Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot-Watt /Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Test Protocols for Tidal Current Energy Converters

1. Summary of the impact (indicative maximum 100 words)

The impact is in the ERPE design of protocols which are subsequently used for evaluation and comparison of the performance of tidal energy converter designs. Researchers within the UK Centre for Marine Energy Research (UKCMER) at ERPE have led much of the fundamental and applied research that has supported the commercialisation of tidal energy technologies through the establishment of new international test standards and protocols.

ERPE researchers have regularly provided evidence which has influenced policy change in marine energy development in the UK and internationally with many ERPE graduating PhD's, subsequently employed in the marine energy sector.

2. Underpinning research (indicative maximum 500 words)

This ERPE research team comprised Professors: Bryden; Ingram; and Wallace, with RA's Couch and Jeffrey (all in post throughout the period) with Professor Borthwick (from 2013).

The important ERPE research contribution here is:

- First definition of the significant tidal energy resource [1] around Orkney and Shetland.
- Development of new flux models [3 - 5] to more accurately estimate tidal energy resources.
- Use this to establish testing guidelines and protocols which now enable accurate comparison of marine energy conversion devices.

Vanguard work by Bryden in 1995 first proposed and justified, with robust scientific evidence, that the North Isles had a significant tidal energy resource that could be harnessed using demonstrable technology. The Pentland Firth and other tidal resources originally estimated by Bryden's research, funded by the EU CEC DGXVII programme [1]. He used measured surface currents and numerical modelling to predict the extent and characteristics of the energy flux in the tidal currents in the Fall of Warness, Orkney, subject to environmental and economic constraint. This catalysed the development of the European Marine Energy Centre (EMEC) in Orkney, as the world's first open sea test facility for tidal and wave energy technologies.

Further underpinning work has been supported by EPSRC, NERC, Scottish Government, Carbon Trust, ETI, TSB and the European Commission, as well as utilities and developers. Bryden and Melville established that existing methods of assessing the extractable energy were insufficient because they were based simply on kinetic energy estimated from channel flow velocities and neglect modifications to potential energy, as depth is altered by energy extraction. The new channel models linking two oceanic volumes were first to suggest that limits to extractable kinetic energy could be around 10% of total flux [2].

Bryden and Couch developed "Site Sensitivity" and "Total Energy" Flux models and the Significant Impact Factor (SIF) technique that improved upon and replaced the "Farm Method" used in most studies before 2004 [3]. The Farm Method was based on the assumption that an array of Tidal Energy Converters would each extract an equal amount of energy from the incoming current. The resulting energy extraction became purely dependent on the number and size of the devices, their efficiency and their packing density within the channel plan area without accounting for changing flow speeds and impact on overall channel flow or energy delivery. The Flux Methods are based on the maximum safe reduction of the incoming total energy flux across the front cross-sectional area of the channel and along the extraction length, independent of device type, efficiency and packing density. The energy, extractable without significantly impacting the underlying hydrodynamic environment driving the flow and its economic yield, more accurately identifies the technical resource further defined by other constraints [4]. This work is extended in [5] and combined with

the SIF [3] to provide a systematic approach to resource assessment for tidal turbines based on the flux method.

Couch extended this work by considering the environmental consequences of extraction in the neighbourhood of headlands where flow is concentrated. Working with oceanographers he has shown that large-scale extraction diminishes headland eddies and causes modifications to sand banks. More recently Borthwick has estimated an upper bound of 1.9 GW, averaged over the spring-neap tidal cycle, for the tidal stream power resource of the Pentland Firth, independently corroborating earlier published results [1, 3].

Marine energy specialist training: The Doctoral training programme in Phases 1 & 2 of SuperGen Marine (http://www.supergen-marine.org.uk/drupal/) trained over 30 researchers, scientists and engineers, now mainly employed in the expanding marine sector. This led to the award of UKCMER (EP/1027912/1, £3.5M, 2011-2016) and IDCORE (EP/J500847/1, £6.5M, 2011-20) and ultimately the training of a further 65 academic and industry-based PhD level qualified staff.

3. References to the research (indicative maximum of six references)

References identified with * are those which best indicate the quality of the underpinning research.

[1] Bryden, I.G., Bullen, C., Baine, M. and Paish, O., "An assessment of Tidal Streams as Energy Sources in Orkney and Shetland", Underwater Technology, Vol. 21, No. 2, pp. 21-29, 1995. DoI:10.3723/175605495783326649.
This paper reported on the results of the feasibility study and, for the first time, reported on field studies of the tidal current energy resource in the Fall of Warness in Orkney and around Shetland. He quantified Fall of Warness as an ideal site for the testing and ultimately the commercial deployment of tidal current technology.

[2] * Bryden, I.G. and Melville, G., "Choosing and Evaluating Sites for Tidal Current Development", Proceedings Institution Mechanical Engineers, Part A: Journal Power & Energy, Vol. 218, pp. 567-578, 2004. DOI:10.1243/0957650042584375. 52 Google Scholar (GS) citations.
This paper described and quantified the issues which need to be considered in assessing a site for the prospective exploitation of tidal current energy.

[3] Bryden, I.G. and Couch, S.J., "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, Vol. 32, pp. 1961-1966, 2007, DOI: 10.1016/j.renene.2006.11.006. 24 GS citations.
This paper demonstrated, using open channel flow techniques, a relationship for the maximum possible rate of energy extraction in a simple tidal channel and that it is theoretically possible, in some circumstances, to extract energy from a tidal channel at a rate greater than the kinetic energy flux.

[4]* Couch, S.J. and Bryden, I.G., "Tidal Current Energy Extraction: Hydrodynamic Resource Characteristics", Proceedings Institution Mechanical Engineers, Part M: Journal Engineering for the Maritime Environment, Vol. 220, No. 4, pp. 185-194, 2006. DOI:10.1243/14750902JEME50. 47 GS citations
This paper identified five fundamental classifications for energetic tidal current regimes and used numerical analysis to assess the key parameters in the identification of a site's suitability for energy extraction.

[5] Bryden, I.G., Couch, S.J., Owen, A. and Melville, G., "Tidal Current Resource Assessment", Proceedings Institution Mechanical Engineers, Part A: Journal Power & Energy, Vol. 221, No. 2, pp. 125-154, 2007. DOI:10.1243/09576509JPE238. 36 GS citations.
This paper brought together the issues identified in 1 to 4 presenting them in a systematic approach to tidal current resource assessment.

[6]* Adcock, T.A.A., Draper, S., Houlsby G.T., Borthwick A.G.L., and Serhadlıoğlu S, "The available

power from tidal stream turbines in the Pentland Firth", Proceedings Royal Society, Series A, July 2013. DOI: 10.1098/rspa.2013.0072
This recent paper provided an upper bound estimated of 1.9 GW for the Pentland Firth tidal stream power resource, further corroborating the earlier work of Bryden.

4. Details of the impact (indicative maximum 750 words)

The economic and societal impacts of the research in [1, 2] have placed Orkney at the world-centre of marine energy demonstration and test. The ERPE research has initiated and established international standards for the development and testing of a tidal and wave energy devices.

Bryden identified the Fall of Warness in Orkney as the most promising tidal energy test site in the UK and this location was subsequently selected for the tidal test site at EMEC http://www.emec.org.uk/ [S1]. This has 14 full-scale test berths and two reduced scale test sites and there have been more grid-connected tidal and wave energy converters deployed than any other single site in the world, with eight tidal devices under test from: Andritz-Hydro Hammerfest, Atlantis Resources Corporation, Bluewater Energy Services, Kawasaki Heavy Industries, Open Hydro, ScotRenewables Tidal Power Ltd, Tidal Generation Ltd and Voith Hydro. EMEC has generated 250 jobs in Orkney and contributed £57M of gross value add to this economy.

In 2006-7 Bryden and ERPE staff in UK Centre for Marine Energy Research (UKCMER) developed the SIF technique [3-5] and subsequently worked with Black and Veatch to produce the 2010 Carbon Trust Report on UK Tidal Current Resource & Economics, http://www.carbontrust.com/media/77264/ctc799_uk_tidal_current_resource_and_economics.pdf.

This estimated more accurately and comprehensively the overall potential annual UK tidal energy resource to be 29 TWh/yr, 60% higher than the previous best estimates [S2]. This was then used by the Department of Energy and Climate Change in 2011 to affirm intentions to further develop these resources as part of the UK plans to establish the industry to deliver the generating capacity in the 2020 Renewable Energy Targets.

The EMEC testing guidelines arose from the fundamental research [3-5] that ultimately became the basis of the tidal and wave performance testing protocols for the UK Government £50M Marine Renewables Deployment Fund (MRDF) to support the installation and operation of tidal and wave energy devices. This in turn expanded into the establishment of the EU Call (ENERGY 2007.2.6.3) in 2008 that uniquely funded the Equitable Assessment of Marine Energy Converters (EquiMar) project http://www.equimar.org/. Led by Ingram, the EquiMar project received funding from the European Community's 7th Framework Programme No. 021338, co-ordinating the effort of 60 scientists, engineers and industry stakeholders from eleven EU countries. This established a suite of protocols to allow fair comparison of marine energy converters under test and evaluation [S3, S4].

These **EquiMar Protocols** became, in 2011, the proving metric in the Scottish Government Saltire Prize competition and were extended further as the basis of the International Electro-technical Commission (IEC) 62600 marine energy standards, providing the foundations for many standards developed by IEC Technical Committee 114, http://www.iec.ch/dyn/www/f?p=103:14:0::::FSP_ORG_ID,FSP_LANG_ID:5738,25. Technical committee TC114: Marine energy - Wave, tidal and other water current converters, which comprises members from 26 countries, has recently published the first UK-led ocean energy Technical Specification 62600-200: Power Performance Assessment of Electricity Producing Tidal Energy Converters that enables the systematic performance evaluation of tidal turbines. The drafting of this international document was led by Ingram and Jeffrey between 2009 and 2012 with contributors including Siemens, Voith Hydro, ESB International, Verdant Power Inc., and Clean Current Inc. Jeffrey further convened the committee that produced IEC 62600-201 TS Ed.1: Marine energy - Wave, tidal and other water current converters – Part 201. Couch was the UK contributor to Part 200: Power Performance Assessment of Electricity Producing Tidal Energy Converters.

ERPE research on the flux method [3-5] has provided confidence to the international investment community of the overall size of the available resource as well its interaction with the tidal energy devices, adopted in IEC 62600-200 (performance) and 62600-201 (assessment) (www.tc114.us/standards-development/project-teams/pt-62600-201/). This work has underpinned the international convergence of an accepted industrial methodology that is currently driving the commercialisation of this sector. *"We are very pleased to see the publishing of this Technical Specification of Tidal Device Performance Assessment which will become the basis of Validation Reports for clients. Jeffrey and his team have done an excellent job to produce the document which is already being used by the sector and will be considered for revision in about three years to take it to the status of a full International Standard."* Managing Director of EMEC [S1].

This fundamental ERPE research has propagated to other marine device test and deployment programmes. In January 2008, Minas Basin Pulp and Power was awarded a contract to build North America's first tidal demonstration facility, FORCE http://fundyforce.ca/about/, in the Bay of Fundy, mimicking the Orkney tidal facility at more extreme conditions "*Minas is indebted to the University of Edinburgh for two reasons: strategic assistance with the tidal demonstration facility and our sponsored tidal energy technology. Your faculty hosted our core 'tidal team' consisting of engineers, scientists, oceanographers, project managers, and even lawyers in an educational session that became the cornerstone of Minas' success back here in Canada. We returned to Nova Scotia with a road map that led us to a) locating a demonstration site in the Minas Passage of the Bay of Fundy and b) obtaining environmental consents for a grid-connected three-berth facility. Within a relatively short eighteen months and under your patient and collegial guidance, we achieved both.*" Chair, FORCE [S5].

Between 2009 and 2012 Oregon and Washington State Universities established the Northwest National Marine Renewable Energy Center in the Pacific NW. MIT, University of New Haven, UMass and University of Rhode Island have established the New England Marine Renewable Energy Center, both with offshore test facilities based on consultancies with EMEC and ERPE staff. Taiwan has agreed to establish, in collaboration with EMEC and ERPE staff, an offshore test facility at Keelung in the South China sea.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Director: European Marine Energy Centre (EMEC), see comments included in Section 4.

[S2] Director, Sustainable Energy Solutions, can confirm that the 2010 Carbon Trust Report estimated the UK tidal energy as 29 TWh/yr, 60% higher than the previous best estimates.

[S3] IEC Central Office, can confirm that the ERPE led Equimar protocols were incorporated in the IEC 62600-200 standard.

[S4] Senior Manager, Sustainability, Emera, and TC114 Chair, can further confirm the inclusion of ERPE research outcomes within the TC 114 standard for marine energy conversion systems.

[S5] Chair: FORCE, Nova Scotia, see comments included in Section 4.

Institution: Edinburgh Research partnership in Engineering – ERPE (Heriot Watt/Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Advanced Wavemaker Designs

1. Summary of the impact (indicative maximum 100 words)

Edinburgh Designs Ltd., (EDL) was spun-out to exploit ERPE research from the original Wave Power Group. With six staff and an annual turnover approaching £2M EDL has supplied the equipment and control systems for wave tanks in 19 countries including the world's largest computer-controlled wave test facility, the US Navy Manoeuvring and Station Keeping Tank. They are currently completing the world's first circular tank, combining waves with currents in any relative direction, which is operated by the 6 person company, "FloWave"
EDL, still run by the founding staff, it is the world-leading supplier of wave-making technology for scientific and recreational facilities.

2. Underpinning research (indicative maximum 500 words)

The ERPE research team comprises Salter (Emeritus Professor), Professors: Bryden; Ingram; and Wallace, Senior Lecturer Bruce, PDRAs: Davey; and Richon, and PhD Robinson (all here throughout the period). PhD Maguire (to 2011) and former RA Taylor were previous team members.

The important research contribution underpinning this case are:

- Design of absorbing wavemaker paddles [2] for the accurate, controlled generation of waves in test tanks.
- Implementation of a curved tank, with associated computer drive, to make more effective use of small facilities [1].
- Design (and construction) with EDL of the worlds first wave and current test tank facility [3] with ducted impeller designs [4, 5].

Waves are reflected off the surfaces of device models on test and from the sides of tanks in which they are being tested to degrade the predictability and repeatability of the waves in the test area. To maximise the useful test area, the original Wave Energy Group in ERPE built the wide tank with wave-makers along the long side, phase controlled to propagate at up to ±20° to its perpendicular centre line. Paddles were driven individually with signals embodying differing frequencies, amplitudes, angles and phases to define individual wave fronts, which summed to generate long-crested multi-spectral or mixed seas. They developed in 2000 impedance-matched beaches at the down-wave end to dissipate residual waves together with absorbing wave-makers that measured the forces on the paddles and fed them back to the control systems to modulate velocity to absorb reflected waves. However, the short sides continued to reflect cross-waves into the test area.

This led to the construction of the Edinburgh Curved Tank in 2002 with EPSRC support (GR/R64438/01 £143k) with 48 absorbing wave-makers in a 90° arc, one side of matched beaches and a single glass wall. It propagates the full palate of 1/100th scale seas, steerable through ±45° about a radial centre line [1].

Edinburgh Designs Ltd (EDL) staff, all originally members of the ERPE Wave Power Group, continue to test developments in their control software in this tank in collaboration with ERPE staff and researchers. ERPE researchers have continued to underpin developments in absorbing wavemakers through numerical and physical modelling to quantify the dependence of absorption characteristics on geometry and control coefficients. They also established and validated in 2011 computational fluid dynamic (CFD) techniques to numerically model wave tanks, in the absence of flow [2].

Experience in the early deployment of another wave energy power extraction technology, Pelamis – also developed within ERPE, identified the need to be able to conduct scale-test models of wave

devices under the influence of tidal currents. This stimulated interest in tidal test machines, not only for flowing water with controllable levels of turbulence, but in generating flow patterns which more closely resemble the tidal ellipses which are encountered [3] in practical seas.

The underpinning research has extended, beyond earlier ERPE research on tidal current energy extraction techniques [6], and evolved into the EPSRC-funded project (EP/H012745/1 £990k 2010-14) to prove numerically and physically the omni-directional combination of waves and currents in a predictable and stable manner, with prescribed levels of turbulence. The final wave plus current tank design adopted phased absorbing wavemakers with force feedback control to enable, for the first time, the practical combination of waves and currents in a stable manner.

This led to the awards of support from EPSRC (EP/102932C/1, £6M) to construct the fully circular FloWave tank, 30m in diameter and 5m deep, in ERPE at Edinburgh. With 168 force-feedback absorbing wave-makers in a 25m circle it can propagate and absorb 1m waves in any direction relative to an array of devices mounted on an elevating floor. Simultaneously 28 1.7m diameter ducted flow drives will circulate water in any relative direction at up to 1 m/s through a test area 18m wide and 2m deep. It will be used to emulate sea conditions at the European Marine Energy Centre (EMEC) and at other coastal sites in European waters at up to 1/20th scale. Stable combination of flow patterns with the wave field, at programmable levels of turbulence, is a highly demanding challenge that has been addressed in the flow conditioning and wave-maker control. Current is generated across the tank by using groups of impellers arranged around its perimeter.

EPRE staff performed both computer simulations and experiments [4] to provide a new method for conditioning flow from ducted impellers to remove swirl and reduce large-scale turbulence with minimum energy loss. Each impeller produces a single flow velocity, which may be different to its neighbours. These differences can lead to a stepped or curved plan view velocity profile in the test section of the tank where a plug profile is required. EPRE staff have recently characterised the maximum allowable velocity difference for a stable plug profile to be generated [5]. The same work allows a shear layer to be used to control force feedback wave makers in the presence of current.

3. References to the research (indicative maximum of six references)

References identified with * are those which best indicate the quality of the underpinning research.

[1] Taylor, J.R.M., Rea, M. and Rogers, D.J., "The Edinburgh Curved Tank", Proceedings 5th European Wave Energy Conference, Cork, Ireland, 2003.
www.mech.ed.ac.uk/research/wavepower/0-Archive/EWPP%20archive/2003%20The%20Edinburgh%20curved%20tank.pdf
This paper described the construction of the curved tank and suggested the first designs of a fully round tank that was the inspiration for FloWave.

[2]* Maguire, A.E. and Ingram, D.M.,"On Geometric Design Considerations and Control Methodologies for Absorbing Wavemakers", Coastal Engineering, Vol. 58, no. 2, 135-142, 2011. DOI:10.1016/j.coastaleng.2010.09.002.
This investigated the effects that geometry and control have on the absorption characteristics of wavemakers and presented the hydrodynamic coefficients bottom hinged flap wavemakers, as applied in reactive and complex conjugate control to achieve increased absorption over a broader band of frequencies.

[3] Davey, T., Bryden, I., Ingram, D.M., Robinson, A., Sinfield, J.L. and Wallace, A.R., "The All-Waters Test Facility – a new resource for the marine energy sector", Proc 4th International Conference on Ocean Energy 2012. Available on request.
This paper described the design and construction of the fully round FloWave, combining waves and currents in any relative direction.

[4] Robinson, A., Bryden, I., Ingram, D.M. and Bruce, T., "The Use of Conditioned Axial flow Impellers to Generate a Current in a Test Tank", Working paper accepted for publication in the

Journal of Ocean Engineering 2013. Available on request.
This paper describes the initial and intermediate propulsion and flow conditioning of currents in the round tank to achieve the required bulk flow-speeds with acceptably low levels of turbulence above the test area for tidal currents.

[5]* Robinson, A., Richon, J-B., Bryden, I., Bruce, T. and Ingram, D.M., "Vertical mixing layer development", European Journal of Mechanics – B Fluids, 2013. DOI:10.1016/j.euromechflu.2013.07.001.
This developed and described the final flow conditioning that creates a shear layer between the plug of flowing water directed ahead of the wave-makers in the round tank, to avoid interference with the force-feedback of the absorbing wave-makers and improve stability of combination.

[6]* Salter, S.H. and Taylor, J.R.M., "Vertical-axis tidal-current generators and the Pentland Firth", Proceedings Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Vol. 221, No. 2, pp. 181-199, 2007. DOI:10.1243/09576509JPE295. 18 GS citations.
This describes an early design of tidal current energy extraction technique based on a vertical-axis approach. It extends 2 ideas introduced in papers from the 2005 World Renewable Energy Conference.

4. Details of the impact (indicative maximum 750 words)

Edinburgh Designs Ltd., the staff spin-out from the ERPE wave energy group (http://www.edesign.co.uk/) specialises in the design, manufacture and installation of a wide range of wave and tidal generators. Since 1987 EDL has established itself as a world leader in the provision of hydrodynamic test equipment, including:

- flap-type ocean wave generators;
- piston-type coastal wave generators;
- wave generating software and measuring equipment;
- beaches and movable floors;
- scientific tidal, wind and flow tanks and recreational tank equipment.

EDL directly employs 6 full-time staff with a turnover exceeding £2M per annum [S1]. They sub-contract manufacture and installation to local and UK companies, depending on the location of each installation, creating significant indirect employment and onward turnover.

They have supplied over 1000 wave-makers to 50 installations in 19 countries into academic, governmental, defence and recreational facilities (http://www.edesign.co.uk/list-of-contracts/) including every academic installation in the UK. Examples of recreational wave makers are surf wave pools, rapid river rides, theme park waves and flow rides. www.edesign.co.uk/product/leisure/ shows the current range of leisure designs.

Since 2008 EDL has:

- supplied the CoAST laboratory at Plymouth University with a coastal basin, ocean tank, sediment flume and tilting tank. All four rectangular tanks are equipped with wave-makers and straight-flow current generators and the ocean tank has a hydraulic moving floor [S3].

- Installed in 2011 wave-making equipment in the 260 m Marin Depressurised Wave Basin at Waginengen in the Netherlands to generate bow-on and beam waves during ship-towing tests. For the first time this enabled the investigation into cavitation in a wave environment and the study of air entrapment under reduced ambient air pressure.

- Created the giant wave and flood scenes for 2012 film *The Impossible* on the 2004 Indian Ocean tsunami, www.edesign.co.uk/2012/12/edinburgh-designs-creates-the-impossible-wave/

- Commissioned on completion, in 2013, the Manoeuvring and Sea Keeping Basin for the US Navy David Taylor Facility in Maryland [S4], with 216 flap generators producing over 1 MW of wave energy, to become the largest computer-controlled wave tanks in the world for testing ship models.

The detailed technical collaboration between ERPE and EDL in wave-maker design and testing was recognised by the 2011 joint award of (EP/H012745/1, £2.1 Million with EDL) to further explore the design of several new wave and current generators for stable wave generation in multi-directional combined tanks and prove that this concept could be applied to a round tank. This led to the subsequent award of EP/102932C/1, £6 Million, to construct the All-UK Waters Combined Wave and Current Test Facility [4] and subsequent formation of the subsidiary company FloWave TT Ltd (http://www.flowavett.co.uk.) with 6 full-time staff. Complementing these investments and subscription by the University of Edinburgh, Scottish Enterprise awarded a further £1 Million to enhance the scientific and staff provision increasing the total investment to £11.2 Million.

"As Managing Director I can verify that Edinburgh Designs continues to have strong technical collaborations with the Wave Power Group at ERPE. In particular we have adopted, into our design portfolio, ERPE research on new methods for integrating waves with current flow generated by an array of impellers. The new Flowave tank has 28 computer controlled impellers arranged in a circle. Each can be programmed so that the direction and velocity of the combined flow within the basin can be controlled in real time. This was a unique opportunity to combine our experience of constructing previous project with new research work conducted within the University. We are very pleased to have been selected to design the new Flowave facility as it further extends our capability from wave makers into full 3D marine current test tank design", Managing Director, Edinburgh Designs [S1].

"Stephen Salter and his colleagues have provided many technical advances in the design of wavemakers and their associated drivers for wave tanks, which have been installed worldwide through the spin-out company Edinburgh Designs. This world-leading technical capability has enabled recent funding for the construction of the new FloWave facility, which gives the UK a world-wide lead in simulating ocean conditions for testing tidal and wave energy devices." Chief Scientific Advisor, Department for Energy and Climate Change [S2].

This world-unique facility, which combines recent ERPE research [4, 5] with EDL's commercial expertise, http://www.edesign.co.uk/portfolio/edinburgh-university/, has had already significant impact on the marine energy and other sectors, with a pipeline of device developers and academic researchers already established. It emulates at up to 1/20th scale the combination of wave and tidal conditions anywhere around European coastlines. The facility simulates conditions at EMEC as a pre-proving ground for technology developers and investors as part of the UK commercial test capability, which ranges from 1:100 scale testing in laboratories to full scale at EMEC and at WaveHub in Cornwall.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Managing Director, Edinburgh Designs Ltd., see comments included in Section 4.

[S2] Chief Scientific Advisor, Department of Energy and Climate Change, see comments included in Section 4.

[S3] www.edesign.co.uk/portfolio/plymouth/shows the Plymouth Marine facility.

[S4] www.edesign.co.uk/portfolio/nswcdd-mask-basin-usa/%20%20 shows, the US Navy, Maryland facility.

Institution:	**Heriot-Watt University**
Unit of Assessment:	**7: Earth Systems and Environmental Sciences**
Title of case study:	**Commercialised fish vaccines essential to sustaining fish health in European aquaculture**

1. Summary of the impact (indicative maximum 100 words)

Heriot-Watt University (HWU) does essential research to underpin testing for market release of over 0.5 billion vaccine doses per annum to fish-farms across Europe. These vaccines prevent established and emerging fish diseases in some 25% of trout and 70% of sea bream and bass production in Europe. These diseases would otherwise compromise security and future expansion of important human food supplies. Vaccines are tested for the UK arm of Merck (USA), representing half the company's fish vaccine product range, four of which are in Merck's top 250 products worldwide. Furthermore, research at HWU on MSD Animal Health (MSDAH) Relera™ vaccine efficacy against novel emerging strains of enteric red mouth (ERM) disease opened-up new markets in Eastern and Central Europe.

2. Underpinning research (indicative maximum 500 words)

Pioneering research on vaccine development was undertaken at HWU from the mid-1990s (McIntosh & Austin 1993 [1]; Durbin et al. 1999 [2]) based on characterisation of key fish-pathogenic bacteria including *Aeromonas salmonicida* (causing furunculosis), *Vibrio (Listonella) anguillarum, V. ordalii* (both agents causing vibriosis) and *Yersinia ruckeri* (causing ERM). This research was initiated by **Austin** (whose has left HWU for career advancement) who provided a basis for effective diagnosis and development of appropriate control measures, including vaccines, probiotics and dietary additives.

The research programme continues under the direction of **Lyndon** (Pieters et al. 2008 [3]; Tinsley et al. 2011a [4], 2011b [5]) and Morris (returned in UoA 6). The work of **Lyndon** and Morris in collaboration with Austin and a leading industrial partner (initially Aquaculture Vaccines Ltd, Saffron Waldon, which was subsequently bought by Intervet-Schering-Plough, and then MSD Animal Health (MSDAH; the UK arm of Merck USA) led to the development of new vaccines. The vaccines developed are based on inactivated cultures of pathogen and several have subsequently been developed commercially by the company as the AquaVac™ series of vaccines.

Under **Lyndon's** current direction, HWU is responsible for the market release testing of safety and efficacy of these vaccines. Further research at HWU has involved identification of novel disease strains, characterisation of vaccine performance in relation to emerging infections (Tinsley et al. 2011b), development of novel vaccine antigens (Scott et al. 2013), and immune modulating feed additives. The facilities at HWU have been audited to Good Laboratory Practice (GLP) standards by the Veterinary Medicines Directorate (VMD; 2009), and have subsequently been re-accredited to Good Manufacturing Practice (GMP) standards by the VMD.

3. References to the research (indicative maximum of six references)

The references identified with * are the ones which best indicate the quality of the underpinning research.

[1]* McIntosh D, Austin B (1993) Potential use of vaccines based on cell-wall-defective or -deficient (L-form) Aeromonas salmonicida for the control of furunculosis. Journal of Aquatic Animal Health 5: 254-258. DOI:10.1577/1548-8667(1993)005<0254:PUOVBO>2.3.CO;2

[2]* Durbin M, McIntosh D, Smith PD, Wardle R, Austin B (1999) Immunization against furunculosis in rainbow trout with iron-regulated outer membrane protein vaccines: Relative efficacy of immersion, oral and injection delivery. Journal of Aquatic Animal Health 11: 68-75 DOI:10.1577/1548-8667(1999)011<0068:IAFIRT>2.0.CO;2

[3]* Pieters N, Brunt J, Austin B & Lyndon AR (2008) Efficacy of in-feed probiotics against *Aeromonas bestiarum* and *Ichthyophthirius multifiliis* skin infections in rainbow trout (*Oncorhynchus mykiss*, Walbaum). Journal of Applied Microbiology 105:723-732. DOI:10.1111/j.1365-2672.2008.03817.x

[4] Tinsley JW, Austin DA, Lyndon AR, Austin B (2011a) Novel non-motile phenotypes of Yersinia ruckeri suggests expansion of the current clonal complex theory. *Journal of Fish Diseases* 34:311-317. DOI:10.1111/j.1365-2761.2011.01237.x

[5] Tinsley JW, Lyndon AR, Austin B (2011b) Antigenic and cross-protection studies of biotype 1 and biotype 2 isolates of Yersinia ruckeri in rainbow trout *Oncorhynchus mykiss* (Walbaum). Journal of Applied Microbiology 111: 8-16. DOI:10.1111/j.1365-2672.2011.05020.x

[6] Scott, C., Austin, B., Austin, D., Morris, P. (2013). Non-adjuvanted flagellin elicits a non-specific protective immune response in rainbow trout (*Oncorhynchus mykiss*, Walbaum) towards bacterial infections. Vaccine 31: 3262–3267 DOI:10.1016/j.vaccine.2013.05.025

4. Details of the impact (indicative maximum 750 words)

Fish vaccines are essential for maintaining aquaculture production in the face of widespread bacterial diseases, which would otherwise constrain production of an essential human food source. Around 205000 tonnes of rainbow trout and 150000 tonnes of sea bass and bream are produced in the EU annually, worth some 1 billion Euros in total (see EC and FAO reports, in Section 5 below).

The work at HWU directly results in excess of half-a-billion doses of fish vaccines being released to market in Europe each year. This equates to treatment of more than 25% of trout and 70% of sea bass and sea bream produced across Europe each year. The vaccines tested include AquaVac™ ERM, AquaVac™ ERM oral and AquaVac™ Relera (vaccines against ERM of which there were 195 million doses in 2012); AquaVac™ Furovac and AquaVac™ FNMplus (vaccines against furunculosis); AquaVac™ Vibrio injection/immersion, AquaVac™ Vibrio oral (vaccines against vibriosis of which there were 250 million doses in 2012), and AquaVac™ Pastuerella (vaccine against photobacteriosis, of which there were 110 million doses in 2012).

The original research at HWU led directly to the production and subsequent development of commercialised vaccines which are currently in use. For example, in relation to ERM, caused by *Yersinia ruckeri* bacteria, approximately 158 million trout are treated annually with either Relera™ or ERM vaccines released to market as a result of quality assurance undertaken by HWU. New strains of the ERM pathogen were originally identified at HWU, resulting in the development of the improved Relera™ vaccine, and research at HWU showed that this vaccine was effective against a range of emerging strains. This observation has in turn opened-up new markets for the vaccine in eastern and central Europe over the last two years. A senior manager at MSD Animal Health confirmed that HWU studies "*of cross-protection undertaken at HWU examining the efficacy of this vaccine against novel emerging strains of the disease opened-up new market opportunities in Eastern and Central Europe*" [**S1**].

The figure of 25% of European trout being treated with these two vaccines is based on the following data: the European trout production is 205000 tonnes (2007) (European Commission 2012a) worth 580 million Euros, at an average production weight of 300 g (FAO, 2013) representing 600 million trout per aunnum. Trout vaccines (ERM) supplied = 157.5 million fish (60 million priming doses Relera; 97.5 million priming doses ERM vaccine) = approx. 26% of European trout production treated using Relera and ERM vaccines released to market on the basis of testing at HWU.

Others vaccines developed are used in the protection of marine species (sea bass and sea bream) in the Mediterranean against vibriosis and photobacteriosis. A senior co-ordinator from the Schering Plough Animal health confirmed "*the key role which research … at Heriot-Watt University has played in the testing and marketing of several fish vaccines produced by MSDAH, including Relera™, ERM vaccine and several of the Aquavac range of vaccines against vibriosis*" [**S2**]. Sea bream production (85 000 tonnes p.a., mean fish size = 500 g in 2007 (European Commission 2012a)) represents 170 million fish, whilst sea bass production (58000 tonnes per annum, mean fish size = 400g (ibid.)) represents 145 million fish, giving a combined total of 315 million fish per annum worth some 470 million Euros (European Commission 2012a). Thus, up to 231 million of these two species (over 70%) are treated with vaccines derived from research at HWU and made available through market release quality control tests required by regulators also undertaken at

HWU. One of MSD Animal Health's Directors [**S3**] can confirm the importance of HWU research to their global business, especially in relation to salmonids.

The beneficiaries of the vaccine release work conducted at HWU include the vaccine production company (MSDAH) which has derived and developed significant commercial products; European fish farm companies which experience substantially reduced losses to disease; European fish processors the supply stream for which is assured in the absence of disease induced losses; European fish retailers for which the supply chain is more predictable for the same reasons; European fish consumers for whom access to a healthy and popular food is maintained and improved; the fish in terms of improved welfare (reduced suffering from debilitating and fatal disease); and the environment because of reduced use of harmful chemical treatments and antibiotics. The nature of the benefits to humans are in terms of improved food security from trout, sea bream and sea bass; safeguarding of profitability and thus sustainability of the industries producing these fish; reduction of disease reservoirs in aquaculture leading to protection of wild fish populations; and reduction of antibiotic use in fish farms and consequently reduced potential for induction of antibiotic resistance in environmental bacteria.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Contacts for Corroboration

[S1] Senior manager, MSD Animal Health, Milton Keynes, UK
Can corroborate many elements of the Case Study especially the use made of particular HWU studies, particularly those on cross-protection.

[S2] Senior co-ordinator, Schering-Plough Animal Health, Middlesex UK
Can corroborate many elements of the Case Study especially the role of HWU research in underpinning decisions on taking a range of vaccines to market.

[S3] A director, MSD Animal Health, Milton Keynes, UK
Can corroborate many elements of the Case Study especially the role of HWU research in their global business particularly their salmonid vaccines.

The importance of *Oncorhynchus mykiss* in aquaculture and the international market:

- European Commission (2012a) Fisheries: fish and shellfish species. http://ec.europa.eu/fisheries/marine_species/index_en.htm
- European Commission (2012b) Trout Oncorhynchus mykiss. Fisheries and aquaculture in Europe 57: 2 pp. http://ec.europa.eu/fisheries/documentation/publications/factsheets-aquaculture-species/trout_en.pdf
- FAO (Food and Agriculture Organisation) (2013) Oncorhynchus mykiss (Walbaum, 1792). Cultured aquatic species information series. www.fao.org/fishery/culturedspecies/Oncorhynchus_mykiss/en

Institution: Heriot Watt University

Unit of Assessment: 7 Earth Systems and Environmental Sciences

Title of case study:

Development of Marine Energy: Testing, planning and wider economic impacts in Orkney

1. Summary of the impact (indicative maximum 100 words)

The International Centre for Island Technology (ICIT) based at Heriot-Watt University's Orkney campus is a multi-disciplinary research team whose focus for over a decade has been research into the socio-economic and environmental barriers to the development of marine renewable energy, particularly in the Pentland Firth and Orkney Waters (PFOW) area and its establishment as a Marine Energy park. This has enabled 1.2GW of marine energy leases by the Crown Estates including an estimated £3billion of related capital investment, as well as the establishment of the European Marine Energy Centre (EMEC), which continues to maintain its impact on the development of marine renewable energy.

Research at the International Centre for Island Technology at Heriot-Watt University has led to a substantial boost to Orkney with £8.8m in Gross Value Added to the local economy, with the creation of 119 jobs (Biggar Economics, 2012) through a dozen spin-out companies.

2. Underpinning research (indicative maximum 500 words)

Research undertaken at ICIT had focussed on the impact of traditional energy activities and analysed the effect of different international legislation regimes would have on companies' management of abandoned platforms (e.g. Side 1997[1]). However, Early EU-funded research (*The Feasibility of Use of Tidal Currents in Orkney and Shetland for Generation on Electric Power*) on marine tidal energy by Bullen at Heriot-Watt (e.g. Bryden *et al*, 1998[2]) signalled potential turbine designs and the suitability of Orkney for marine renewables research, investigating the potential sites and leading to a feasibility study for a marine energy test centre. ICIT's contribution to the project was an analysis of the potential of the tidal resource at the Falls of Warness, Island of Eday, Orkney. The activity involved and strengthened ICIT's connection with the economic development directorate at Orkney Islands Council which enabled further development over the following years.

ICIT worked closely with EMEC for example undertaking analysis of the MetOcean data gathered at Billia Croo wave test site. Working with EMEC these analyses were made available to developers deploying at the wave site and inform them of the site conditions, which helped in device design, assessment and deployment.

Kerr and Johnson's research (e.g. **Kerr** 2006) on local authorities, planning policy and renewable energy applications was further developed through a Scottish Funding Council Strategic Research Development Grant, SRDG (MReDS, 2007-2013[G1]). These activities led to a developing engagement with Marine Scotland, and other stakeholders and to participation in the EU FP7 funded our "Monitoring and Evaluation of Spatially Managed Areas" (MESMA 2009-2013 [G2]) research programme. MESMA research is focused on development of a generic marine spatial planning framework to inform policy and practice in Europe and beyond. Data from twelve case studies in thirteen countries is employed and **Side**, **Kerr** and **Johnson** lead the case study of the Pentland Firth and Orkney Waters (PFOW) and in particular has been identified as an early example of development-led marine planning (e.g. **Johnson** *et al*. 2012[5]). They identified high, but frequently conflicting, priorities on marine planning, ranging from economic growth and job creation, to conservation and ecosystem-based management, and the potential obstacle to marine renewable energy developments that these may pose; specific examples include fisheries, community benefits and conflicts arising from EU conservation Directives (e.g. **Johnson** *et al*., 2013[6]).

The PFOW case study has established a close collaboration with Marine Science Scotland including the holding of joint workshops and public consultation. Underpinning research includes a digitalised planning framework model (e.g. for use by marine planners); development and evaluation of marine planning tools; a metadata portal and library; and a marine governance analysis and comparison across European countries.

Emerging from the SRDG, MESMA and related research on the EPSRC Supergen II [G3](**Side**) has been a growing concern over the impacts on the ecosystem of energy extraction (Shields *et al*. 2011[4]), which with the direct support and engagement of Marine Scotland Science has led now to 2 successful EPSRC Grand Challenge projects (TeraWatt, June 2012 - June 2015[G4]) and EcoWatt2050 (March 2014 - February 2017[G5]) with this focus. These projects provide data for field developers, informing EIAs (see also [G6]) and the consenting process as well as a range of monitoring and modelling studies being undertaken. They feed directly into the noise modelling methodologies being developed for a wave device developer (Pelamis) and collision monitoring methodologies adopted by a tidal turbine developer (Scotrenewables). Identification of deficiencies in noise monitoring technologies has led to a proof of concept proposal for an ambisonic hydrophone buoy, which will enable a cost efficient means to discriminate the spectral and directional features of underwater noise, and to a number of consultancy studies.

The work has also led to a close relationship with Crown Estate and its marine renewables leasing studies with the appointment of **Side** to the Crown Estate Operating Agreement Panel.

3. References to the research (indicative maximum of six references)

The references identified with * are the ones which best indicate the quality of the underpinning research.

[1]* Side, J. 1997. "The Future of North Sea Oil Industry Abandonment in the Light of the Brent Spar Decision". Marine Policy 21(1): 45-52. DOI: 10.1016/S0308-597X(96)00045-0

[2]* G Bryden, S Naik, P Fraenkel, C.R Bullen. 1998. "Matching Tidal Current Plants To Local Flow Conditions", Energy 23(9):699-709. DOI: 10.1016/S0360-5442(98)00021-8

[3] Osalusi, E., Side J.C. & Harris, R.E. 2009. "Structure of turbulent flow in EMEC's tidal energy test site. International Communications in Heat and Mass Transfer", 36(5):422-431 DOI:10.1016/j.icheatmasstransfer.2009.02.010

[4]* Shields, M.A., Woolf, D.K., Grist, E.P.M., Kerr, S.A., Jackson, A.C., Harris, R.E., Bell, M.C., Beharie, R., Want, A., Osalusi, E., Gibb, S.W. & Side, J. 2011. "Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment". Ocean and Coastal Management 54(1):2-9 DOI: 10.1016/j.ocecoaman.2010.10.036

[5] Johnson, K., Kerr, S. & Side, J. 2012. "Accommodating Wave and Tidal Energy - Control and Decision in Scotland", Ocean and Coastal Management 65, 26-33. DOI: 10.1016/j.ocecoaman.2012.04.018

[6] Johnson, K., Kerr, S. & Side, J. 2013. "Marine renewables and coastal communities - experiences from the offshore oil industry in the 1970s and their relevance to marine renewables in the 2010s", Marine Policy 38, 491-499. DOI: 10.1016/j.marpol.2012.08.004

Grants

[G1] MREDS: Advancing Marine Renewable Energy Research Capacity in Scotland. (Scottish Funding Council Strategic Research Development Grant, Total £1.1M, 2007 – 2013, Lead: HWU-Side, Partners UHI & EMEC)

[G2] MESMA: Monitoring and Evaluation of Spatially Managed Areas (EU, FP7, £125k, 2009-2013, HWU Co-I: Johnson)

[G3] Supergen (EPSRC EP/E040136/1, £160k, 2007-2011, HWU Co-I: Side)

[G4] TeraWatt: Large scale Interactive coupled 3D modelling for wave and tidal energy resource and environmental impact (EPSRC EP/J010170/1, Total £980k, 2012-2015, Lead: HWU-Side, 6 partners)

[G5] EcoWatt2050: Impacts of Very Large Scale Arrays and their Regulation (EPSRC EP/K012851/1, Total £950k, 2013-2016, Lead: HWU-Side, 8 partners)

[G6] QBEX: Quantifying benefits and impacts of fishing exclusion zones around Marine Renewable Energy Installations (NERC NE/J012351/1, £17k, 2012-2015, HWU Co-I: Side)

[G7] Brahan Codar UK HF Radar Demonstration Project (Marine Scotland Science, £10k, 2012-2013, Lead: HWU-Johnson)

4. Details of the impact (indicative maximum 750 words)

Development of Marine Energy: Testing

A senior spokesperson from EMEC [**S1**] has stated that the "*very idea of a Scottish test facility for*

wave and tidal energy largely stemmed from discussions between HWU, industry and government (HIE). A combination of Heriot-Watt's presence in Orkney and ICIT's research into the local energy resource, and environment, helped single out Orkney as the preferred location for EMEC."

EMEC is the world's only accredited test facility for wave and tidal energy devices. It has attracted £36m of investment and employs 23 staff. Assessment by Highlands and Islands Enterprise has suggested a GVA for the County of £54m from marine renewables and £120M for Scotland as a whole. [**S1**] attributes this to there being a test centre in Scotland, so they are benefits to which EMEC (and indirectly therefore HWU) justifiably lays claim on behalf of the sector. He goes on to state that "*ICIT's presence in Orkney plays an important part in maintaining Orkney's undoubted high profile in the world of marine energy*".

OpenHydro was the first developer to use the tidal test site at the Fall of Warness off the island of Eday when its test rig and 250kW open centred turbine were installed. In 2008, the device was the first tidal turbine to be grid connected in Scotland and subsequently the first to successfully generate electricity to the national grid in the UK. Since 2008, over 15 companies (including E.On, Scottish Power, and Scotrenewables Tidal Power), have used the test facility at EMEC. Scotrenewables Tidal Power Ltd (SRTP) and associated companies in Orkney now employ over 25 people locally having raised over £17m capital in the development tidal turbine designs. Initial designs were developed through a Royal Society of Edinburgh Enterprise Award to an ICIT PhD student. The Fellow, now a senior company spokesman [S2] attests "*My research on the Heriot-Watt Campus provided the vital springboard in the field of marine renewables*". SRTP have developed an innovative floating tidal energy converter known as the Scotrenewables Tidal Turbine. Nine different scale models of the device have been tested extensively over the past 10 years both offshore and in laboratory environments. The culmination of this development work has been the construction of the 250kW prototype which weighs 100 tonnes and measures 33 metres long towards the end of 2010. The device was successfully connected to the national grid at the European Marine Energy Centre at the end of March 2011.

In March 2010, the Crown Estate announced 1.2GW of marine energy leases in Orkney waters and the wider Pentland Firth, which included an estimated £3 billion of related capital investment, A senior member of Orkney Islands Council [S3], observed that "*none of it would have happened without the foresight of Heriot-Watt University and its presence in Orkney*".

Development of Marine Energy: Planning, and socio-economic & environmental impacts

European legislators have adopted ambitious policy initiatives relevant for the oceans, seas and coasts, to be implemented in the next 10 to 20 years. These initiatives include the 2008 Marine Strategy Framework Directive (2008/56/EC), the 2009 Renewable Energy Directive (2009/28/EC) and more recently the Proposal for a Directive to establish a framework for maritime spatial planning and integrated coastal management (COM 2013:133). The MESMA Project deliverables and associated publications make an important contribution to the draft Directive. MESMA research is focused on development of a generic marine spatial planning framework to inform policy and practice in Europe and beyond. The Pentland Firth and Orkney Waters (PFOW). PFOW area is a UK designated 'Marine Energy Park' in 2012, and the Marine Spatial Plan is a pilot which sets the standard for all Scottish waters. A member Marine Scotland's Marine staff responsible for managing the development of the Plan [S4] notes the significant "*work put into the workshops and public consultation events during July 2013 [by ICIT] for the Planning Issues and Options and draft Environmental Report consultation papers for the Pentland Firth and Orkney Waters (PFOW) marine spatial plan. Our collaboration has worked well and we have benefited from our different but mutually complementary skills- the added dimension which HWU and the MESMA programme have brought to the preparation of the PFOW plan has been invaluable*."

The strength of ICIT's links with policy organisations in both the development of research and delivery of impact is recognised for example by senior staff in Marine Scotland responsible for Marine Energy development across the country [S5]. They pay particular attention to ICIT's "*willingness to increase their understanding of end-user needs*" and this has been instrumental in determining "*the extent of future marine renewables development, and clarify our understanding of*

the ecological impacts of these technologies".

Wider Economic Impacts in Orkney

"*Activity at the Orkney campus is predominantly research driven*" and accounts for "*nearly 6% of the Gross Value Added (GVA) of the Orkney economy and supports more than 2% of employment on the Islands*" (Biggar Economics 2012[S6]).

The Orkney campus has been a particularly significant source of start-up activity. A report commissioned by Highlands and Islands Enterprise in 2011 (Westbrook 2011[S7]) identified 10 active start-up companies that had been established by former students and staff at the Orkney campus. Taken together these businesses employ 90 FTEs, 88 of whom are based in Orkney. Through these spin-outs the Orkney Campus has contributed £8.8m in GVA to the local Orkney economy, with the direct creation of 119 jobs and rather more "*if the initiative in putting forward the initial case for a test centre, and its lobbying for EMEC to be located in Orkney was also quantified in terms of net additional employment in the islands*" (Westbrook 2011[S7]). The presence of such research activity in remote areas is a significant factor in the number and sustainability of this economic activity; "*if the Orkney campus did not exist, the founders of these businesses would probably be located elsewhere in Scotland in areas that may offer more employment opportunities and therefore fewer incentives to start-up independently*" (Biggar Economics 2012[S6]). In addition, most of these start-ups relate directly to the environmental/energy research developed at ICIT (including Scotrenewables, Aquetera, Xodus Aurora, North Isles Environmental Ltd., Credo Green, Opus Plus Ltd.) (Table 7.5 in Biggar Economics 2012[S6]).

Scotrenewables employs over 25 people having raised over £17m capital in the development of its tidal turbine. Scotrenewables [S2] confirmed "*Without ... the ongoing support from the Heriot-Watt research activity, the establishment of Scotrenewables Tidal Power and associated companies in Orkney would certainly not have been possible*".

Environmental impacts research has informed and led to the creation of specialist environmental consultancies such as Aquatera. Aquatera employs over 15 members of staff in Orkney and over 25% are Heriot-Watt graduates (www.aquatera.co.uk).

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Senior Spokesperson, Marine Energy Centre (EMEC) Ltd
Will clarify the role of HWU in establishing EMEC and the development of marine renewable energy using the facility since 2008.

[S2] Senior Manager, Scotrenewables Tidal Power Ltd (SRTP)
Will describe the importance of ICIT to marine renewables development and to enterprise creation in the region.

[S3] Senior Member of Orkney Islands Council will corroborate the importance of ICIT to marine energy leases.

[S4] A Marine Scotland Manager responsible for Marine Renewable Energy
The role of ICIT in driving the PFOW Marine Spatial Planning and Marine Energy Park Development.

[S5] Marine Renewable Energy Programme Manager, Marine Scotland Science
Will describe how ICIT work with policy and company interests to develop research to deliver impact.

[S6] Biggar Economics (2012). Heriot-Watt University, Economic Impact Study.
http://www.hw.ac.uk/documents/Heriot_Watt_University_Economic_Impact_Report.pdf

[S7] Westbrook S (2011) Orkney Renewables Centre: Economic Impact Assessment for Highlands and Islands Enterprise. A report for HIE by Steve Westbrook, Economist. Available on request.

Institution: Heriot-Watt University

Unit of Assessment: 7: Earth Systems and Environmental Sciences

Title of case study: Sustainable marine management implementation

1. Summary of the impact (indicative maximum 100 words)

Based on biogenic reef research at Heriot-Watt University (HWU), nine Marine Protected Areas (MPAs) have been designated and established in the Northeast Atlantic, Caribbean and Eastern Pacific, and a further six are under consideration. These MPAs represent 10% of the Caribbean Sea area, 6% of the UK's inshore Special Areas of Conservation (SAC) and 18% of the MPAs under consideration in Scotland. In addition, our ecological assessments of the biodiversity value and structure of biogenic habitats, and their sensitivities to widespread stressors, stakeholder conflict assessment and economic assessments have underpinned the objectives, management measures and assessment of MPAs, and other marine spatial planning initiatives, undertaken in the context of both the current marine environmental conditions and future climate change trajectories.

2. Underpinning research (indicative maximum 500 words)

For over 20 years, marine scientists at HWU's have been continuously discovering biogenic reefs formed by molluscs, polychaetes and corals whilst researching the distribution, biodiversity value and function of them (e.g. Moore *et al.,* 1998 [5]; **Roberts** *et al*. 2009 [6]). These habitat types have increasingly become the focus of protective spatial management measures as their biodiversity value has become better appreciated.

North Atlantic Research

HWU researchers have investigated reproductive biology, associated biodiversity and rates of reef regeneration by the flame shell *Limaria hians*. Similar work has been conducted by **Lyndon** and **Mair** with other colleagues on the horse mussel *Modiolus modiolus* and the fan worm *Serpula vermicularis* supported by Scottish Government funded projects totalling £312k. **Sanderson** joined HWU in 2010 when he developed this work further with **Mair** and **Porter** and other colleagues at HWU supported by a further three Scottish Government funded research projects totalling £163k. Reefs formed by flame shells (*Limaria hians*) and fan-worms (*Serpula vermicularis*) have been mapped during aforementioned projects, including the world's largest known flame shell bed. Horse mussel reef research dates back to annual environmental monitoring studies conducted in the late 1970s and 1980s by **Mair** and **Lyndon** investigating density, biodiversity and population structure whilst further projects have investigated biological health.

Caribbean and Eastern Pacific Research

With support from a £120k Defra Darwin Initiative project, **Mair** mapped habitats of conservation importance in the Colombian Caribbean (Mitchell *et al.* 2001 [4]). This was the first international research collaboration the Colombian government agency, Coralina, had undertaken. Subsequently, **Side** undertook research with EU INCO-DC (International Cooperation with Developing Countries) Framework support (£300k) in collaboration with Coralina and the Charles Darwin Research Foundation in the Galapagos Islands. The research by **Kerr** and **Side** integrated fisheries stock assessment, stakeholder conflict analysis and socio-economic assessments to underpin MPA designation (Seaflower biosphere reserve) and management in both Seaflower and Galapagos (Davos *et al*. 2007 [2]). **Mair** collaborated with researchers in the Smithsonian Tropical Research Institute and Darwin Initiative support (£220k) to map habitats and evaluate patterns of biodiversity in Las Perlas Archipelago including reef forming Sabellariidae (**Mair** *et al.* 2009 [3]).

Pressures on biogenic habitats

Biological impact studies on biogenic reefs (*Limaria*, *Serpula, Lophelia* & *Modiolus* spp.) showing the sensitivity of biogenic habitats to anthropogenic stressors have been developed in close collaboration with government agencies leading to impact before publication (e.g. Cook *et al*., 2013 [1]). Based on this understanding of impact, **Sanderson**, **Mair** and **Porter** with other HWU staff have ongoing research interests in indicators of Good Environmental Status (JNCC funded research project; £50k) and restorative potential though Esmee Fairbairn Foundation funding

(£89k). Research by **Porter** and **Sanderson** has used habitat modelling under IPCC scenarios to show the potential for the biogeographic range of protected habitats to change their distribution in relation to international MPA networks. Similarly, **Roberts** is leading work on calcifying biogenic habitats for the UK Ocean Acidification programme sponsored by NERC, Department of Environment and Climate Change, Defra and LWEC.

3. References to the research (indicative maximum of six references)

The references identified with * are the ones which best indicate the quality of the underpinning research.

[1] Cook, R. L., Fariñas-Franco, J., Gell, F., Holt, R., Holt, T., Lindenbaum, C., **Porter, J.S.,** Seed, R., Skates, L., Stringell, T. & **Sanderson, W.G.** 2013. The substantial first impact of bottom fishing on rare biodiversity hotspots: a dilemma for evidence-based conservation. PLoS ONE 8(8): e69904. doi:10.1371/journal.pone.0069904

[2]* Davos, C., Siavakara, K., Santorineou, A., **Side, J.,** Taylor, M., & Barriga, P. 2007. Zoning of marine protected areas: Conflicts and co-operation in the Galapagos and San Andres archipelagos. Ocean & Coastal Management 50 (3-4) 223-252. doi:10.1016/j.ocecoaman.2006.03.005

[3] **Mair, J.M.,** Sibaja-Cordero, J.A., Arroyo, M.F., Merino, D., Vargas, R., Guzman, H.M., & Benfield, S., 2009. Mapping benthic faunal communities in the shallow and deep sediments of Las Perlas Archipelago, Pacific Panama. Marine Pollution Bulletin, 58, 375-383. doi: 10.1016/j.marpolbul.2008.10.015

[4] Mitchell, A., Garcia, M., Mow-Robinson, J.M., Karpouzlie, E. & **Mair, J.** 2001. Marine mapping techniques using remotely sensing data in the archipelago of San Andrés, Providence and Santa Catalina (Colombia). Proceedings of the IX Latinamerican Congress on Marine Science (COLACMAR), San Andres, Colombia, September 17-29, 4 pages.

[5]* Moore C.G., Saunders G.R. & Harries D.B. 1998. The status and ecology of reefs of *Serpula vermicularis* L (Polychaeta: Serpulidae) in Scotland. Aquatic Conservation V8 pp645-656. DOI: 10.1002/(SICI)1099-0755(199809/10)8:5<645::AID-AQC295>3.0.CO;2-G

[6]* **Roberts, J.M.,** Davies, A.J., Henry, L-A., Duineveld, G.C.A., Lavaleye, M.S.S., Dodds, L.A., Maier, C., van Soest, R.W.M., Bergman, M.I.N., Huhnerbach, V., Huvenne, V., Sinclair, D., Watmough, T., Long, D., Green, S., van Haren, H. 2009. Mingulay reef complex: an interdisciplinary study of cold-water coral habitat, and biodiversity. Marine Ecology Progress Series 397: 139-151. DOI:10.3354/meps08112

4. Details of the impact (indicative maximum 750 words)

The UN Convention on Biological Diversity (CBD) establishes that 10% of coastal and marine environments should be conserved through protected areas by 2020, an ambition that is not yet even half realized. Across the North East Atlantic, Caribbean and Eastern Pacific, nine Marine Protected Areas (MPAs) have been designated based on HWU research and a further six are under consideration since the inception of the CBD at the 1992 Rio Earth Summit.

1. **Mair's** research with the Colombian government agency Coralina led (in combination with **Kerr** and **Side**) to the designation of the San Andres archipelago as a United Nations Man and Biosphere Seaflower Reserve in 2000 (Mitchell *et al*. 2001 [4]). At the United Nations Convention on Biological Diversity Conference in Nagoya, in October 2010, Coralina won the International Union for the Conservation of Nature's (IUCN) Countdown 2010 Biodiversity Award for the work in San Andres. A senior member of staff [S1] of Coralina, wrote: "*The management of the reserve has been challenging work ……. but…. based on good scientific information [inc work by Mair]. It was a great honour therefore to have our work recognised by …. Nagoya 2010…..*". Elsewhere, **Mair's** collaboration with the Smithsonian Tropical Research Institute (STRI) in Panama led directly to the protection of Las Perlas Archipelago as a marine Special Management Zone and underpinned subsequent management (Mair *et al*., 2009 [3]). A senior staff member at STRI [S2] expressed the Institute's "*gratitude to the Heriot-Watt*

University for ……the ground research work that allowed the Panamanian government to designate the Archipelago Las Perlas as a Special Management Zone…… should help in guiding science-based decisions…."

2. HWU researchers (Mair, Sanderson and Lyndon) have a track record of research on temperate biogenic structures that has led to the designation of European MPAs called SACs under the EU Habitats Directive. Before 2008, these have been designated at Loch Sunart, Loch Creran, Loch Duich Long and Alsh and Sullom Voe based on their work. Since 2008, the Isle of Man government have used work by Sanderson and Porter (Cook et al. 2013 [1]) as a core component to the permanent protection of 6 km2 of horse mussel (Modiolus modiolus) reef in the Irish Sea. "*This research* [Cook et al. 2013 [1]] *supported the permanent protection of the reef as part of the Ramsey Marine Nature Reserve, designated in October 2011*.", [S3]. In November 2012, the cold water corals of East Mingulay became part of another MPA of European importance (a candidate SAC) based on Robert's on-going biodiversity research (Roberts et al. 2009 [6]). Marine Scotland, [S4] confirm that "*the GIS data supplied by [HWU] for Marine Scotland Science's 2010 survey of the Mingulay Reef Complex was a key component in the design of our survey [and was] key to the process of re-defining the boundary for proposed East Mingulay Special Area of Conservation (SAC)*"

3. Based on a track record of 23 commissioned projects from Scottish Government's scientific and statutory conservation advisors, Scottish Natural Heritage and Marine Scotland Science continue to commission HWU to undertake research, survey and evaluate marine habitats as potential MPAs. Since 2008 research by Lyndon, Mair, Porter, Roberts and Sanderson (and other colleagues) has been key to policy implementation in the form of MPA proposals under the Marine (Scotland) Act (2010) in Blue Mull Sound, Wyre and Rousay Sounds, Noss Head, Southern Trench, Lochs Linnhe, Etive, Leven and Eil (www.scotland.gov.uk/marineconsultation). A senior marine advisor at Scottish Natural Heritage, [S5] confirms "*HWU involvement in survey, research and assessment ... has contributed to the designation and sustainable management of a number of Special Areas of Conservation (SAC)*".

4. Biogenic habitat research by **Mair**, **Porter**, **Sanderson** and **Roberts** has underpinned MPA policy within the North East Atlantic for 'threatened and/or declining species and habitats' under the Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention). The research was widely assimilated in assessments published between 2008 and 2010 on the status and key threats for deep water sponge aggregations, horse mussel beds and cold water coral habitats. These assessments have led to an international policy to protect biogenic habitats as 'Priority Marine Habitats' in an MPA network across 15 North East Atlantic countries. For deep water sponge aggregations, their significance has been recognised globally through **Roberts'** work under the United Nations Environment Programme (Section 5: Hogg *et al*., 2010 [S6]) and these and other habitats have been identified in Ecologically or Biologically Significant Marine Areas (EBSMAs) beyond national jurisdictions in the North-East Atlantic through **Roberts'** work on the International Council for the Exploration of the Seas (Advice Drafting Group June 2013, Copenhagen).

5. Research to support sustainable development, especially protected areas, has been enhanced through a programme of outreach. MPA biogenic habitats have been widely promoted at three annual Dunbar Science Festivals (2011-13) by **Sanderson, Porter**, **Mair** and **Roberts** (each >3,000 visitors), the 2013 Orkney International Science Festival (**Sanderson, Porter**, **Mair**) and the Edinburgh Science Festival during National Science and Engineering Week in March-April 2013 (**Mair**, **Porter**, **Roberts**). **Roberts** integrated a school visit in the Outer Hebrides (Benbecula) into an MPA research cruise on RV James Cook in May 2012.

6. HWU has a strong track record of environmental indicator development under the Water Framework Directive (**Fernandes**). Research by **Lyndon**, **Mair**, **Porter Sanderson** and **Roberts** since 2008 has been widely cited in the development of the UKs biodiversity indicators of Good Environmental Status for biogenic structures under the EC Marine Strategy

Framework Directive (see section 5: Moffat *et al*. 2011 [S7]), an area where **Sanderson** provides on-going advice to the UK and EU (through DEFRA and OSPAR Benthic Expert Groups).

7. **Kerr** and **Side's** research in the Galapagos (e.g. Davos *et al*. 2007 [2]) provided baseline data (fisheries and socio-economic) for the establishment of the Seaflower biosphere reserve in San Andres and on-going fisheries management in the Galapagos Marine Reserve (GMR). Capacity building exchanges included training for Charles Darwin Research Station (CDRS) and Coralina (San Andres) [S2] research staff at ICIT. Additionally an ICIT PhD student (Alex Hearn) was in post as Co-ordinator of Fisheries Research at CDRS 2002-2008. **Kerr** was recently invited back to the Galapagos to present at a 2010 UNESCO workshop exploring socio-economic aspects of future management of the GMR.

Overall, the beneficiaries of HWUs sustained research into biogenic reef habitats are a number of government agencies, NGOs and communities involved in protected area management throughout Central America and North Western Europe. Sustainable protected area management can be highly socially valuable to communities and economies beyond conventional resource extraction because the ecosystem services of biogenic reefs can, for example, stabilise sediment, maintain water quality and sequester carbon as well as providing human food and recreation.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] A senior member of staff of Coralina and

[S2] A senior manager of the Smithsonian Tropical Research Institute

Will confirm the importance of HWU research to the management of San Andres and Las Perlas Archipelagos. [S2] Can also corroborate HWU's role in the development of research staff based in CDRS and San Andres.

[S3] Senior member of the Isle of Man Government's biodiversity team:

Will confirm the role of HWU research in the designation and management of Ramsey Marine Nature Reserve.

[S4] Marine Scotland Science:

Will confirm the importance of HWU research and analyses in establishing East Mingulay as a Special Area of Conservation.

[S5] Senior Member of Scottish Natural Heritage's marine team:

Will confirm HWU research contribution to the designation and sustainable management of Special Areas of Conservation (SAC) under the EC Habitats Directive since the 2008.

[S6] Hogg, M.M., Tendal, O.S., Conway, K.W., Pomponi, S.A., van Soest, R.W.M, Gutt, J., Krautter, M., Roberts, J.M. 2010. Deep-sea Sponge Grounds: Reservoirs of Biodiversity. UNEP-WCMC Biodiversity Series No. 32. UNEP-WCMC, Cambridge, UK.

[S7] Moffat, C., Aish, A., Hawkridge, J.M., Miles, H., Mitchell, P.I., McQuatters-Gollop, A., Frost, M., Greenstreet, S., Pinn, E., Proudfoot, R., Sanderson, W. G., & Tasker, M. L. 2011. Advice on United Kingdom biodiversity indicators and targets for the Marine Strategy Framework Directive. *Healthy and Biologically Diverse Seas Evidence Group Report to the Department for Environment, Food and Rural Affairs.*