

There were thirteen research work packages in Phase 1:

1. Appraisal of Energy Environment &Converters Interaction;
2. Methodologies for Device Evaluation and Optimisation;
3. Engineering Guidance;
4. Offshore Energy Conversion and Power Conditioning;
5. Chemical Conversion and Storage;
6. Network Interaction of Marine Energy;
7. Lifetime Economics;
8. Moorings and Foundations;
9. Novel Control Systems for Marine Energy Converters;
10. Full-scale Field Validation;
11. Testing Procedures for Tidal Current Devi1ces;
12. Economic and Social Impact of Marine Technologies;
13. Dissemination and Outreach.

Some results of the work carried out are summarised below-

- The physical consequences of extraction on marine energy resources before and after device deployment are now much more quantifiable. Resources are now assessed better, based upon firm scientific principles.
- New software and hardware prediction and measuring techniques and equipment are available for numerical and physical modelling of wave and tidal current energy converters at laboratory and full scale.
- The impact of individual or aggregate production of marine energy converters and their control strategies can be modelled to improve their network integration.
- Different chemical media and their capacity to store and return marine energy economically were identified and tested.
- Synergies were shown between wind, wave and tidal energy resources that reduce aggregate network impact.
- The relative economic efficiency of wave energy schemes of equal capacity can now be assessed with greater confidence and used to systematically quantify the importance for economic development of the marine industry.
- Fundamental non-linear effects of combined device and mooring response are better understood in terms of influence on peak loading and conversion efficiency.
- Adaptive control techniques have been developed to improve yield and neural-network predictors explored for next-wave forecasting

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- A systematic study of full scale mooring and turbulence data has identified crucial parameters for assessing the interactions between the technology and the environment.
- The difference between measured forces on tidal device components fixed in flowing water compared to being towed in still water has been identified and resolved.

Dissemination of the activities of the consortium took place via the SuperGen Marine web-site http://www.SuperGen-marine.org.uk.

Phase 1 staff acknowledge with gratitude the assistance of the following organisations.

AEA Technologies Ltd	Aquatera
Aquamarine Power Ltd	Artemis Intelligent Power
Black and Veatch	Carbon Trust
The Crown Estates	DTI
Entec	ECN Nantes (Fr)
EMEC	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 & Southern Energy
SNH	Teamwork Technologies
TU Delft (NL)	Wavegen

III. UK Energy Research Centre

The UK Energy Research Centre is a focal point for UK research on sustainable energy. It takes an independent, whole-systems approach, drawing on engineering, economics and the physical, environmental and social sciences. The Centre's role is promotes cohesion within the UK energy research effort. It acts as a bridge between the energy research community and the wider world, including business, policymakers and the international energy research community. It is entering its second five-year phase of funding. Within its Future Sources of Energy Theme staff charted the capacity and ongoing nature of energy research in the UK Research Landscape and Atlas. Additionally they worked with their research communities to produce energy technology R&D Roadmaps for: Marine; Solar PV, BioEnergy, Carbon Management, Fuel Cells, Wind, Nuclear Fission and Fusion. All roadmaps were created by consultation with the community, have been internationally peer-reviewed, and are maintained by UKERC on behalf of the user community. They are living documents that will be evolved recognising technology advances, changes in policy, and increased understanding of the environment.

IV. The Marine R&D Roadmap

The roadmap was built upon a landscape document after four workshops using the Battelle methodology featuring the outcomes of over forty Delphi method interviews, available from http://www.ukerc.ac.uk.

The roadmap is guiding the wave and tidal energy community in the UK down a deployment pathway towards a target of achieving 2GW installed capacity by 2020. It embodies science and engineering needs and priorities but also considers policy, environmental and commercialisation aspects of sectoral development through a shared vision and deployment, commercial and technical strategies. The vision of the sector is to:

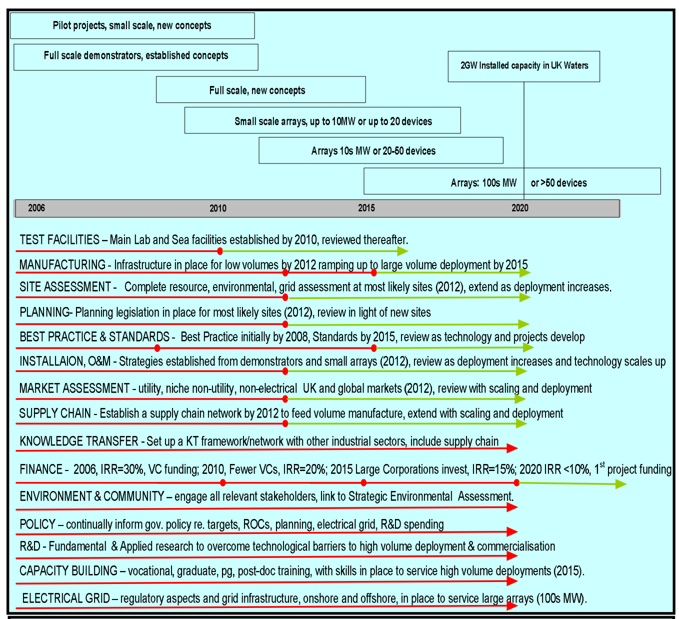
- exploit energy from waves and tidal currents in an environmentally and socially responsible way, aiming for an installed capacity of 2GW by 2020 in UK waters;
- stimulate policy and funding instruments to overcome barriers to deployment;
- establish a commercially viable industry supported by an extensive supply chain to build skills capacity at all levels;
- become competitive with other energy sources by 2020.

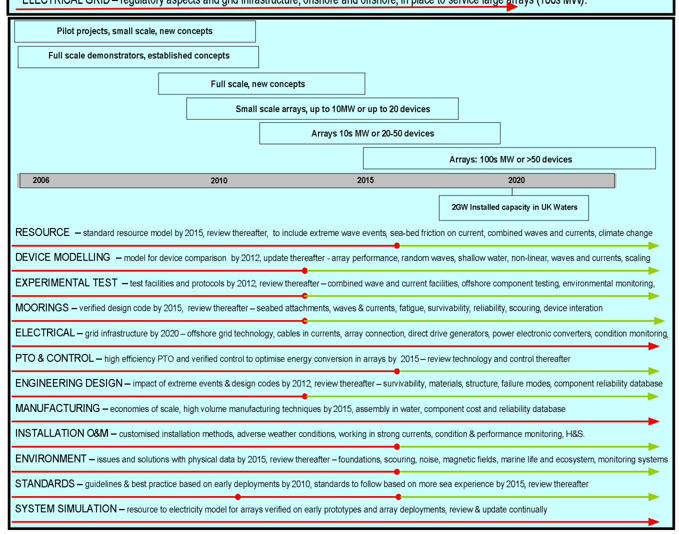
The roadmap highlights the key challenges up to and beyond 2020 to achieve the deployment strategy as:

Predictability;Manufacturability;Affordability;Installability; Survivability; Operability; Maintainability and Reliability

The commercial strategy below defines the mechanisms and infrastructure required to achieve the various stages in the deployment strategy.

Although dependent on both deployment and commercial strategies, the underpinning science and engineering strategy





is focus for this roadmap. It is divided into twelve Technology Working Areas shown above, which represent the technology development chain in marine renewable devices. Although the roadmap has been written for the UK, the core science and engineering are applicable internationally, set within the context of a particular country's policy, regulation and infrastructure.

V. SUPERGEN MARINE PHASE 2

The Marine Consortium secured continuation funding for Phase 2, supporting a further four years research from October 2007, now bringing together the Universities of Edinburgh, Queens Belfast, Lancaster, Heriot-Watt and Strathclyde.

Work completed in Phase 1 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 should be developed to enhance the effective exploitation of energy. During Phase 1, a selection of developers has moved from concept to prototype development and this identified specific needs for further fundamental research. The research in Phase 2 builds on experiences and questions arising from early device tests, the deployment of prototype devices, the UKERC R&D road-mapping and UK Department of Trade and Industry Protocol processes also established by SuperGen staff during Phase 1, and, implicitly, the outcomes of Phase 1, evolving the original aim, now *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 includes research on: device arrays and how these will influence local and regional energy and 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 nature and remoteness 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 to and across the stakeholder community.

A Research Advisory Forum meets at the time of the Annual Assembly to reflect and advise on ongoing work and future direction for the research. Its valued membership includes representatives from: Pelamis Wave Power, Ocean Power Technology; Marine Current Turbines, Open Hydro, Scottish Power, Scottish & Southern Energy, E-On, NPower, EdF, The Carbon Trust, The Energy Technologies Institute, EMEC, NaREC, The Crown Estates and Scottish Natural Heritage.

VI. WORKSTREAMS

There are twelve workstreams scheduled to be completed by October 2011. **Early progress of WS1-7 is reported in companion papers at this conference.**

WS 1 Numerical and physical convergence

Continually increasing computing power led to the development in Phase 1 of sophisticated numerical models and detailed experimental measurement techniques. It is now possible to examine new generations of wave and tidal technology using a robust combined physical and numerical modelling approach. However, better modelling tools are required, from geographic to device scale, to allow detailed investigation of the design and positioning of single devices and arrays. This workstream is combining new software, experimental hardware and methods to improve convergence between the output of numerical models and laboratory measurements to quantify and increase confidence in performance predictions of new designs and how they may be expected to behave in deployment. These modelling tools are being closely integrated with other Phase 2 workstreams.

A draft experimental testing protocol has been produced, covering Fourier analysis, aliasing, wave measurement hardware, wave reflection analysis, multi-directional spectra, video motion tracking, wave generation (deterministic and non-deterministic), tank calibration, and phase locking. The final version is now peer-reviewed and ready for publication. It also encompasses the development of a dynamic database for experimental and numerical results. The development of the planned Numerical Modelling protocol will be more straightforward but has been delayed until the experimental protocol is finalised to ensure a compatible approach, especially in relation to the numerical synthesis of random waves. Rapid progress is being made on the development of a robust CFD model of force feedback wave-makers, as used in tanks and basins across the consortium. Work is ongoing on a novel laser wave gauge and successful preliminary tests have been conducted in the Edinburgh wave basin. Consequent funding has developed an entirely novel floating wave-tape

that uses optical fibres and signal processing to measure wave shape in tanks, as illustrated below.

WS 2 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 components used to drive the power take off system. This begins with the response of the working 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 workstream is exploring whether optimal designs can be evolved for the physical form and response of the wave collector using a combination of genetic algorithms, numerical modelling and rapid prototyped models tested in tanks. Descriptions of the surface geometry are now available, defined using by B-splines whose control points are direct input into the performance prediction software and readily implemented within the genetic algorithm search space. These results contribute to overall understanding of the optimisation procedure and the relative merits of the different techniques. Investigation of surface descriptions compatible with panel-based software and their representation as suitable genotypes is ongoing and a skeleton framework for the cost function is now available. The GA components are implemented in MATLAB code and are evolving new collector shapes against varied constraints.

WS 3 Combined wave and tidal effects

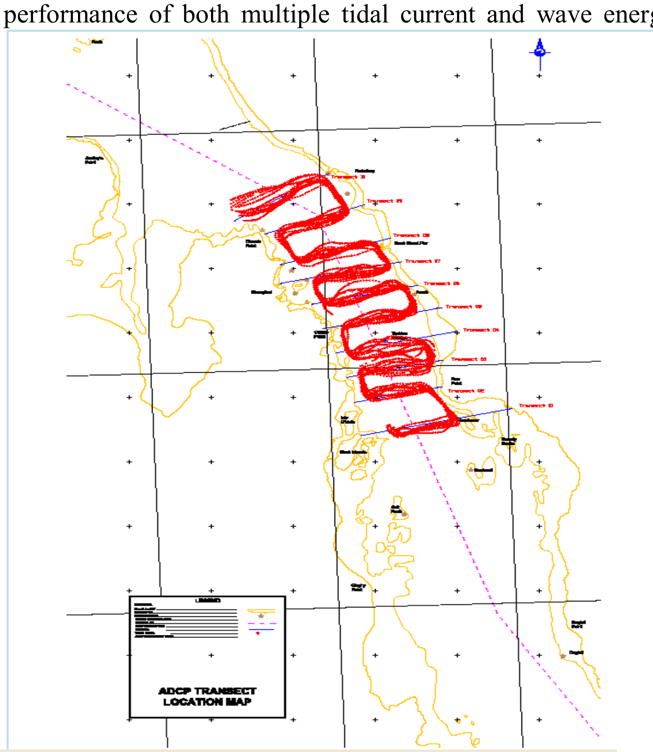
Until now tidal current and wave power devices have not been optimised for operation in mixed current and wave environments. Unfortunately most inshore wave environments are subject to tidal and other current effects and many of the largest tidal sites, such as the Pentland Firth, are exposed to direct 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. Early deployment experience confirmed the need to be able to predict and mitigate the effects of tidal currents on wave devices and waves on tidal current devices.

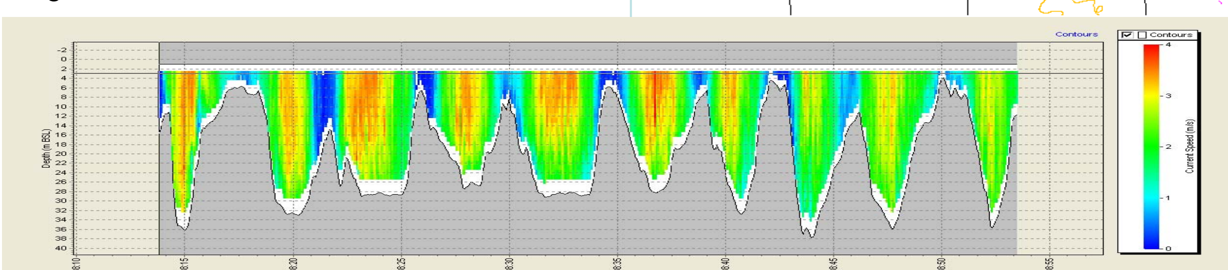
This workstream is developing an understanding of the effects of waves on tidal currents and tidal energy converters and the effect of tidal currents on waves and wave converters. It is formulating an integrated design methodology to reduce counter productive effects in mixed environments and will considerably extend the exploitation of resources. A multi-jet current generation facility has been designed and installed in the Edinburgh wave tanks.

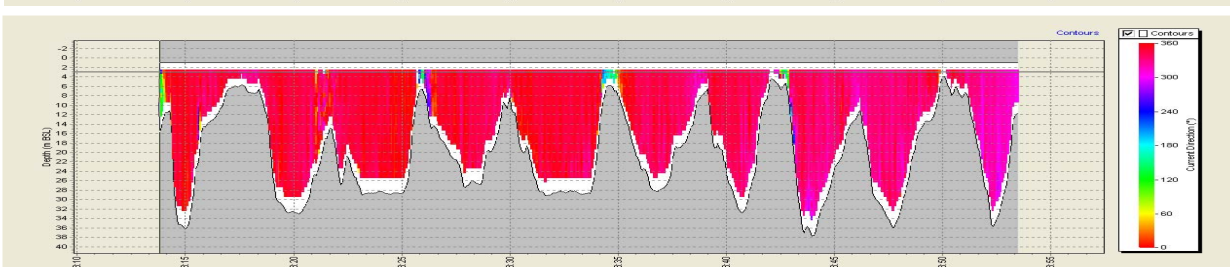
Discussions with staff at the European Marine Energy Centre in Orkney are planning an experimental observation programme around devices on test. Discussions with equipment providers continue to develop engineering specifications and requirements for next-generation test equipment. The construction bottom-mounted OWC and floating over-topping models has been completed and both are ready for initial calibration, prior to testing in combined wave and currents.

WS 4 Arrays, wakes and near field effects

As the sector moves from the deployment of individual prototypes 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 workstream is exploring how array interaction affects design optimisation and performance of both multiple tidal current and wave energy







converters to enable more accurate quantification of the environmental consequences of large scale energy extraction, including localised perturbations to the energy and momentum fluxes.

A framework for environmental impact assessment has been developed and demonstrated by a case study of the Strait of Messina. Analysis of the interaction of tidal current turbine arrays with sedimentation processes has demonstrated that energy extraction from the system acts to reduce gross sediment transport rates and that the positioning of the array with respect to the underlying tidal hydrodynamics has a large impact on the gross sediment transport. Simulations have demonstrated that energy extracted from regions of tidal asymmetry have a much greater effect on sediment dynamics than energy extracted from regions of tidal symmetry, with implications for site selection. A deployment site for testing a floating OWC array in Strangford Lough in Northern Ireland has been surveyed in the transects shown above to map spatial and temporal variation and identify the best device location. A flexible frequency-domain numerical model for arrays of WECs has been developed using WAMIT to generate the hydrodynamic coefficients and Matlab to calculate array performance. The model has been compared to theoretical optimal configurations and found to be in general agreement. It has also been used to investigate the optimum performance of an array of heaving buoys deployed at a North Atlantic site.

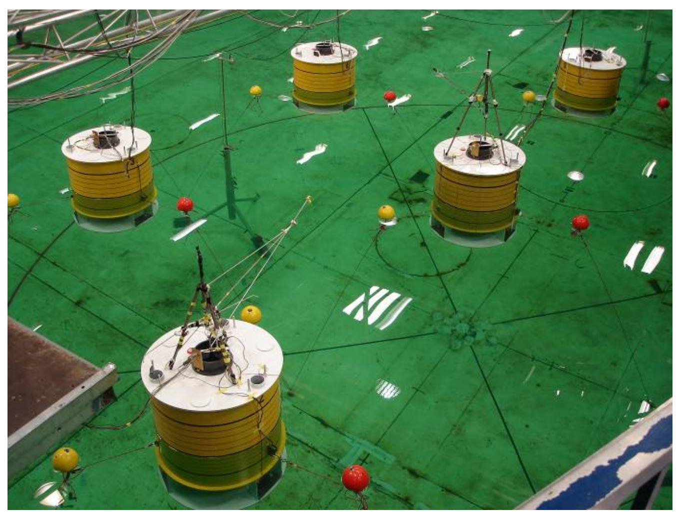
WS5 Power take-off and conditioning

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. Adopting direct drive generators reduces the number of moving parts but, because of their low speeds and consequent high torques, conventional machine topologies result in large and costly generators. This workstream is combining the design of the prime-mover, drive-train, generator and power electronic converter to fully integrate and define lighter, lower-cost machines operating at slow speeds with improved efficiency over a wide range of loads. Optimising cost and performance has produced new iterative integrated structural, electrical and thermal design techniques that are being verified using numerical modelling techniques and experimental tests.

Models of air-cored PM tubular machines, iron-cored PM tubular machines, variable reluctance PM machines, linear PM synchronous machines have been completed as exemplified above. These machine models are being used to compare topology types. Generic structural models for the different machine types are being developed with Genetic Algorithms being implemented for design optimisation. An analysis of hydrostatic bearing designs for iron-cored and air-cored machines has been completed. Work is progressing on new materials for bearings and a wet test rig is being designed to investigate a hybrid fluid and interface bearing using these new materials.

WS6 Moorings and positioning

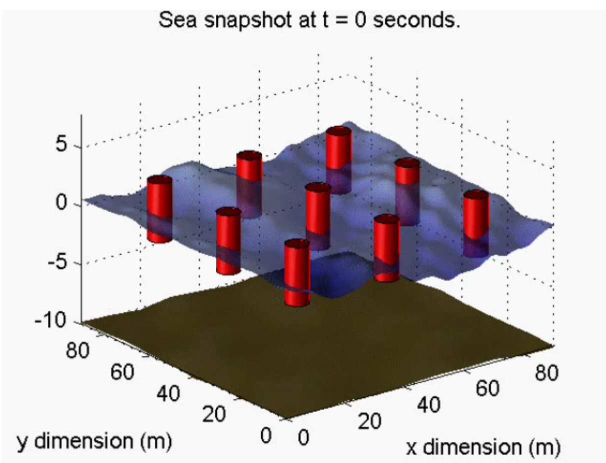
Phase 1 identified that moorings are still a significant challenge in the design and operation of floating marine energy converters. Their behaviour, when used in arrays of wave energy converters under the joint action of waves, current and wind has still to be fully investigated. This workstream is further developing and validating 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 is also examining the combined response of taut systems and “deep-moored” tidal devices. Mooring responses are being measured under combined wave and tidal current action and compared with numerical models to predict long-term effects of combined loadings on survival and make an assessment of suitable generic mooring configurations for array deployment.



A successful bid for access to the Marintek Ocean Basin in Trondheim in Norway allowed the design, prototype testing and construction of five buoys for array testing as shown above. A prototype buoy with internal oscillating water column power absorption and mooring system was tested at Heriot-Watt to confirm the design of devices for the array tests at Trondheim and to gain results on the effects of mooring stiffness on device dynamics. Five heaving buoys were constructed at 1:20 scale and subsequently exhaustively tested in Trondheim and the results are now being analysed. A 1/7 scale model tidal device has been sourced for the tidal tests.

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 being short-term stationary. 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. This workstream is modelling the effects of non-linearity and the non-stationary nature of the marine resource on wave and tidal current energy conversion and modelling the interaction of arrays of devices with one another and with weak electricity networks, as shown below.



Early results show that, even in broader spectrum inshore seas, the spacing and alignment of heaving buoys can increase or decrease constructive addition of their output power and the cyclic variation of power flow in the offshore and onshore network. Where the network is relatively weak, as is often the case at early deployments, the variability of this power flow can manifest itself as a cyclic pattern in the local network voltage with unacceptable reductions in supply quality. Improved siting is being explored to reduce low frequency variability and co-coordinated control and on-board energy storage is being explored to reduce higher frequency variation.

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 an initial 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. This workstream is assessing the effect of this uncertainty on the calculations of device reliability and availability. Reliability methodologies from other industries, particularly wind are being adapted for marine energy applications.

A conceptual model of a free stream horizontal axis tidal turbine, fixed to the sea bed, with a single indirect drive power train has been completed. Based on the model, the reliability and availability of the tidal turbine is being checked using proprietary software using currently available data on the failure rates of the turbine subsystems and components. Relevant failure rate data from OREDA and the wind industry are being collected and analysed. Since it is difficult to validate the obtained values of failure rates without actual data from prototype tidal turbines, parallel work is estimating the failure rate of blades using Monte Carlo simulations.

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. This workstream is building 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 are being 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.

A detailed examination of the established techniques and principles of portfolio theory to analyse electricity (and energy) scenarios is nearing completion, extending to six UK electricity generation technologies, including, for the first time, wave and tidal. This work has demonstrated that levelled cost comparisons are likely to be a very misleading basis for assessing the potential contribution of renewable energies in general, and marine in particular, to future UK electricity generating portfolios. Modelling simulations are being conducted on behalf of the Scottish Government, in parallel with the SuperGen program, to inform the Scottish Climate Change Bill.

WS10 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 sector to demonstrate minimal environmental disturbance. This workstream is establishing the sensitivity of marine environments around Orkney and in Strangford Lough to the extraction of energy to quantify the risk from device developments and to evaluate subsequent mitigation, monitoring or avoidance strategies. It is conducting 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 is also studying the impact of related anchoring and mooring systems and the collision risk of large biota such as seals with tidal turbine blades.

Prior to deployment of the MCT SeaGen in Strangford Lough, a 2.5 year dataset of seal, porpoise and bird activity within an area approximately 0.75km upstream and downstream of the turbine was obtained on a 100m x 100m spatial grid resolution. Observations have been made from a fixed position on the shore on a monthly basis as part of the MCT "Environmental Monitoring Programme". The data is being made spatially discrete to analyse the effects of time of day, season and tide on the animal activities and provide the baseline pre-tidal turbine installation data required for comparison with the comparable post-installation data to be obtained. Detailed benthic video observations have also been made at four locations downstream from the turbine together with an adjacent reference site. General video scans were also obtained from immediately under the turbine pile and also from the vicinity of one of the legs of the pile. The images from the detailed video observations have been quantified and the data analysed; preliminary conclusions suggest that, following comparison with similar data obtained prior to deployment of the turbine pile, the only changes recorded are the expected seasonal changes in the benthic community.

WS11 Doctoral Training Programme

The DTP 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. 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 students enrolled engage in research complementing the aims of WS1-10. They all participate in a quarterly 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 are open to other participants. Students in the programme present their work at internal and public events.

WS12 Dissemination and Outreach

Consortium staff and students continue to collaborate with existing marine energy research being undertaken in the UK/EU and worldwide. Government, agency and industrial in-reach are delivered at 8 six-monthly workshops to inform and enable the community to provide feedback on the direction of the proposed research. Workshops, seminars and conferences are organised to outreach to the beneficiary and research community to bring into context the UK research activities with activities being undertaken elsewhere in Europe, America, Canada and New Zealand.

VII. Conclusions

The SuperGen programme has introduced and established a new era of support and collaborative working in sustainable power generation and supply in the UK. Through innovative programmes like SuperGen Marine, university partnerships and industry collaborations have been established to conjoin activity leading to additionality and increase progress. Many countries around the world are emulating the infrastructure and framework demonstrated in these programmes to enable R&D progress in the nascent industries. The R&D roadmapping carried out by UKERC and SuperGen has also been considered and adapted regionally or nationally in a number of other countries and is being used to inform energy policy and planning. There are many obvious areas and opportunities for international collaboration in areas such as resource assessment, numerical and physical modelling, network impact, reliability studies, capacity building and roadmapping.

VIII. Acknowledgements

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IX. References

The output and findings of the consortium are published in peer-reviewed journals and at conferences. This paper is based on and draws heavily from the *SuperGen Marine Energy Research Monograph*, found at http://www.SuperGen-marine.org.uk. Phase 1 produced 133 articles, whose abstracts and references are in the monograph. Phase 2 has produced 44 articles, whose references are to be found on the website. The complete Marine Energy R&D roadmap is to be found, along with many others at http://www.ukerc.ac.uk