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.