SUSTAINABLE SEAS

Ko ngā moana whakauka

National SCIENCE Challenges

Innovation Fund Research Proposal Template 2.2.2

A. PROJECT TITLE

Energy from Tidal Currents—Kick-starting a new marine industry with huge potential

B. PROJECT TEAM

Project Leader:	Investigators:
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C. ABSTRACT

Energy is the critical mainstay of our daily lives, from growing and transporting food to manufacturing and powering the vast array of technological innovations we depend on. New Zealand faces the conflicting imperatives of expanding our energy supply for a growing economy, while rapidly transitioning to green energy sources in order to mitigate the worst impacts of climate change. Based on historically-low growth figures given in a 2016 MBIE report [1] New Zealand's renewable electricity generation must almost double by 2050, if we are to achieve a 100% renewable generation target. MBIE also noted the need for 3,000-4,000MW of new generation by 2040. We are fortunate in having large untapped sources of renewable energy in the oceans surrounding us. The scale of these resources goes well beyond meeting predicted demand to exporting "green" energy in high value forms. This proposal is a first step in unlocking one of those marine sources: tidal current energy.

Raukawa Moana (Cook Strait), a focal area for the Sustainable Seas program, is arguably the best site in the world for generating power from tidal currents, a highly predicable renewable energy source [2-6]. The upper limit for production from the Strait is 15,000MW [2], enough to power two New Zealands. In more practical terms, could Cook Strait economically deliver enough to power Auckland—around 1,000MW? A critical first step to unlocking this huge potential, is estimating the scale of investment required to meet Auckland's current needs. This requires novel tools and methods to overcome the immense computational barrier required to make these estimates for wide-ranging scenarios of tidal farm sizes and locations [6]. The scientific challenge of this project lies in developing these methods.

With commercial-scale turbines in the water [7,8], with the first of 269 1.5MW turbines being installed in the UK [9]; large-scale tidal turbine farms are on the horizon. With NZ's huge tidal

resource, the biggest single barrier to industry investing in developing a generation capacity is the absence of information on the scale of investment required. This investment from industry is essential if marine energy development is to move to the next stage, which would require detailed hydrodynamic modelling and engineering designs, plus full assessments of the environmental, economic and cultural impacts.

With this in mind, the aim of this project is to provide quantitative data and tools to stimulate industry investment, in order to kick-start a new sector of the marine economy. This 'seeding' project would address three fundamental questions: (1) How much power could farms produce for a wide range of scenarios for size and location? (2) What are the impacts of large-scale power generation on tides and tidal flows within Cook Strait? (3) What is the scale of the return on investment for these scenarios? These questions will be answered by developing a novel hybrid approach to incorporating turbines within standard hydrodynamic models, in order to overcome the immense computational barrier required to model the large numbers of wide-ranging scenarios that must be trialled in early stage development.

D. RELEVANCE TO CHALLENGE OBJECTIVE

By kick-starting a new "green" marine industry this project directly addresses the Challenge's objective to *Enhance utilisation of our marine resources within environmental and biological constraints*. The background to the Challenge's Research and Business (R&B) plan specifically references marine energy a number of times, e.g. "Potential new sectors to the marine economy include …renewable energy".

By developing the modelling tools needed to rapidly evaluate wide-ranging turbine farm scenarios, this project falls squarely within Project 2.2.2's aim of *Methods to increase diversification in marine economies.* Marine energy is specifically listed as a target for 2.2.2's RfP in the Challenge's R&B plan. The Challenge's alignment with key national strategies in its plan also lists quotes from the EEZ (2012) Act, which identifies the need for *… greater certainty for new ventures in energy generation…*. The core aim of this project is to provide greater certainty to simulate investment in marine energy.

E. INTRODUCTION

The proposed research will contribute directly to overcoming the major barrier to industry investing in tidal current energy—the absence of information on the scale of investment required and the income from that investment. Core to providing this quantitative information is determining the power output from a large number of turbines. This is a complex non-linear problem, as large-scale power production modifies the available resource [11-16]. As a result, modelling large tidal turbine farms is computationally challenging, and requires novel approaches to model the large number of farm scenarios that must be trialled in early stage investigations. The approach developed would initially be applied to Cook Strait, kick-starting the investment required to unlock its potential to supply a large part of our electricity needs.

By enabling the development of an unutilised energy source, this project would add value to the NZ marine economy is several ways. Firstly, this reliable marine energy will enable long-term economic growth across a wide range of sectors. Developing 1000s of MW of renewable marine energy would allow new high value-low volume exports of this energy (e.g. high purity silicon from Southland for manufacturing "green" computer chips and solar cells, where electricity supply is a constraint for a new billion dollar industry [10]). Secondly, developing tidal energy within New Zealand would create new marine engineering, technology and service industries for a worldwide renewable energy industry. This would build on NZ's existing marine expertise (eg. carbon fibre tidal turbine blades).

Thirdly, tidal current energy would significantly reduce risks to our economy. Our hydro dams are susceptible to dry years and winds don't always blow or blow too strongly. Highly predicable tidal current energy would mitigate these risks.

In 2016 tidal energy was only a small component of NZ's future energy plans [1], 200MW for a proposed Kaipara Harbour scheme, despite 1000s of MW of potential in NZ waters. The path to market which realises this potential starts with this project. It develops the tools to rapidly provide fundamental information, lowering the barrier for investors. This information would enable them to support turbine trials in NZ conditions, and carry out full assessments of environmental, cultural and economic impacts. The next stage would be installation of turbines and on-shore infrastructure in a staged manner. This development could also establish NZ within niches of the tidal turbine supply chain, e.g. in turbine mooring design and manufacture.

By developing the information required to create stakeholder buy-in, this project aligns with the business case developed by the Aotearoa Wave and Tidal Energy Association [18]. AWTAEA's plan is for a Marine Energy Centre in the Cook Strait region as a global hub, linking turbine technology developers, researchers and servicing industries. It is a joint development with the European Marine Energy Centre, a global centre of excellence [19]. The NZ centre would have ocean-based test facilities and be a development hub for marine energy in the Asia-Pacific region.

F. AIMS

This project has two aims that directly contribute to the objectives of project 2.2.2 (*Methods to increase diversification in marine economies*). The first aim is to develop a hybrid-modelling tool to rapidly determine power production and the impacts on tidal flows of large-scale tidal turbine farms, in order to provide greater certainty for initial investments in developing New Zealand sources of marine energy. This tool is critical to early stage development, where large numbers of wide-ranging scenarios for farm size and location must be trialled. This first aim would develop a modelling tool that balances computational effort with model resolution, by creating a hybrid approach to how turbines are incorporated within the hydrodynamic model. This modelling tool could be used in any region, but initially in the Cook Strait region to achieve the second aim: a "proof of concept" for tidal current energy for a range of farm scenarios. This proof of concept is highly relevant to industry generators to ensure long-term energy supply, and also relevant to Māori, who have long-term interests in both guardianship and development of marine resources.

G. PROPOSED RESEARCH

Overview: This project will evaluate the number of turbines required to generate power outputs ranging from 200MW to 2000MW for a number of locations within the Strait, along with determining how power extraction would impact on tides and tidal currents throughout the Strait [6]. Economic analysis will be used to estimate the viability of the scenarios for ranges of costs and power prices [28-31]. The results will be communicated through a refereed publication and NZ conference presentation and meetings with potential stakeholders. To achieve these outcomes, MetOcean Solutions' existing Finite Element unstructured grid hydrodynamic model of tides in Cook Strait will be adapted to explore scenarios for tidal farm development. This hydrodynamic model will be modified to incorporate a novel hybrid approach to evaluating the power extraction by the turbines.

A key hurdle to estimating power production from large-scale tidal farms is the computational cost of optimising turbine drag coefficients in order to maximise power generation for each farm scenario [11-12]. In addition, a critical part of early stage development is the necessity to evaluate large numbers of scenarios for farm size and location. This requires many model runs to optimise each of many scenarios, creating a computational barrier to investment [6]. Developing and implementing a novel hybrid approach for inclusion of tidal turbines within the model is the scientific challenge of this project and will surmount this barrier. This approach will balance the benefits of the computational speed of the less realistic non-optimised distributed-drag models [e.g. 20], with the much more realistic but costly models optimising the drag of individual turbines [17, 21].

Work plan:

- Establish a high-resolution Finite Element unstructured hydrodynamic model grid for inner Cook Strait, refined in key areas around farm locations (Figure 1). Extract tidal boundary conditions from either a calibrated and validated New Zealand scale Princeton Ocean Model (POM) or the Regional Ocean Modelling System (ROMS) model. Establish contacts within industry stakeholders, beyond initial contacts with Meridian, for consultation during the project.
- Set up and test a SCHISM [27] hydrodynamic model of inner Cook Strait. The model would be calibrated and validated against published results for the tidal currents in the Cook Strait Narrows [22-24] and other available measurements. Calibration of the modelled currents will be done using available Acoustic Doppler Current Profiler data sets, e.g. [22, 32], to ensure the model reproduces the amplitude and phase of the tidal currents well. This reduces the uncertainty in the modelled currents, which can't be quantified without unachievably-large data sets.
- Develop and test the hybrid approach to include turbine farm drag within the hydrodynamic model and develop processes and algorithms to maximise power production.
- Run a first farm location scenario within a 4km square targeting the strongest tidal currents within the Strait; those to the west of Cape Terawhiti. From the model runs, produce power curves for a range of turbine numbers, producing 200 MW to 2000 MW. Optimised each scenario to maximise the farm power output using 8-12 model runs.
- Develop economic assessments by combining analysis of physical hydrodynamic modelling with the economic model, in order to assess the ranges of costs and electricity prices required to make farms economic over their projected lifetime.
- Carry out model runs, optimisation and economic range assessment for three other 4 km square locations within Cook Strait, one location to the north and south of Cape Terawhiti, and a third within the weaker flows on the western side of Cook Strait.
- Analyse results for all locations and farm sizes and produce a refereed publication and conference presentations. Results will be shared with industry through meetings.

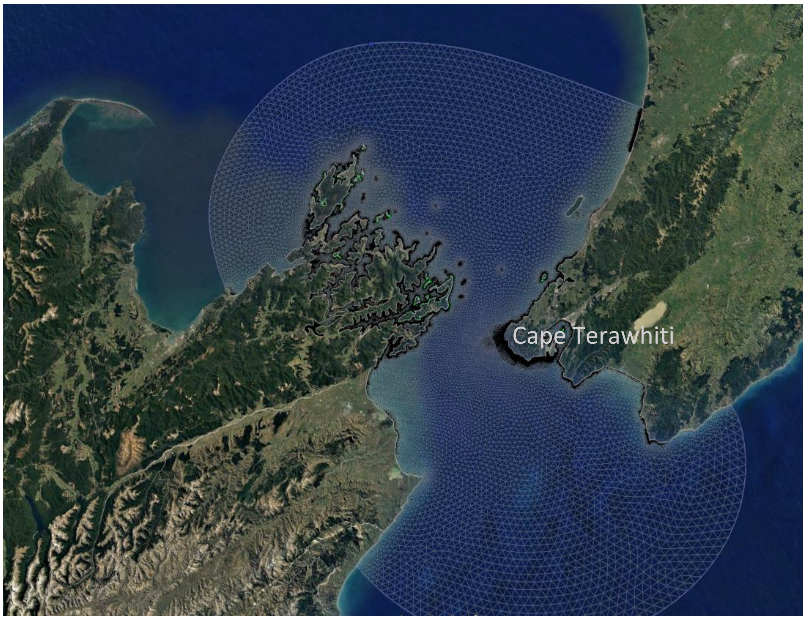

Figure1: Proposed SCHISM hydrodynamic tidal model grid for Cook Strait. SCHISM is an open-source model that is widely supported by the scientific community [27]

The parallel work plan for the Vision Mātauranga would begin with an intern establishing contacts within iwi with cultural and economic ties to Raukawa Moana–Cook Strait who are prepared to share their knowledge. The intern will gather knowledge and stories, while sharing knowledge about tidal current energy and what is being learned within this project. Along with the modelling results, the collated iwi and shared knowledge would form a foundation for a much deeper future consultation process about tidal energy development within Cook Strait.

Existing turbine modelling approaches: To estimate power output and the impact on flows, turbines must be included within the coastal hydrodynamic model [6]. Ideally, turbines would be modelled as highly detailed 3D elements within the model. However, the long time required to run these hydrodynamic models makes them prohibitively expensive, restricting them only modelling a few turbines [5]. One approach to reducing the computational cost of modelling individual turbines is to use a 2D-model with enhanced bottom drag at the turbine locations [e.g. 17, 21]. This requires the model to have a 1-2 m resolution grid around the turbines, resulting in long run times and making its use prohibitive for assessing large numbers of scenarios.

At the other end of the spectrum of approaches is the "distributed drag" farm model [5]. This increases bottom drag over the whole area occupied by the farm, rather than individual turbines. This can significantly speed computation by only requiring a coarse 100-200 m resolution model. However, it is difficult to connect the power lost by the flow to the farm to the number of turbines within the farm, a crucial part in determining the scale of investment required. One way has been to estimate turbine numbers based on the turbine manufacturer's rated power output [e.g. 20]. This approach does not include essential physics. Firstly, turbines can physically produce much more, or less, than the manufacture's rated output, depending on farm design [15]. Secondly, it does not account for the density dependence of the energy lost to mixing behind the turbines (up to 40%). Thirdly, to date the enhanced bottom friction coefficient has not been optimised, which can significantly increase power output [11]. These limitations create a high level of uncertainty in estimates based on the distributed drag approach as used to date.

Hybrid turbine model: The hybrid approach to be developed in this project significantly reduces this uncertainty by combining two existing approaches which balance physical realism, with computational run times. The approach combines a distributed drag coefficient with an extension of the classic actuator disk turbine model, which connects the farm drag coefficient to the number of turbines in the farm [26, 11]. This model accounts for both density dependent mixing losses and the effects of farm design on turbine output.   In this initial assessment tool the actuator disk model will be used to give the combined drag coefficient of rows of turbines, each with the same number of turbines. The drag coefficient also depends on a tuning parameter which will be optimised. Multiple hydrodynamic model runs will be used to search for the tuning parameter that maximises power output. An efficient search technique has already been developed and tested within a current tidal energy Marsden Grant (PI-Vennell).

The improved physical realism of the hybrid approach will give much more reliable estimates for turbine numbers and power output than existing distributed drag approaches. Its 2D-model results will be compared to existing 1D-model results for Cook Strait [2]. It is beyond the time limits within the project to implement, run and compare its results to an individual turbine 2D-model for large farm in Cook Strait. Comparisons would be made with published individual 2D turbine models of hypothetical channels [17]. The model will advance modelling efforts within Cook Strait by providing a tool required for assessment of its world class resource, which could be applied to other regions.

Economic Modelling: Renewable energy sources such as wind, solar and tidal energy have the advantage of being "free" energy sources. Significant initial capital investment to tap into this energy source is required. With commercial-scale turbines entering operation internationally, it is expected that manufacturing costs will rapidly fall over the next decade. Thus at this stage, the future capital costs are not well known. Two economic modelling approaches to evaluate site economic feasibility will be considered.

The first approach is life-cycle cost, which assesses this capital investment and associated fixed and variable costs over the expected life of the turbines and infra structure [28]. This modelling will be done using the software @Risk. When costs are not well known, this software can incorporate distributions of these costs. It then uses Monte Carlo simulation to estimate the likelihood of the many possible outcomes. The approach is designed to identify and to rank the drivers of viability for the focus of future detailed engineering and oceanographic feasibility.

The second approach, is a development of life cycle cost analysis: Levelised Cost of Energy (LCOE) [29]. LCOE is a commonly used metric to evaluate the cost competitiveness of renewable and conventional generation technologies. The LCOE is the minimum real electricity price ($/kWh) that a power plant must receive to break even on investment costs over the life cycle of the facility. LCOE mapping [30] would be used to estimate the likely ranges of costs and power prices required to develop viable economic tidal power generation Cook Strait.

The foundation of any economic assessment is estimating the physical size of the resource.   The complex interaction between the size resource and the flows within the Strait means that the physical modelling is the science challenge of this project. Standard economic approaches are used here to build on this science within the scale of the project. This standard economic modelling is restrained to a broad-brush understanding of how sensitive the economics are to major drivers of costs and income. A full and detailed economic assessment would be carried out by a developer of a farm within the Strait.

H. RESEARCH ROLES

Researcher	Organisation	Contribution
Brett Beamsley	*MetOcean*	*Hydrodynamic model development, implementation of hybrid power optimisation technique and project lead.*
Ross Vennell	*Cawthron*	*Development of hybrid optimisation technique, model running, data interpretation, publication and project coordinator.*
Ben Knight	*Cawthron*	*Design and implementation of hybrid power optimisation, running model, output organisation and interpretation.*
Chris Batstone	*Cawthron*	*Economic modelling and interpretation.*
Remy Zynfogel	*MetOcean*	*Hydrodynamic model implementation.*

I. LINKAGES AND DEPENDENCIES

By focusing on a new sector of the marine economy this project provides an opportunity to develop a new sector within the challenge, which directly contributes to its objectives. This project would diversify and extend the outcomes of the Challenge to a wider range of marine resources. The proposed research compliments several projects within the Challenge's programmes, in particular:

Valuable Seas: Theme 2: Adding value to our marine economy:
2.1.1 Development of valuation frameworks and principles. This project extends this project by developing the tools required for a valuation framework for tidal current energy. The new industry stimulated by this project would directly link to Project **2.2.1: Creating value from a blue economy.** The aim of this tidal energy project is to value the services provided by tidal currents and assessing the impacts on tidal currents, also complementing Project **2.1.3 Measuring ecosystem services and assessing impacts.**

Dynamic Seas: 4.2.2 Stressor footprints and dynamics. One aim of 4.2.2 is to "enable footprints of activities to be identified and quantified" and has selected Cook Strait as the regional focus. This proposed tidal energy project complements existing work on activity footprints by quantifying the impact of energy extraction on tides and tidal currents within Cook Strait. Part of 4.2.2 focuses on observations and modelling of Cook Strait and its connection to Tasman/Golden bays. This tidal energy project would extend that modelling to inner Cook Strait and share knowledge about models, grids and boundary conditions.

Our Seas: 1.2.1 Frameworks for achieving and maintaining social licence. An important component of developing a new industry is obtaining the social licence to operate in our coastal ocean. An essential component of this is providing the public with information on the effects of any new industry in the coastal zone. This tidal energy project creates tools to rapidly provide that information on impacts and benefits, which is critical to the early stages of any new development.

The participation of a VM intern within the project will also provide linkages to the **Tangaroa programme**, and in particular an emerging project on Kaitiakitanga in Practice. The VM contribution to this tidal energy project would provide diversity to case studies that may form part of an emerging project on iwi engagement within the challenge.

We also plan to make contact with a Canadian developer who is planning a turbine array in the Bay of Fundy, with a view of establishing a collaboration. A member of our wider tidal energy group visited the developer in 2016.

J. RISK AND MITIGATION

This project would use standard hydrodynamic models, which already include the ability to enhance drag in the particular regions of the model chosen as farm sites [27]. Thus, it does not require significant modifications to the code, thereby minimising the risk of failing to meeting milestones. An inherent part of this project is getting a balance between computational effort /run times and model resolution. A risk is that this balance is harsher than expected based on our experience to date, and it is not possible to complete all the runs on the best available computing resource. We would address this by either reducing the number of farm locations, or the number of scenarios for turbine density carried out at each location.

K. ALIGNED FUNDING AND CO-FUNDING

A letter of support is attached from the Aotearoa Wave and Tidal Energy Association (AWTEA). They are developing plans for a broader industry centred on a Marine Energy Research and Testing Centre to be based in the Wellington region. This Centre is being developed in collaboration with the European Marine Energy Centre, established in 2003 and thriving as a global energy for testing tidal turbines and wave power devices in the Orkney Islands.

An existing Marsden Grant (PI-Vennell, $940,000) is using hydrodynamic models related to SCHISM to understand how power production scales with the number of turbines in idealised shaped channels. The Marsden project is developing and testing the techniques to optimise power output from the model farm, which will be used within this new project developing a hydrodynamic model of a real channel—Cook Strait. The economic modelling within this innovation fund project adds to this Marsden Grant, which is only modelling power production. This innovation fund project will go beyond this to develop a broad economic modelling approach. This will be used to inform the developers of future economic modellers which components should be the focus for their refinement efforts.

The models used in this project would be the same as that used in SS-Dynamic Seas (SCHISM and ROMS), thus creating mutually beneficial efficiencies in model setup, grids and boundary conditions.

L. VISION MĀTAURANGA (VM)

Māori as Tangata Whenua and Kaitiaki have deep, long-term spiritual and economic interests in the sustainability and growth of marine resources. Specifically for this project, it is recognised that mana whenua iwi have a strong connection to Raukawa Moana through long-term occupation, and therefore invested cultural and economic interests. The Vision Mātauranga component within this project would develop a two-way exchange and dialogue with the mana whenua iwi of Raukawa Moana, around Mātauranga Māori, values, stories and developmental interests, with knowledge about a new marine industry and its benefits. Some of the potential benefits are economic, as well as in employment related to technology development and marine services needed by the new industry.

Vision Mātauranga for this project would centre on the exchange of knowledge about Raukawa Moana and tidal energy, as a first step towards assessing the wider feasibility of developing a major new industry. The project would include an intern, drawn from a local iwi. They would gain knowledge of tidal energy, modelling and potential benefits of the industry, which they could bring to iwi. They would also gather knowledge of stories, cultural values and views on potential benefits from the guardians of Raukawa Moana.

This project would fund a part fund an intern to engage and interview individual members of local iwi as a first step in gathering local cultural knowledge which they are willing to share, while also beginning the process of sharing knowledge of current tidal energy. A level of engagement suitable to this first step towards understanding the physical, economic and cultural issues, which will need to be addressed before tidal current energy, can be developed within the Strait. These issues would need to fully addressed as part be part of a broad-based engagement carried out by a future developer.   It is intended that the intern partly funded by with this project would also be partly funded by the 4.2.1 project who will be engaging with the same iwi.

M. CONSENTS AND APPROVAL

The project focuses on modelling and uses existing dataset for calibration. Thus no ethics approval or consents are required.

N. REFERENCES

[1] Electricity demand and generation scenarios: Scenario and results summary, August 2016, Ministry of Business, Innovation and Employment, 24 pages. Plus result files at http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/modelling/electricity-demand-and-generation-scenarios/edgs-2016,

[2] Vennell, R., Estimating the power potential of tidal currents and the impact of power extraction on flow speeds, *Renewable Energy*, 36,12,3558–3565,2011

[3] Vennell, R, The Energetics of Large Tidal turbine arrays, Renewable Energy, 48,210–219, 2012

[4] Draper, S.; Adcock, T. A. A.; Borthwick, A. G. & Houlsby, G. T. Estimate of the extractable Pentland Firth Resource, *Renewable Energy*, 63, 650-657, 2014

[5] Karsten, R.; McMillan, J.; Lickley, M. & Haynes, R. Assessment of tidal current energy in the Minas Passage, Bay of Fundy, Proceedings of the I MECH E Part A Journal of Power and Energy, 222, 493-507, 2008

[6] Vennell, R.; Funke, S.;Draper, S; Stevens, C; & Divett,T. Designing large arrays of tidal turbines: A synthesis and review, *Renewable and Sustainable Energy Reviews*, 41, 454–472, 2015

[7] http://www.seageneration.co.uk/

[8] http://www.newswire.ca/news-releases/cape-sharp-tidal-generates-canadas-first-in-stream-tidal-energy-at-force-602465285.html

[9] http://www.bbc.com/news/uk-scotland-highlands-islands-37985293

[10] http://www.stuff.co.nz/business/81497289/southland-silica-receives-interest-from-asia-and-united-states-investors

[11] Vennell, R. Tuning turbines in a tidal channel, *Journal of Fluid Mechanics*, 663, 253-267, 2010

[12] Vennell, R. Tuning tidal turbines in-concert to maximise farm efficiency, *Journal of Fluid Mechanics*, 671, 587-60, 2011

[13] Vennell, R. & Adcock, T. A. A. Energy storage inherent in large tidal turbine farms, *Proceedings of the Royal Society A*, 470:2013.0580, 18, 2014

[14] Vennell, R. An optimal tuning strategy for tidal turbines, *Proceedings of the Royal Society A: Mathematical and Physical Sciences*, 472:20160047, 2016

[15] Vennell, R. Exceeding the Betz limit with tidal turbines, *Renewable Energy*, 55, 277–285, 2013

[16] Vennell, R. Realizing the potential of tidal currents and the efficiency of farms in a channel, *Renewable Energy*, 36,3558–3565, 2012

[17] Divett, T; Vennell,R; & Stevens, C. Optimization of multiple turbine arrays in a channel with tidally reversing flow by numerical modelling with adaptive mesh, *Philosophical Transactions of the Royal Society A: Mathematical and Physical Sciences*, 371: 20120251, doi:10.1098/rsta.2012.0251, 2013

[18] http://www.awatea.org.nz/information/white-paper/

[19] European Marine Energy Centre (EMEC), Orkney Islands, http://www.emec.org.uk /about-us/

[20] Plew, D. R. & Stevens, C. L. Numerical modelling of the effect of turbines on currents in a tidal channel, Tory Channel, New Zealand, *Renewable Energy*, 57, 269-282, 2013

[21] Funke, S. W., Farrell, P. E. & Piggott, M. D. Tidal turbine array optimisation using the adjoint approach,

Renewable Energy, 63, 658-673, 2014

[22] Vennell, R., Acoustic Doppler current meter measurements of tidal phase and amplitude in Cook Strait, New Zealand. *Continental Shelf Research* 14:4, 353-364 , 1994

[23] Vennell, R. Oscillating barotropic currents along short channels, *Journal of Physical Oceanography,* 28, 8, 1561-1569, 1998

[24] Vennell, R. Observations of the phase of tidal currents along a strait, *Journal of Physical Oceanography*, 28, 8, 1570-1577, 1998

[25] Garrett, C. , & Cummins, P. The power potential of tidal currents in channels, *Proceedings of the Royal Society A:Mathematical and Physical Sciences,* DOI: 10.1098/rspa.2005.1494, 2005

[26] Garrett, C. , and P. Cummins, The efficiency of a turbine in a tidal channel, , *Journal of Fluid Mechanics*,588, 2007

[27] Semi-implicit Cross-scale Hydroscience Integrated System Model - http://ccrm.vims.edu/schismweb/

[28] Johnstone, C.M.; Pratt, D.; Clarke, J.A.; & Grant, A.D. A techno-economic analysis of tidal energy technology, *Renewable Energy*, Volume 49, Pages 101–106, 2013

[29] US. Energy Information Administration. "Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2015", http://www.eia.gov/forecasts/aeo/electricity generation.cfm, 2015

[30] Baker, E.; Fowlie, M.; D. Lemoine, D & Reynolds, S.S.The economics of solar electricity, *Annual Review of Resource Economics* 5, 387–426, 2013

[31] Vazquez, A.; & Iglesias, G. LCOE (Levelised Cost of Energy) mapping: a new geospatial tool for tidal stream energy. *Energy* 91, 192-201, 2015