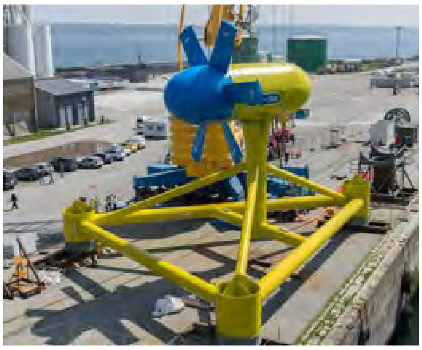
Tidal Energy in Australia

Assessing Resource and Feasibility

in Australia's Future Energy Mix

November 2020

Final report of the Australian Tidal Energy (AUSTEn) three-year project to map Australia's tidal energy resource in detail and assess its economic feasibility and ability to contribute to the country's renewable energy needs



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Executive Summary and Highlights

The AUSTEn project has mapped Australia's tidal energy resource in unprecedented detail, assessed its economic feasibility and ability to contribute to the country's future energy needs, and characterised in detail two potentially prospective tidal energy development sites to aid forthcoming developers. Project outcomes will aid the emerging tidal energy industry to develop commercial-scale tidal energy projects.

Motivation

Australia is home to some of the largest tides in the world. Tidal energy systems are considered to have the highest technical maturity in the ocean renewable sector and several national and international tidal energy developers have been prospectively seeking opportunities for Australian tidal energy projects. However, knowledge of Australia's tidal resource, its spatial extent and technical implementation remain insufficient for the tidal energy industry, regulators, policy makers and research community to make any assessment of their risks for investment in potential projects. The project was established to support prospective developers, financiers, regulators and policymakers, by providing critical baseline information, and establish what contribution tidal energy could make to Australia's future energy mix.

Benefits

The outcomes of this project provide considerable benefit to the emerging tidal energy industry, the strategic-level decision makers of the Australian energy sector, and the management of Australian marine resources by helping them to understand the resource, risks and opportunities available, and overcoming current barriers to investment by increasing the competitiveness of tidal energy against other forms of ocean renewables. Detailed field and numerical studies for the two sites have been delivered, providing tidal project developers a head start in commissioning their site prior to deployment of their technology. Further case studies were developed showing the potential of tidal energy in Australia's energy mix.

Beyond mapping Australia's national tidal energy resource, outcomes from the project extend to a range of purposes for other marine stakeholders, including marine spatial planning and environmental management, marine prediction for shipping and SAR, defence, oil and gas exploration and offshore wind and wave energy.

Project Participants

The AUSTEn project is a collaborative effort between research partners - the Australian Maritime College at the University of Tasmania, The University of Queensland and CSIRO; Industry partners - Mako Tidal Turbines, Sabella and SIMEC Atlantis Energy; and international collaborators – Bangor University, UK and Acadia University, Canada. The project is co-funded by the Australian Renewable Energy Agency (ARENA) Advancing Renewables Program.

Industrial partner involvement has brought valuable real project experience to deliver the outcomes. The broad collaborative research team has maximised domestic knowledge of both Australia's marine estate and electrical systems and ensured strong international exposure. The project further benefitted from regular and sustained interaction with further project stakeholders (governmental bodies, regulatory bodies, grid and network experts as well as tidal and wave turbine engineering firms, developers and academia) throughout the project.

Project Innovation

This Australian first project consists of three inter-linked components that have delivered:

- A National Australian high-resolution tidal resource assessment (~500 m resolution), feeding into the Australian Renewable Energy Mapping Infrastructure (online resource atlas).
- Focused case studies at the Banks Strait, Tasmania, and the Clarence Strait, Northern Territory for energy extraction, involving field based and high-resolution numerical site assessments, as well as in-situ environmental measurements and observations.
- Technological and economic feasibility assessment for tidal energy integration to Australia's electricity infrastructure, including consideration of important issues such as grid integration, and competitiveness against existing and new sources of generation, intermittency and farm design. Case studies at six key sites also outlined opportunities for adding tidal generation to the energy mix.

Results

A newly developed national Australian unstructured high-resolution hydrodynamic tidal model has identified the spatial extent of tidally energetic sites around Australia, and significantly enhanced understanding of Australia's national tidal stream and range energy resources. The most energetic sites are predominantly distributed across the northern shelf of Australia, particularly on the North-West shelf, with sparse distribution to the south of Australia that include Banks Strait, NE Tasmania, and Port Philip Heads, Victoria. However, the tidal velocities of order 2-2.5 m/s, are lower than seen in other parts of the world (UK, Europe, Canada and the US), where Tidal Energy Converters (TECs) currently installed are deployed in sites with flows of approximately 4 m/s.

Extensive field campaigns were conducted to characterise promising sites at Banks Strait in NE Tasmania, and Clarence Strait in the Northern Territory. High-resolution numerical models of these two sites were successfully developed, calibrated and validated, with assessments of the tidal energy resource to international standards completed. These case studies located tidal velocities up to 2.8 m/s suggesting these sites are unlikely to be developed using current generation of TECs that seek flows greater than 4.0 m/s to be commercially viable. However, the moderate flows, suitable depth ranges and bottom compositions suggest these sites may be viable for TECs better suited to harnessing lower velocity flows. Although current speeds were lower than that found at promising sites internationally, for both the Banks and Clarence Strait sites, the potential area nationally for tidal turbine deployment was found to increase substantially when selecting sites with maximum flow speeds greater than 1.5 m/s, opening up new areas for potential TEC deployments. For both sites, the network capacity would need to be increased to take advantage of the substantial tidal energy resource.

Using power curves from off the shelf (OTS) TECs, the extractable power was determined from the national and regional resource assessments. Estimates of extractable power were also determined using TEC power curves adjusted for local conditions (flow speeds). As the amount of electricity produced depends not only on the resource, but also on the local electricity grid, studies of the electricity infrastructure at the most energetic sites around Australia were also performed. These included sites connected to Australia's National Electricity Market (NEM), as-well as the Darwin Katherine Interconnected System (DKIS) and isolated grids including off-grid communities. The levelized cost of energy (LCOE) for tidal energy was determined at these sites using OTS and adjusted extractable power estimates. The LCOE estimates for Banks Strait, TAS and Clarence Strait, NT are in the range 1–1.75 $/kWh, indicating that tidal needs to achieve significant cost reductions, over and above those attributable to learning and those obtainable by modifying TECs, to better suit Australian conditions to be competitive with wind and solar PV. Levers to imitate these cost reductions were identified to guide developers in reducing these LCOE costs.

Six case studies are presented outlining examples where tidal energy may have application in Australia's future energy landscape, exploiting reliability and cost advantages in a distributed energy system. Tidal energy can provide renewable energy plants with an additional level of power availability and security and could have particular application to aquaculture, emergency services, essential services, defence and energy/fuel export industries. Offshore applications could include supplying power for environmental monitoring and data acquisition installations, marine surveillance, weather stations and decommissioned oil and gas rigs where most of the necessary support and power management infrastructure is already in place.

Publicly Availability Resources

- The AUSTEn National Tidal Model hourly tidal elevation and velocity outputs are made openly available via CSIRO's Data Access Portal. *CSIRO Data Access Portal: http://hdl.handle.net/102.100.100/374951?index=1*
- Tidal energy resource layers from both the AUSTEn National Tidal Model and the high-resolution Banks Strait, Tasmania and Clarence Strait, Northern Territory models are available via the Australian Marine Energy Atlas on the Australian Renewable Energy Mapping Infrastructure (AREMI) website. *Australian Renewable Energy Mapping Infrastructure (AREMI) Link: https://nationalmap.gov.au/renewables/*
- The data collected as part of the Banks Strait and Clarence Strait field campaigns are available on the Integrated Marine Observing System Australian Ocean Data Network (AODN) data repositories database, with the bathymetric surveys uploaded to Geoscience Australia's Aus-seabed database to improve the national bathymetry dataset.
- *Integrated Marine Observing System AODN Link: https://portal.aodn.org.au/*
- *Geoscience Australia Aus-Seabed Link: http://www.ausseabed.gov.au/*
- Research from this project has also presented and published both nationally and internationally to highlight the emerging Australian tidal energy sector. http://www.austen.org.au

Recommendations

Recommendation 1: Technical improvements to tidal energy converter (TEC) design to increase capacity factors that are then competitive in relation to the Australian available tidal resource.

Recommendation 2: Tidal energy should primarily be reserved for applications where intermittency can't be tolerated, for example high security / backup power in remote regions, or chemical processing for renewable fuels where tidal energy can save millions of dollars of capital expenditure, or for operating in environments on- or off- grid where tidal energy is the best resource to supply dispatchable power cost effectively.

Recommendation 3: The ability of hydrodynamic models to accurately resolve high flow currents is highly dependent on the quality of the bathymetry available. Ongoing collection of bathymetry for Australia's marine domain provides broad benefits to many sectors in the blue economy, of which offshore renewable energy is an emerging participant.

Recommendation 4: Carry out detailed cost benefit analysis of hybrid solar/tidal and wind/tidal energy farms aimed at providing up to 30 percent dispatchable (continuously available) electricity for wind/tidal and 50 percent dispatchable electricity for solar/tidal energy farms.

Recommendation 5: Five potential sites should be assessed in further detail (Warrumiyanga, Yimpinari, Wadeye and Tharramurr, Ardyaloon and Derby and Banks Strait) due to having the strongest tidal resources in Australia together with communities that have ownership and ready access to regional areas associated with the sites, as well as a track record of industrial and commercial development.

Recommendation 6: The north eastern corner of Tasmania where Banks Strait is located may have significant opportunities for development of green industries such as green steel and hydrogen production due to its tidal energy resource.

Recommendation 7: Development of a national Australian oceanographic modelling system capable of meeting Australia's industry and governmental needs. For the offshore tidal energy sector, this will provide benefits of integrated knowledge of wave influence, and contribution of non-tidal flows (wind and density driven circulations) at prospective sites.

Recommendation 8: The available resource at small-scale high flow sites not identified by the national model requires targeted efforts to determine the resource viability.

Recommendation 9: The national tidal energy resources presented via Australia's renewable energy mapping infrastructure present only the theoretical resource. Considerations of alternative uses of the marine domain must be addressed as this may limit the areas of development.

Recommendation 10: Perform full-scale ADCP measurements of flow field surrounding an operating TEC / TEC array, include near and far-field regions, to enable calibration and validation of numerical turbine models and to understand the impact of turbulence on the TEC device loads and performance.

Recommendation 11: Wave-current interactions, especially if prevalent for extended periods of time, can impact TEC device installations, operations and maintenance, and should assessed in the selection of sites for project development.

Recommendation 12: Existing technical guidelines (e.g. IEC) for site characterisation should be extended to include accurate procedures for turbulence measurements and parametrization in tidal energy sites.

Recommendations 13: Development of new numerical models that link the non-hydrostatic ocean models as used in this study with hydrostatic computational fluid dynamics turbine models that resolve the boundary layer flow over the turbine blades, allowing for the simulation of the entire flow field at all scales.

Recommendation 14: Instruments for site characterisation should be chosen such that they can accurately provide simultaneous measurements of currents, waves and turbulence (and other environmental parameters) over the required period. Data of this form can provide valuable information for a more targeted environmental impact assessment study and can minimize uncertainties surrounding in-stream tidal turbines.

Recommendation 15: As outlined as a core area for action in the UN Global Compact Sustainable Ocean Principles (UNGC, 2020); increased, ongoing mutual collection, sharing and standardised management of data from ocean based industries alongside Government, defence, academic and non-governmental communities; will enable development of best future decision making tools for emerging and current ocean industries.

The oceans contain 97% of the earth's water and 71% of the earth's surface is covered by seawater. Approximately 3 billion people live within 200 km of the coast and migration is likely to cause this number to double by 2025. Ocean energy will supply electricity, drinking water, seafood and other products at competitive prices, creating jobs and reducing dependence on fossil fuels.

International Energy Agency - Ocean Energy Systems

Project Lead Statement

"TIDAL ENERGY CAN MAKE A SIGNIFICANT CONTRIBUTION TO AUSTRALIA'S RENEWABLE ENERGY MIX. DUE TO ITS PREDICTABILITY, AND OUT OF PHASE GENERATION WITH SOLAR AND WIND, IT CAN SUPPORT GRID DIVERSITY WHERE THERE IS EXISTING HIGH PENETRATION AND PROVIDE AUSTRALIA ENERGY SECURITY."

I am pleased to provide you with this synthesis of the AUSTEn *Tidal Energy in Australia* project.

Up until now, the knowledge of Australia's tidal energy resource, its spatial extent and technical implementation remained insufficient for the tidal energy industry, regulators, policy makers and research community to make any assessment of their risks and opportunities for investment in potential projects.

Over the last three years, with our project partners, the AUSTEn *Tidal Energy in Australia* project has mapped the country's tidal energy resource in unprecedented detail and used this information to assess its economic feasibility and ability to contribute to Australia's renewable energy needs.

Through the completion of a National Australian high-resolution tidal resource assessment, which feeds into the Australian Renewable Energy Mapping Infrastructure (AREMI online resource atlas) we have a greater understanding of the Australian tidal energy resource, its predictability and known potential sites for exploration. Field based and high-resolution numerical site assessments, with in-situ environmental measurements and observations over 9-12 months at two promising locations, the Banks Strait, Tasmania and Clarence Strait, Northern Territory, provide tidal energy developers an international benchmark of knowledge about the bathymetry, seabed composition, and current, wave and turbulence conditions. Studies of the technical and economic feasibility of tidal energy were also performed to aid the emerging tidal energy industry to develop commercial-scale tidal energy projects, focusing on integration to Australia's electricity infrastructure and important issues such as grid integration and competitiveness with existing and new sources of generation, intermittency and farm design.

Six important case studies are presented that inform on the most prospective market opportunities for tidal energy in Australia with on- and off- grid applications, and indicating the grid-value proposition where high penetration of solar and wind exists, where hydrogen generation is being considered and for energy security.

Importantly, the AUSTEn project has unlocked the pathway forward for an Australian tidal energy industry with key recommendations including; technical improvements to turbine design to increase capacity factors that are then competitive in relation to our available tidal resource, improved sharing of ocean data through national research infrastructure capabilities and agencies, advances in technical guidelines for site characterisation assessments and development of an integrated national oceanographic system.

Throughout this work sharing and collaboration has been paramount. Engagement with our industry stakeholders and international tidal energy experts has brought the work of AUSTEn to the forefront internationally. The AUSTEn Tidal Energy Workshop held in Perth 2018 allowed us to share our progress with the research, industry and government community and improve the outcomes of this project. Hence, I thank ARENA for their support, my research partners for their dedication to this project and industry stakeholders who shared their valuable knowledge, technology and data with us.

I trust that the outcomes from the AUSTEn project will be a valuable reference for both current developers and an informative guide for new players in the region.

PROFESSOR IRENE PENESIS

Project Lead, AUSTEn Project

Contents

1. Introduction

Aside from a basic understanding and preliminary estimates of resource at a few locations, knowledge of Australia's tidal resource, its spatial extent and economic feasibility remains insufficient for prospective tidal energy companies to make informed investment decisions to initiate major projects for Australian waters. To resolve these issues, this project assessed the technical and economic feasibility of tidal energy in Australia, based on the best understanding of resource achievable. Over three-years the $5.85 million project was led by the Australian Maritime College, University of Tasmania, in partnership with CSIRO and University of Queensland, industry partnership with Mako Tidal Turbines, Sabella and SIMEC Atlantis Energy, and formal international collaboration with Bangor University, UK and Acadia University, Canada.

A number of key challenges have hampered characterisation and thus potential utilisation of the Australian tidal resource: The lack of a national tidal model at a high enough resolution to accurately capture the national resource has limited identification of opportunities. Difficulties in model calibration also occur, as few field surveys have been performed at sites where the flow is sufficiently high to be attractive to commercial tidal energy development. On the economic front, the lack of understanding of the national tidal resource has hampered the calculation of economic parameters such as LCOE. All these factors have increased risk for potential tidal developers in Australia.

This project, through the numerical and field survey assessments combined with economics, has addressed these challenges, allowing for a step-change in the development of the Australian tidal energy industry. The project consisted of three interlinked components shown in Figure 1 to support the emerging tidal energy sector:

Component 1 focused on development of a national high-resolution hydrodynamic tidal model, to build a national perspective of the available tidal energy resource. This component¸ led by CSIRO Oceans and Atmosphere, has provided functionality to the Australian Renewable Energy Mapping Infrastructure (AREMI), through addition of national tidal energy resource information to the Australian Marine Energy Atlas (formerly the Australian Wave Energy Atlas).

Component 2 focused on two key priority sites (Banks Strait, Tasmania, and Clarence Strait, Northern Territory), carrying out targeted site assessments using both field measurements and high resolution numerical modelling methods, in part to validate and refine the national scale assessments in Component 1 and to support the economic assessment in Component 3, and as targeted site assessments to accelerate tidal energy investment in Australia. Component 2 was jointly led by researchers at the Australian Maritime College, University of Tasmania and the University of Queensland.

Component 3 worked with the resource information derived from Components 1 and 2 and examined grid integration and the economics of tidal energy at the sites identified in Components 1 and 2 around Australia. This component explored the impact of the potential integration of the uniquely predictable tidal energy on various electricity networks around Australia. Component 3 was led by CSIRO Energy.

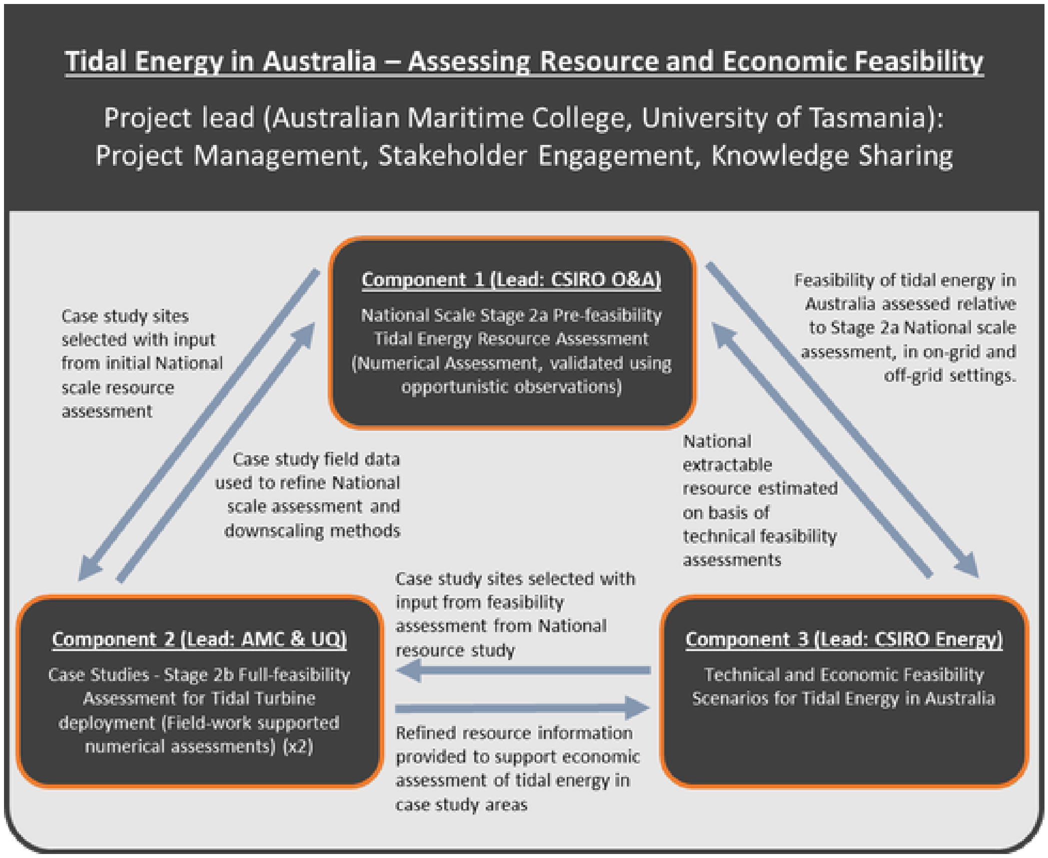

Figure 1: Interlinked components of AUSTEn project

This report synthesises the findings of all components to communicate outcomes of the project. Chapter 2 outlines current TEC developments worldwide, with examination of key performance parameters. To establish Australia's tidal energy potential, Chapter 3 reports on the development of national and regional models as well as field survey campaigns at two promising tidal energy sites. Chapter 4 uses the developed numerical models of Chapter 3 and the TEC parameters outlined in Chapter 2 to identity promising regions nationally and determine potential tidal energy farm power outputs at these identified sites. This identified technical resource is then reconciled against an examination of identified on and off-grid electrical demand integrated within current and future grid-connected scenarios. Further research was performed by examining economic parameters such as LCOE and energy mix investigations. Following on, Chapter 6 contains six case studies to outline potential application of tidal energy at sites nationally for several end-use industries. Chapter 7 includes details of the AUSTEn Tidal Energy workshop held in Perth, WA in 2018. Key summaries and recommendations developed from the studies are included in Chapter 8 to end the report.

2. Tidal Technology Assessment

The potential of tidal stream and tidal range energy resources to generate power worldwide has been estimated as three terawatts, of which one terawatt is dissipated in shallow waters[1]. However, the sites that have been identified to date as likely to be most productive and accessible, limit the estimated extractable power to about 120 gigawatts. Estimates for Australia's share of this resource vary between one and two percent[2]. In 2013 the IEA estimated that the world used 18 terawatt-years of energy so that the identified extractable tidal power would have met just 0.7 percent of global energy requirements[3]. While small this is not insignificant if one takes into account a critical distinguishing feature of tidal flow that is its regularity, which requires much less storage to provide continuous power in Australia than either solar or wind resources[4]. As the electricity grid moves towards predominantly variable renewable sources of energy the value of predictability should make reliable renewable resources such as tidal power much more cost competitive.

The last fifteen years have seen an increase in research on ocean renewable energy and a burgeoning of ideas and prototypes. This report has largely focussed on those devices and arrays that are greater than 100 kilowatt (kW) rated power and either currently operating at a commercial scale, or in production, or being developed beyond the conceptual and proposal stage. Tidal hydro kinetic energy schemes place TECs in tidal streams where they access flowing water to generate electricity during the ebb and flow periods of the tidal cycle. Such machines vary in size from units rated at a few hundred watts to units that can supply two or three megawatts of power. The widely used term 'free stream' suggests both the relatively unobstructed physical environment of the machine and the relatively low environmental impact it might have compared to barrage systems. However, there is a continuum in the impact on water flow of TECs that varies with the density of their distribution from relatively sparse tidal farms to densely packed tidal arrays, tidal fences and tidal bridges through to barrage systems. The physical effectiveness of tidal energy extraction and the selection of an appropriate TEC depends critically on the appropriate placement of the converter in both regional and local hydrodynamic environments. TECs generally include a hydraulic to electrical energy converter such as a turbine, a means of transporting and controlling the electricity generated so that it is suitable for connection to an electricity grid, and a base to support and house local infrastructure, commonly either a gravity, monopile or mooring structure.

Tidal power has been used commercially since at least 900 AD when it was used to mill grain and flush fishing channels. Its long-term use on a large scale to generate electricity dates back to the 1960's. The largest and longest running tidal stream converters, at Uldolmok, South Korea, are 500 kW triple helical Gorlov turbines with a total capacity of 1.5 MW and with a plan to expand the capacity to 50 MW[5]. More recently a number of horizontal axis turbine commercial scale units have also completed grid connected sea trials, the largest, longest running systems being the Marine Current Turbines SeaGen at Strangford Lough[6], the Orbital generator at the EMEC tidal site in Orkney[7], the AndrrHS1000 at EMEC[8] and the SIMEC Atlantis Energy AR1500 devices at the Meygen tidal energy test site[9], the floating 280kW Plat-I by Sustainable Marine Energy (utilising Schottel Hydro Turbines) in Grant Passage, Canada[10], and the D10 Turbine by Sabella in the Fromvuer Passage, Brittany[11]. A number of test sites have been developed worldwide, including Fundacion Soermar

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[1] Z J Wang and Z W Wang, (2019). IOP Conf. Ser.: Earth Environ. Sci. 240 052015

[2] J.Twidell, T. W. (2006). Renewable Energy Resources. London and New York: Taylor and Francis.

[3] International Energy Agency, (2017). Key world energy statistics. Retrieved from http://www.iea.org/statistics/.

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[5] Tethys, (2017). Uldolmok Tidal Power Station. Retrieved 28 May 2018, from USDOE Pacific Northwest National Laboratory (PNNL) https://tethys.pnnl.gov/about-tethys

[6] Tethys, (2016). Strangford Lough - MCT (Seagen). Retrieved 29th May 2018, from USDOE - Pacific Northwest National Laboratory (PNNL) https://tethys.pnnl.gov/annex-iv-sites/strangford-lough-mct-seagen

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[8] ANDRITZ HYDRO Hammerfest (UK), (2018). Tidal Turbines. Retrieved 30th September 2020, from http://www.andritzhydrohammerfest.co.uk/tidal-turbines/

[9] Atlantis Resources, (2018). Project Development and Operation Meygen. Retrieved 30th September 2020, from https://www.atlantisresourcesltd.com/projects/meygen/

[10] Sustainable Marine Energy, (2020). Retrieved 30th September 2020, from https://sustainablemarine.com/news

[11] Sabella, (2011). Retrieved from https://www.sabella.bzh/en/projects/d10

Centro Technologico, Spain, Fundy Ocean Research Centre for Energy (FORCE), Canada, European Marine Energy Centre (EMEC) Ltd, Scotland, Site Expérimental Estuarien pour l'Essai et l'Optimisation d'Hydroliennes (SEENEOH), France, and Tidal Test Centres in China. In Australia, at least 14 tidal power trials have been performed as shown in Table 1. However, no large-scale turbines or tests sites are currently located in Australia, although a 15 kW Mako demonstration turbine is located in Gladstone Port, Australia and at Saratoga Island, Singapore[12].

Table 1: Australian tidal power trails. Italic font indicates information is uncertain[13]

Location	Year	Device type	Company	Power rating	Indicative depth of operation (m)
Darwin	1996	Tyson Turbine fluted cone axial turbine (pontoon)	Northern Territory University (NTU)	< 1 kW	1
Darwin	1998	NTU Swenson axial turbine (pontoon)	NTU	2.2 kW	1-2
King Sound	2000-2014	Barrage dam investigation	Tidal Energy Australia and Hydro Tasmania	40 MW	\
Clarence river	2004	Aquanator	Atlantis Energy Ltd	5 kW	2
San Remo	2006	Aquanator	Atlantis Resources	100 kW	2
San Remo	2007	Submersible tidal generator	HydroGen Power Industries	5-50 kW	up to 20
Brisbane	2007	Submersible tidal generator	HydroGen Power Industries	5-50 kW	up to 20
San Remo and Stony Point	2008	Floating tidal turbine laboratory	EnGen Institute	\	*2*
Corio Bay	2008	Solon ducted axial turbine	Atlantis Resources	160 kW	10
Melbourne	2009	3D printed multi-axis turbine array	Cetus	*1 kW*	1
Newcastle	2012	Sea Urchin axial turbine (pontoon)	Elementary Energy Tech.	*2 kW*	1-2
San Remo	2012	Cross-flow turbine tidal desalination	Infra Tidal	15 kW	2.5
Tamar Estuary	2016	Ducted axial turbine (pontoon)	Mako	*10 kW*	2
Gladstone port	2018	Ducted axial turbine	Mako	\	\

In recent years there has been a move to more complex tidal stream energy converters sometimes referred to as third-generation tidal turbines. Table 2 summarises the principal commercial or near commercial scale technologies currently available. It is notable that only one generator in this list is not a horizontal axis turbine. These include novel designs for TEC inspired by vertical axis wind turbines, screw turbines adapted from the principles of the Archimedes screw pump but run in reverse, oscillating hydrofoils that drive a vertical piston using a reciprocating wing and tidal kites designed to carry a small turbine and fly it through a closed trajectory within the tidal stream. These claim potentially higher electricity production for environments that are less appropriate for horizontal axis turbines.

[12] Mako Tidal Turbines, (2017). Retrieved 30th September 2020, from https://www.mako.energy/singapore-demonstration-project

[13] Auguste, C., Marsh, P., Nader, J.R., Cossu, R., and Penesis, I. (2020). Towards a tidal farm in Banks Strait, Tasmania: Influence of tidal array on hydrodynamics. Energies (under review).

Table 2: Number distribution of TEC technologies at CRL1 (Commercial Readiness Level) and TRL3 (Technology Readiness Level) or above

Technique	Number of examples
Helical screw generator	1
Horizontal axis	11
Horizontal axis (floating submerged tethered)	1
Horizontal axis (floating, radial blades)	1
Horizontal axis (tidal kite)	2
Kepler	2
Kinetic Keel	1
Oscillating hydrofoil+	1
Transverse horizontal cross flow	2
Vertical axis (C2C)	1
Vertical axis (Darrieus)	1
Vertical axis (Oryon watermill)	1
Vertical axis H Darrieus	1

Integrated TEC and energy storage technologies

Renewable energy storage systems have proliferated in the last two years with the recognition that storage technologies are now available to address the key issue of intermittency of variable renewable electricity generation. Tidal energy resources already provide a high level of supply predictability and the energy storage required for tidal energy to meet the grid's increasing need for dispatchable power is about six hours compared with several days for wind energy and about sixteen hours to 38 hours for solar photovoltaics. This can be further improved by taking advantage of energy supply phase diversity between tidal sites to minimise semi diurnal intermittency. Technologies used for renewable energy storage are physical as in: compressed air, pumped hydro, molten salt and fly wheels; or electrochemical in the form of a wide range of battery technologies, and hydrogen produced by electrolysis.

Turbine energy power

The maximum energy that a single turbine can capture when it is set up as an open disk actuator, that is with no shroud and distant from other structures, is limited by the Betz coefficient. This sets an energy conversion limit of 16/27 (about 59%) of the wind or water kinetic energy $\rho A u^3$ available from a fluid of density 'ρ' flowing at a velocity 'u' through an area 'A' equivalent to the cross-sectional area of the turbine rotor. Unenclosed and isolated tidal stream turbines set up in this way achieve 25% to 35% of this energy value. The Betz limit can be exceeded either by enclosing the turbine in a shroud and blade structure or by appropriately distributing turbines in a channel, or by designing more complex TEC devices (R.Vennell, 2013). Tidal power can be evaluated for a local water velocity 'u' as:

$$P = 0.5\rho\, C_p\, u^3 A$$

where power *P*, device swept area A, density of water ρ, turbine power coefficient C_p, and the local water velocity *u*.

A turbine's power coefficient is widely used as a performance indicator, which is taken as the ratio of the electrical energy delivered over a fixed period of time to the corresponding energy extracted from the gas or fluid that flows through it. The power coefficient can be more difficult to evaluate than the turbine efficiency, which is the ratio of the mechanical energy delivered to the turbine rotor shaft compared to the electrical power generated. Whereas a ducted turbine's power coefficient can be measured quite precisely, the power coefficient for an open and isolated tidal stream turbine can be awkward to evaluate because of the indeterminate nature of the stream boundary. In free stream turbines the tidal stream velocity is often used as a surrogate for hydraulic energy and the turbine performance is given as a graph or table of electrical power generated at different water velocities. The turbine power coefficient and resource availability operate together to determine a generator's capacity factor.

Capacity factor is the ratio of the average deliverable power to the maximum rated power that a generator can produce. It depends both on the machine design and its local energy resource environment. The cyclic nature and predictability of tidal power make capacity factor a useful index of the energy that can be generated by tidal energy devices operating in a well characterised tidal resource. It is scalable and can be used to describe a single generator, or groups such as arrays, tidal fences or tidal bridges, or large regional tidal generator farms.

To determine tidal power and capacity factor for a given TEC array, assessments of tidal resource are required. These assessments involve the development of numerical models that are calibrated and validated against field measurements to ensure their accuracy. These assessments include examination of wave-current interaction and influences such as turbulence and shear in the water column.

3. Fieldwork Surveys at Banks and Clarence Straits

Fieldwork was undertaken at two candidate sites to characterize the tidal resources in areas of strong tidal currents. A second objective was to determine if the exceedance of overachieving current fieldwork guidelines provides for better site characterizations. The results from the fieldwork also contributed to the national and regional fine-scale model studies, as calibration and validation data. The sites examined were Banks Strait, Tasmania and Clarence Strait, Northern Territory, as both sites were identified as having promising tidal current[14].

Assessing the tidal stream resource requires a uniform methodology that will ensure consistency and accuracy in the estimation, measurement and analysis at sites that could be suitable for the installation of tidal energy converters. Resource assessments measure and describe the resource (by deriving a velocity distribution for a site), to understand the potential for the power extraction of an array of TECs (by combining the velocity distribution with the power curve of the TECs), and to ensure that the tidal resource available is not over-extracted. It is intended to be applied at various project development stages, from regional assessments to the various stages of specific site assessments (from initial investigations to detailed assessment), and to provide suitably accurate results that can be used to derive 'annual energy production' assessments at the various project development stages. For a Stage 2b or Stage 3 site assessment as detailed in the EMEC guidelines (2009), the following studies are recommended to be completed before a permit is given and technology is developed:

- Seabed – multibeam transects to collect accurate bathymetry of the site; sub-bottom profiling for high-resolution marine sediment imaging; penetrometer casts to describe the surficial seafloor sediments; and bottom grabs for the collection of sediment samples to determine sediment size and type.
- Tidal currents, waves and turbulence – performed using different sets of instruments, Acoustic Doppler Current Profilers (ADCPs, current only), Acoustic Wave And Current profilers (AWACs, both wave and currents) and high-resolution velocity current profilers (AD2CPs, current, wave and turbulence), in order to determine the water column flow properties including tidal range, tidal current velocity, and turbulence; wave climate including wave height, wave direction and period; wave-current interaction; and general met-ocean observations.
- Water column properties – baseline information including water column temperature, salinity, conductivity and turbidity, sediment concentration as well as optically derived biological and nutrient information including dissolved oxygen, coloured dissolved organic matter, fluorescence and photosynthetically available radiation.
- Environmental assessment – a detailed literature review on the biotope and habitat mapping (bird and fish species, mammals, seafloor substrate etc.).

The field campaign studies were performed in Banks Strait, Tasmania in 4 different campaigns over 11 months from March 2018 to February 2019, and in Clarence Strait, Northern Territory in 3 different campaigns over 9 months from May 2019 to January 2020 as outlined in Table 3. The different field activities in the campaigns are highlighted in Table 4. For both field campaigns, the following standards / guidelines were followed:

- International Electrical Commission Technical Specification 62600-201 Technical Specification, Marine energy – Wave, tidal and other water current converters – Part 201: Tidal energy resource assessment and characterization.
- European Marine Energy Centre Assessment of Tidal Energy Resource, Marine Renewable Energy Guides.

[14] Penesis, I., et al., (2018). Tidal energy in Australia–Assessing resource and feasibility to Australia's future energy mix. AWTEC 2018 Proceedings, p. 507.

Table 3: Dates, vessels, crew members and passengers on campaigns for Banks and Clarence Strait field campaigns

Campaign number	Dates	Number of days	Vessel	Number of crew members	Number of scientists
Banks-1	13-3-2018 to 29-3-2018	17	AMC FTV Bluefin	5	10
Banks-2	9-7-2018 to 13-7-2018	5	Moortech Soul Commitment	3	4
Banks-3	6-12-2018 to 12-12-2018	7	Dell Richey II	4	6
Banks-4	15-2-2019 to 16-2-2019	2	Dell Richey II	4	3
Clarence-1	21-5-2019 to 27-5-2019	7	Bhagwan Marine Lauri J	5	8
Clarence-2	18-9-2019 to 22-9-2019	5	Bhagwan Marine Bhagwan K	4	4
Clarence-3	4-1-2020 to 6-1-2020	3	Bhagwan Marine Lauri J	5	4

Table 4: Field activities at the different promising sites

Activity	Measurement/ Collection	Type	Banks Strait				Clarence Strait		
			1	2	3	4	1	2	3
Multi-beam	Bathymetry	Transects	✓				✓		
Sub-bottom profiler	High-resolution marine sediment imaging	Transects			✓				✓
ADCP moorings	Currents / Waves/ Turbulence	Deployments	✓	✓	✓		✓	✓	
		Retrievals	✓	✓	✓	✓		✓	✓
Temperature mooring	Temperature	Deployments	✓	✓			✓	✓	
		Retrievals		✓	✓			✓	✓
CTD Casts	Conductivity, Temperature, Depth, Turbidity	Cast	✓	✓	✓	✓	✓	✓	✓
Rosette casts	Water samples, Conductivity, Temperature, Depth, Turbidity, Dissolved Oxygen	Casts	✓						
Water sampling	Water samples	Sampling			✓		✓		
Core sampling	Sediment chores	Sampling	✓						
Penetrometer	Surficial seafloor sediments	Cast	✓	✓	✓		✓		
Optical Laser diffraction instruments (LISST)	Sediment flux	Casts	✓	✓	✓				
Bottom Grab sampling	Sediment samples	Sampling			✓		✓		
Camera footage	Pictures and videos	-	✓	✓	✓	✓	✓	✓	✓
Drone footage	Pictures and videos	-	✓						
ROV operation	Retrieve moorings stranded in sand	-			✓				

Data Availability

The data collected as part of these field campaigns are available on the Integrated Marine Observing System Australian Ocean Data Network (AODN) data repositories database, with the bathymetric surveys uploaded to Geoscience Australia's Aus-seabed database to improve the national bathymetry dataset.

Integrated Marine Observing System AODN Link: https://portal.aodn.org.au/

Geoscience Australia Aus-Seabed Link: http://www.ausseabed.gov.au/

Banks Strait Site Characterization

The Banks Strait is located at the North-East of Tasmania as shown in Figure 2 and forms the channel between Swan Island and Clarke Island. The Banks Strait connects the Bass Strait with the Tasman Sea, and is characterized by strong currents due to the significant difference in tidal phase between the Bass Strait and the Tasman Sea with a semi-diurnal tidal cycle. Along with its proximity to an existing power grid in the north-east of Tasmania, the Banks Strait offers potentially advantageous conditions for the installation, generation and transmission of electricity generated by tidal energy converters (TEC). While sporadic bathymetry surveys by the Australian Navy indicate depths between 25 – 60 m, before this project no accurate high-resolution seabed elevation and composition data existed for the Banks Strait.

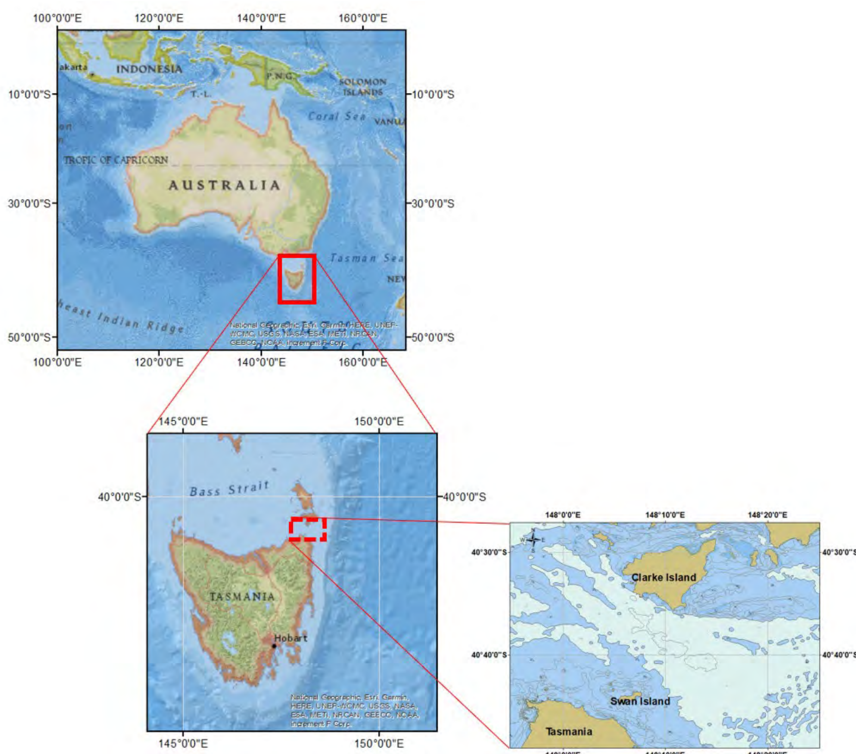

Figure 2: Map of North East of Tasmania and part of the Furneaux Group (Image credits: AHS map 441147 and 441148)

Seabed Characterisation

Bathymetry

The bathymetry survey covered an area of approximately 210 km^2 (Figure 3) with depths ranging from 10 m to depths exceeding 60 m. Based on the bathymetry the area between Clarke Island and Swan Island can be classified into three zones:

- A plateau with relatively consistent depths between 30 m to 40 m towards the southwest (near Swan Island);
- A deeper channel in the middle of Banks Strait with depths between 50 m and often exceeding 60 m; and
- Another plateau to northeast around Clarke Island with depths between 30 m to 40 m.

The seafloor around Clarke Island is more complex featuring a rugged structure and sand-waves with dune heights of 8 m, apparent glacial north-east to south-west gouge marks.

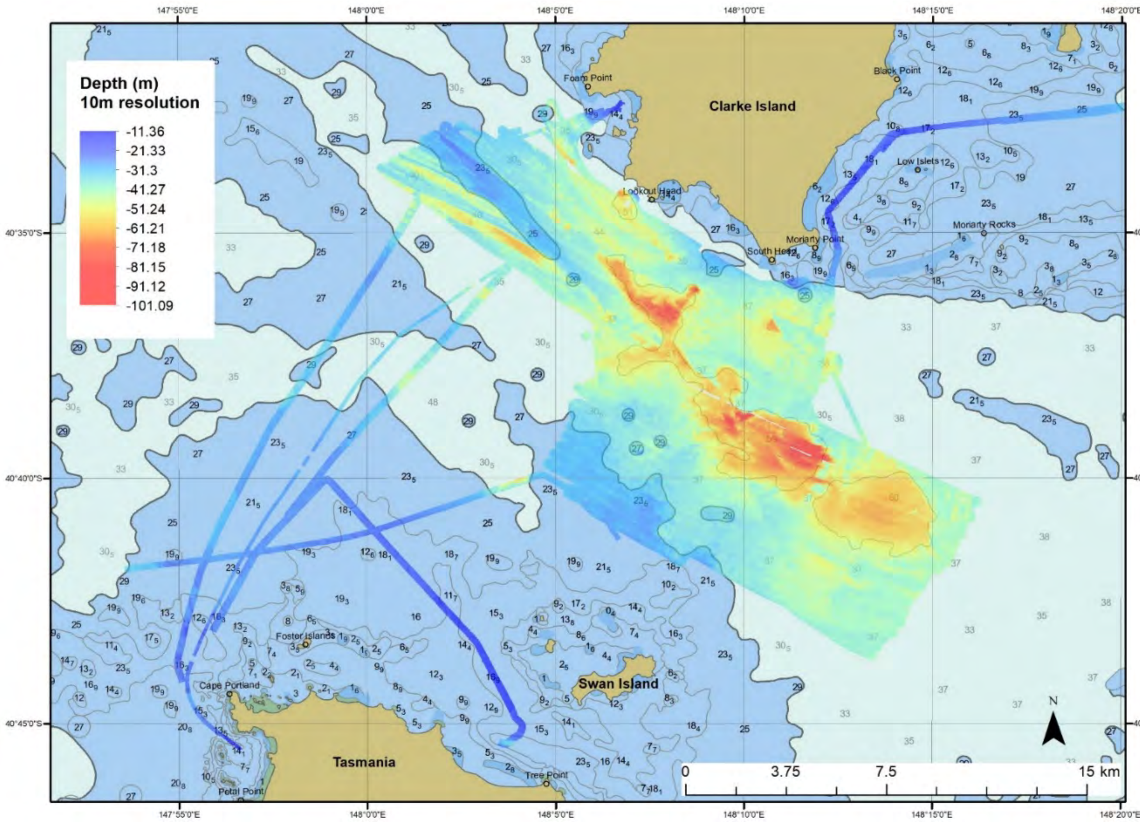

Figure 3: Overview of collected bathymetry superimposed with navigational chart

Sub-Bottom Data

Most of the sub-bottom data determined that the seafloor in Banks Strait is largely homogenous rock or reef. However, there is a region near the South-East corner of Clarke Island, between South Head and Moriarty Point where sand overlaying rock/reef was determined with a sand layer cover up to 7 m measured, and likely much thicker (Figure 4).

Penetrometer

The analysis of the seafloor is further corroborated by surficial sediment data from penetrometer drops which exhibit characteristics for non-cohesive sediments. The majority of penetration depths range between 0.01 and 0.05 cm which is typical in coastal areas dominated by bedrock. However, several drops revealed penetration depths (> 0.1 m) and were likely carried out over softer sandy patches. Generally, the substrate in the area is homogeneous consisting of hard substrate, typically rock and reef structures with some sandy areas located in the region near Clarke Island and some areas in the southwest of the survey area in Banks Strait towards Swan Island.

Bottom Grab

A similar result was obtained by sediment samples taken with a bottom grab within the bathymetry surveys. Failure to retrieve any sediment usually indicates a hard substrate and areas previously classified as sandy patches confirmed sand was the dominant fraction consisting mainly of coarse and very coarse sand. The bottom grab survey was extended to areas where no bathymetry information was available, mainly in shallower areas with depths < 30 m towards Swan Island and mainland Tasmania. Similar to the results obtained from the sandy areas near Clarke Island mostly coarse sand was discovered.

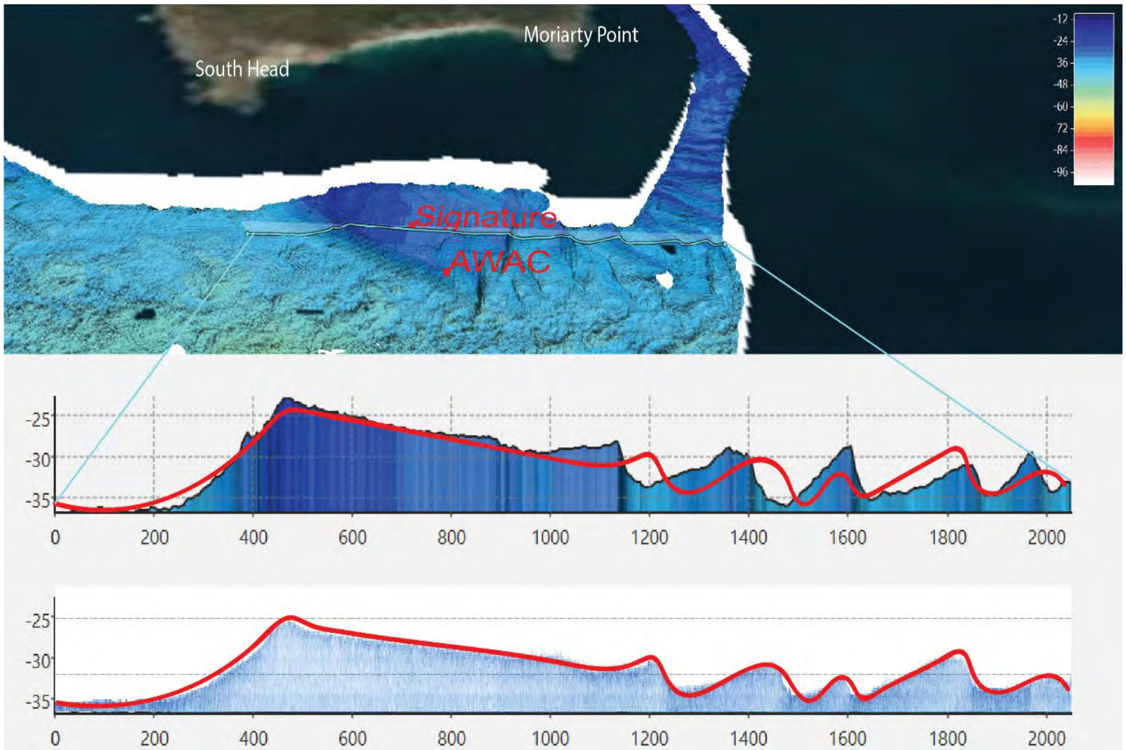

Figure 4: The sub-bottom profile from South-East Clarke Island in December 2018 (bottom) versus the previous multibeam profile (top) from March 2018

LISST

In order to understand the sediment transport regime, LISST profiles were undertaken at various locations and tide conditions. Most of the data reveal particle sizes ranging from 80 µm to 150 µm in the water column. Though the LISST casts are indicative of an active transport regime, it is unclear whether the sediment is eroded or deposited in Banks Strait, especially in the highly exposed centre of the channel. The hard substrate that was dominant in these regions suggests that the sediment does not originate or remain in the system.

On the other hand, a comparison between sand dunes in March and December show a distinct migration pattern of the dunes (Figure 4) indicative of a dynamic sediment transport regime.

From the data collected it can be concluded that Banks Straits exhibits an active sediment regime in all areas with sand cover which limits it to regions around Clarke Island and shallower regions near Swan Island.

Waves, Tidal Currents and Turbulence Characterisation

A total of 9 frames were deployed during the first campaign in March 2018, 4 in July 2018, and 2 in December 2019. The ADCPs on these moorings were set to collect Currents, Waves, and/or Turbulence (Figure 5).

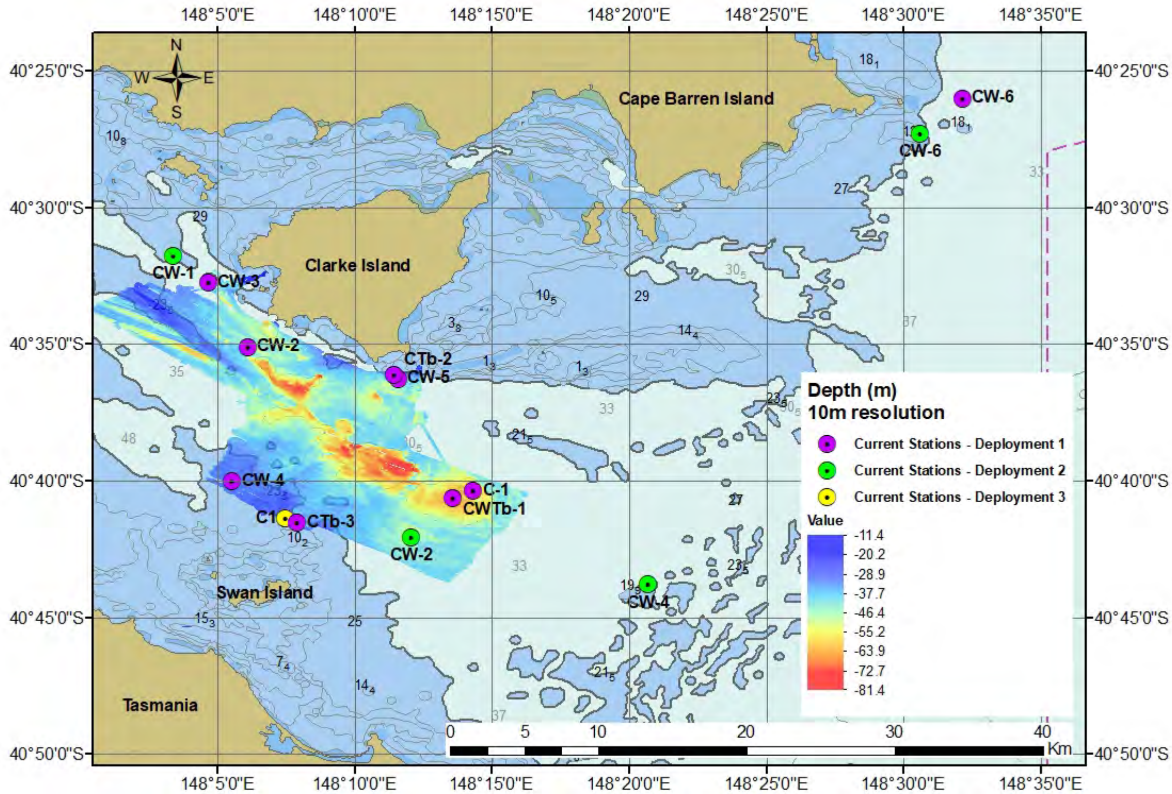

Figure 5: Map of all the ADCP stations measuring Currents deployed in Banks Strait from March 2018 -February 2019

For consistency, in the following the naming convention for the stations is "[measurement types][Station Number]_[Site][Deployment number]":

- [measurement types]: C for current measurement, W for wave measurement and Tb for turbulence measurement;
- [Station Number]: 1 to 6;
- [Site]: A for Banks Strait and B for Clarence Strait;
- [Deployment number]: 1 to 3.

CW4-A1 relates to station 4 which measured both current and wave in Banks Strait and in deployment 1.

Currents

For each station successful deployment, the data was processed to derived tidal range, current magnitude in the water column, current direction and vertical velocity profiles for flood and ebb. An example is presented in Figure 6 for the station CW4, deployment 1, for the month of March 2018.

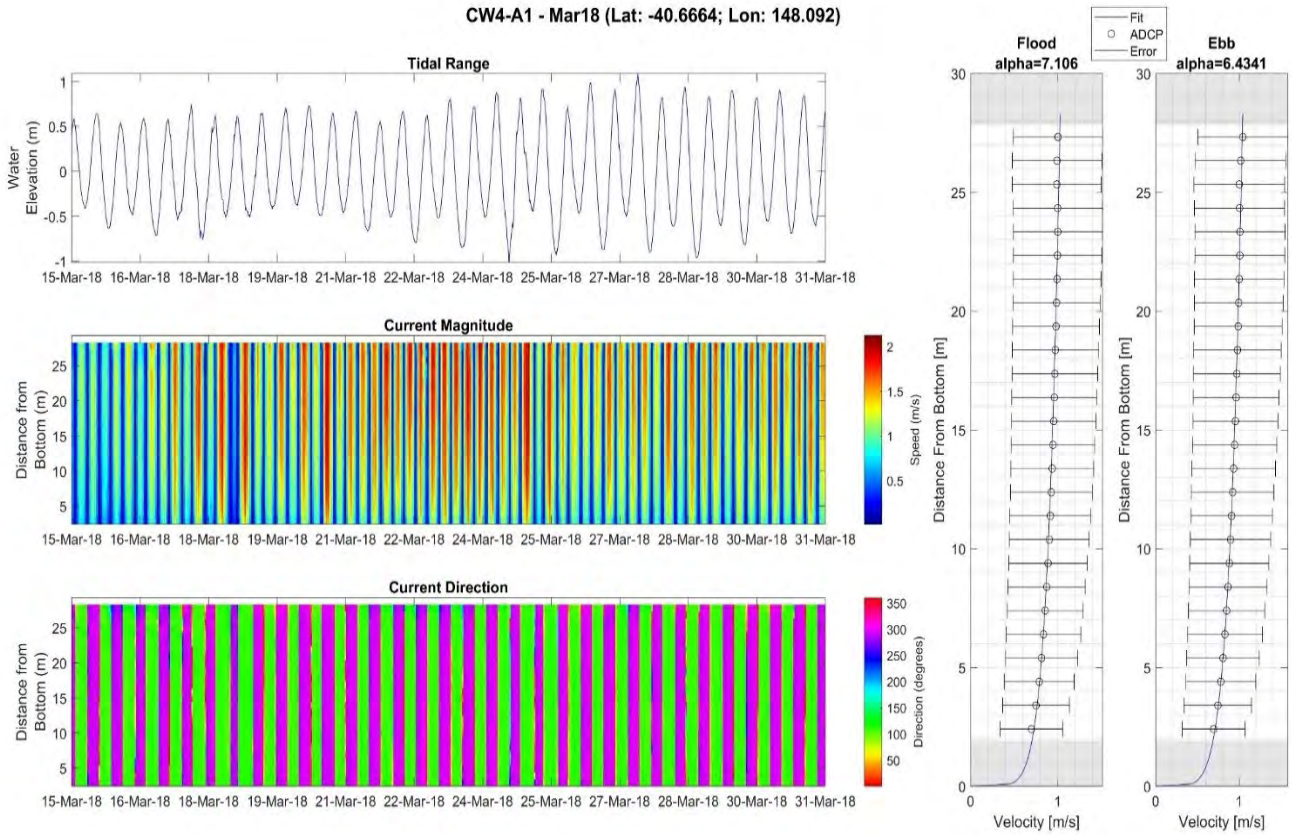

Figure 6: Tidal Range, Current Magnitude, Current Direction and Vertical Plots for Flood and Ebb for Station CW4-A1, for the month of March 2018

For analysis purposes the channel was divided in 4 sub-areas and results will be presented referring to them as:

- The Clarke Island Area, with 3 ADCP deployments covering March to September 2019;
- The Centre of the Channel, with 4 ADCP deployments covering March to September 2018;
- The Swan Island Area, with 2 ADCP deployments covering March to June 2018 and December 2018 to February 2019; and
- The Cape Barren Area, with 2 ADCP deployments covering April to October 2018.

Table 5 shows the statistics for all current data measured in the Banks Strait. These values correspond to the entire period of good data measured by each ADCP.

Table 5: Statistics of ADCP Current Data over the full measurement period

Area	Station	Sensor	Depth (m)	Dates of data collected (UTC)	Tide	Velocity			Directionality	
						Mean Speed (m/s)	Maximum Speed (m/s)	Standard Deviation (cm/s)	Principle Axis (°)	Ebb/Flood Asymmetry (°)
Clarke Island Area	CW1-A2	RDI Sentinel V50, 500kHz	31.6	12/07/2018	Flood	0.5578	1.4594	3.6406	306.9678	182.9608
				6/09/2018	Ebb	0.5423	1.5242	3.5975	124.007	
	CW3-A1	Nortek AWAC, 1MHz	33	22/03/2018	Flood	0.6964	1.8594	5.3106	314.36	163.7734
				16/06/2018	Ebb	0.6154	1.5988	3.9682	160.5866	
	CW2-A1	RDI Sentinel V50, 500kHz	43.8	22/03/2018	Flood	0.7981	2.156	5.4757	306.9178	173.8113
				11/07/2018	Ebb	0.8289	2.1534	6.0091	133.1065	
Centre of the Channel	CW2-A2	RDI Sentinel V50, 500kHz	44	12/07/2018	Flood	0.5208	1.9392	2.7297	311.0073	165.4651
				22/09/2018	Ebb	0.6202	1.7553	3.366	145.5422	
	CWTb1-A1	Nortek Signature 500kHz	58	22/03/2018	Flood	0.5046	1.4179	3.0391	277.7656	158.2389
				9/07/2018	Ebb	0.6615	1.8588	5.5788	119.5267	
	C1-A1	RDI Workhorse 300kHz	56	17/03/2018	Flood	0.5063	1.3948	2.7204	270.265	153.4271
				10/07/2018	Ebb	0.6136	1.9601	3.0133	116.8379	
	CW4-A2	Nortek AWAC, 1MHz	35.8	12/07/2018	Flood	0.4423	1.0665	2.557	280.6858	167.6142
				8/09/2018	Ebb	0.5016	1.2796	1.9462	113.0716	
Swan Island Area	CW4-A1	Nortek AWAC, 1MHz	30	15/03/2018	Flood	0.9015	2.2316	5.0649	284.7868	163.8331
				9/06/2018	Ebb	0.89851	2.1892	5.4665	120.9537	
	C1-A3	RDI Workhorse 300kHz	26.8	5/12/2018	Flood	0.9947	2.3036	3.5304	292.4452	191.1148
				15/02/2019	Ebb	0.8759	2.262	4.1368	101.3304	
Cape Barren Area	CW6-A1	Nortek AWAC, 1MHz	36.8	24/04/2018 – 13/07/2018	All	0.3226	1.3645	2.9752	-	-
	CW6-A2	Nortek AWAC, 1MHz	30.9	13/07/2018 – 6/10/2018	All	0.3536	1.2118	2.6415	-	-

The highest currents speeds are in three main areas:

- 4 to 7 km north of Swan Island, around 40° 40' 30.87'' S; 148° 6' 29.46'' E, with a maximum current speed of 2.3 m/s, mean speeds of 0.9 m/s and Ebb/Flood asymmetry ranging 164.1° to 191.4° (stations CW4_A1 and C1_A3);
- 2.2 km southwest of Clarke Island's Lookout Head, at 40° 35' 5.136'' S, 148° 6' 6.767'' E, with a maximum current speed of 2.15 m/s, mean speeds of 0.8 m/s and Ebb/Flood asymmetry of 173.9° (station CW2_A1);
- In the Deep pocket of the Centre of the Channel, 8 km northeast of Swan Island and 9 km southeast of Clarke island, around 40° 41' 6.52'' S; 148° 12' 55.74'' E, with a maximum speed of 1.96 m/s, mean speeds of 0.55 m/s and Ebb/Flood asymmetry of 160.7 (stations C1_A1, CWTb1_A1 and CW2_A2).

The Cape Barren area is outside of the Banks Strait and therefore has very different Current Speed tendencies. In this area the maximum speed was 1.36 m/s, measured in July 2018. Over the entire period of measurement, the maximum current speeds were 1.15 m/s in average and the mean speeds were 0.32 m/s in average.

Figure 7 summarises the general trends of the currents in the Banks Strait, extracted from ADCP measurements from March to September 2018, and from December 2018 to February 2019 and shows the three higher flow areas in the channel.

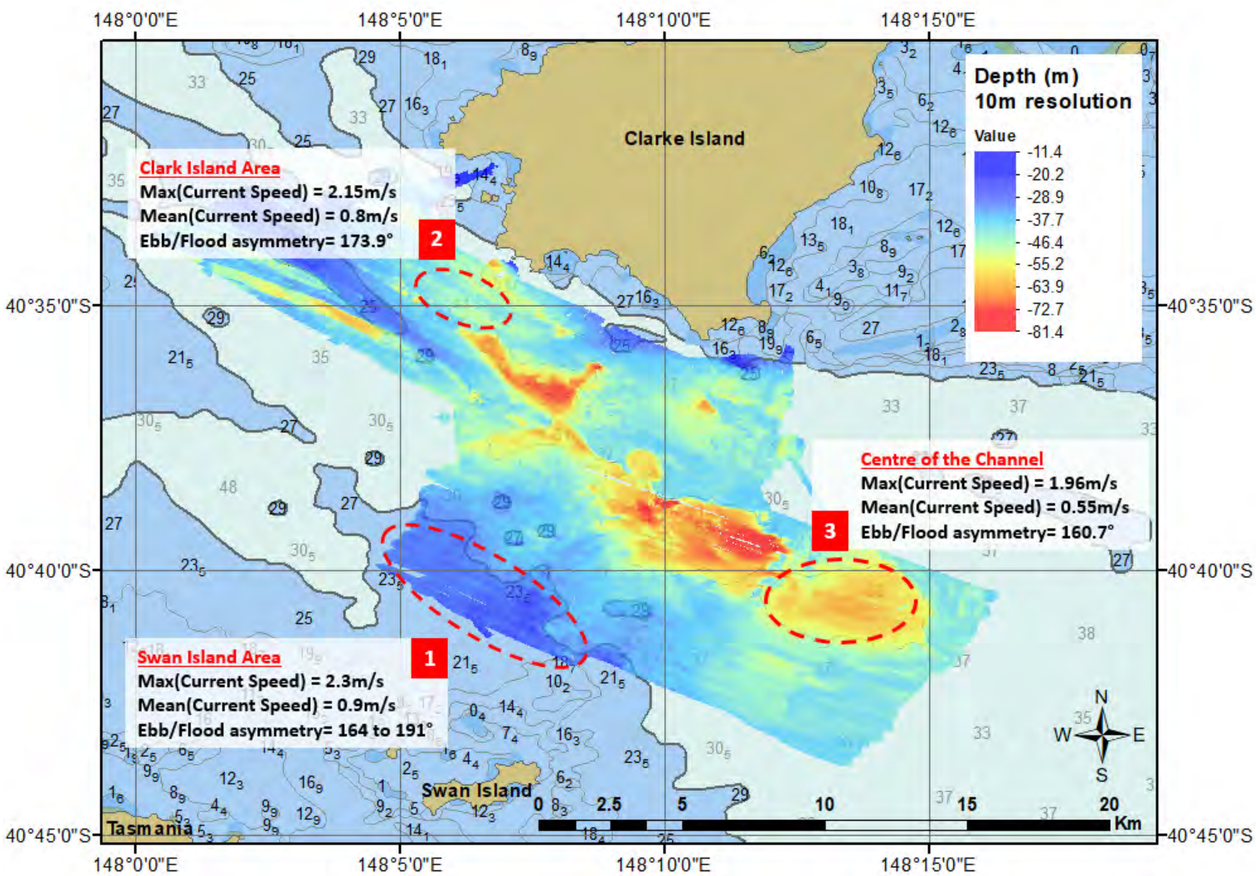

Figure 7: Summary of the Current trends in the Banks Strait from measurements taken from March to September 2018, and from December 2018 to February 2019. This figure shows the three areas with highest current speeds in the channel

Wave

Five waves stations were deployed in March 2018 (Deployment 1) and 3 were deployed in July 2018 (Deployment 2). See map in Figure 8. The station CW5 deployed in March 2018 was not retrieved, so only seven wave data sets are presented in this report.

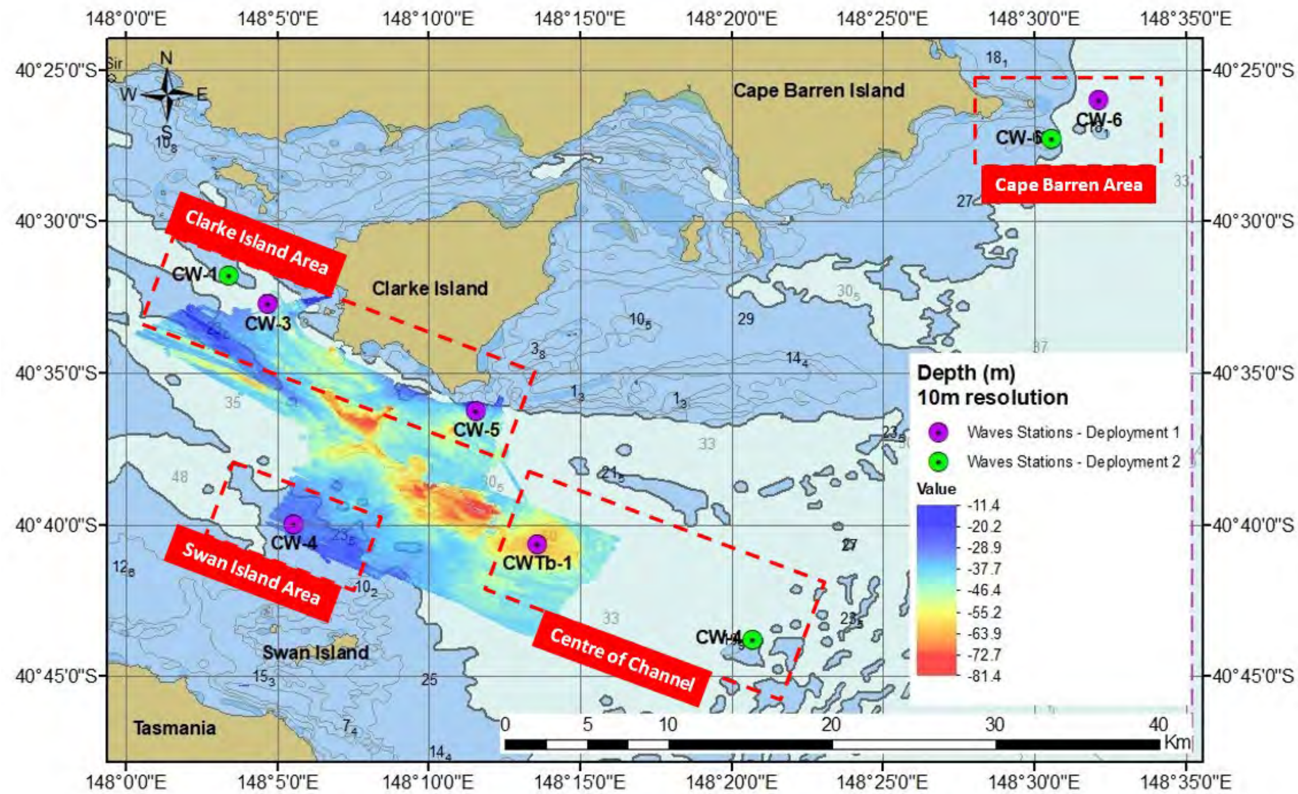

Figure 8: Map of all the ADCP stations measuring Waves deployed in the Banks Strait from March to October 2018

For each station, significant wave height, mean period, peak period, mean direction, peak direction, wave rose and power distribution were derived. An example of wave rose and power distribution for CWTb1 deployment 1 is presented in Figure 9 and Figure 10.

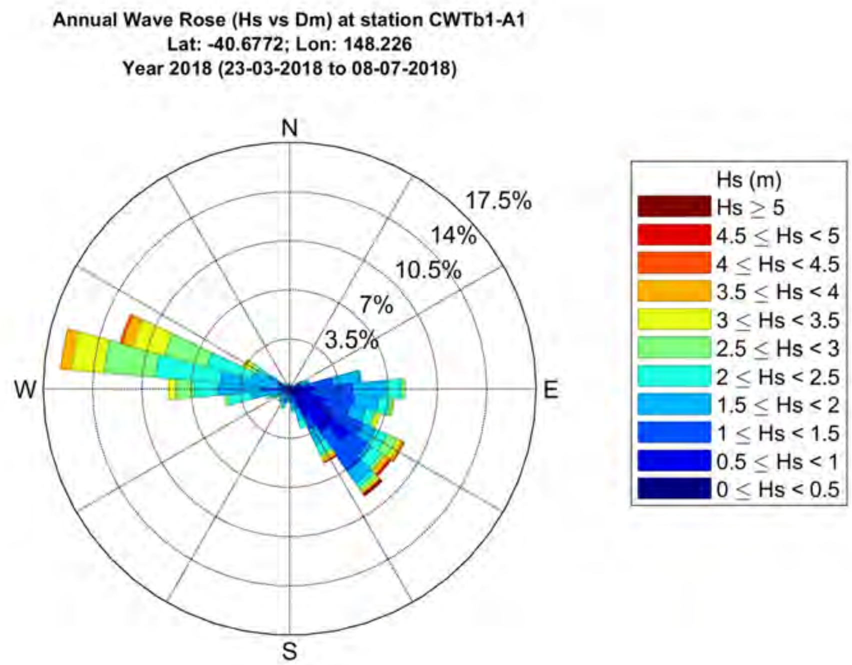

Figure 9: Annual Wave Rose at Station CWTb1, Deployment 1, from 23-3-2018 to 8-7-5-2018

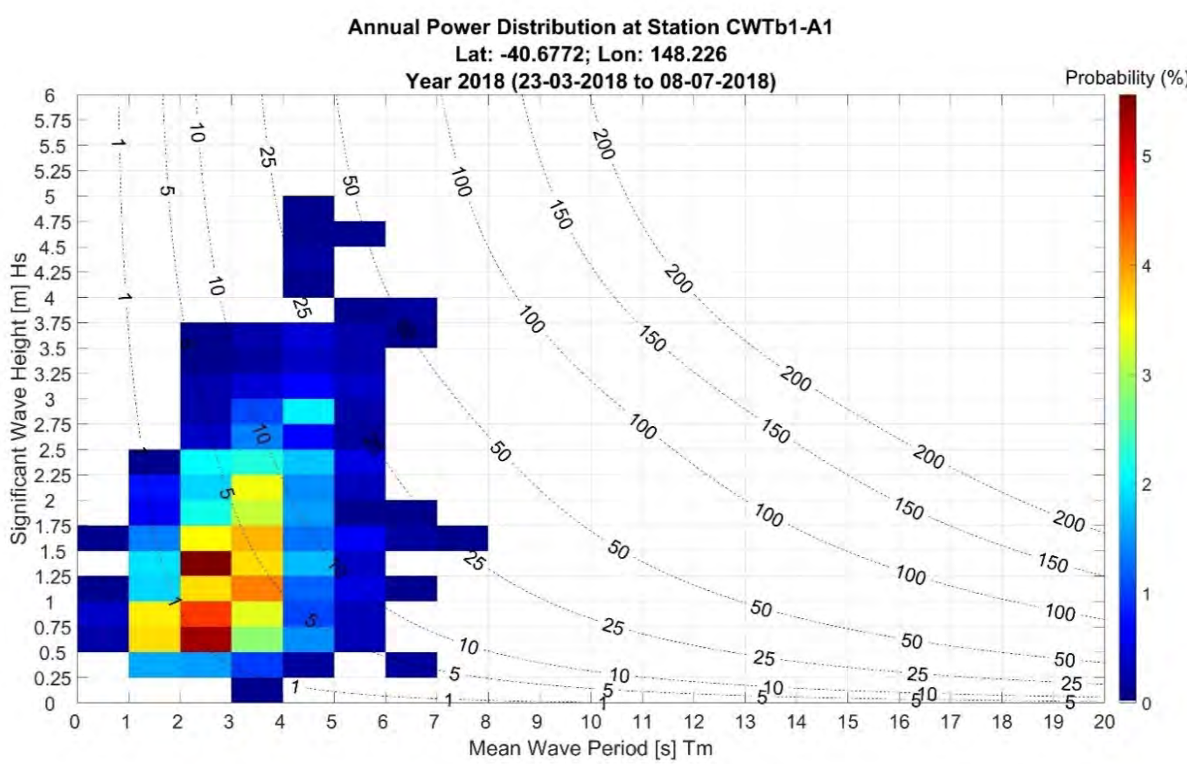

Figure 10: Annual Power Distribution at Station CWTb1, Deployment 1, from 23-3-2018 to 8-7-5-2018

Table 6 shows the minimum, maximum and average values of the Significant Wave Height Hm0, Mean Zero crossing period Tz, Mean Period Tm, Peak Direction, Peak Spread, Temperature and Power density at the seven ADCP stations that were measuring waves in the Banks Strait, from March to October 2018.

Table 6: Statistics of ADCP Wave Data over the full measurement periods

Area		**Clarke Island Area**		**Centre of the Channel**		**Swan Island Area**	**Cape Barren Area**	
Station		CW3-A1	CW1-A2	CWTb1-A1	CW4-A2	CW4-A1	CW6-A1	CW6-A2
Sensor		Nortek AWAC, 1MHz	RDI Sentinel V50, 500kHz	Nortek Signature 500kHz	Nortek AWAC, 1MHz	Nortek AWAC, 1MHz	Nortek AWAC, 1MHz	Nortek AWAC, 1MHz
Depth		33	31.6	58	35.8	30	36.8	30.9
Dates of data collected (UTC)	**Start**	22/03/2018	12/07/2018	23/03/2018	12/07/2018	15/03/2018	24/04/2018	13/07/2018
	end	19/05/2018	5/09/2018	8/07/2018	22/08/2018	10/05/2018	13/07/2018	6/10/2018
Hm0 [m]	**Min**	0.2	0.18	0.49	0.41	0.04	0.53	0.48
	Max	4.46	6.13	5.17	3.06	5.26	6.83	4.4
	Mean	1.25	1.06	1.76	1.38	1.45	1.37	1.23
Tz [s]	**Min**	-	-	3.47	-	-	3.57	3.17
	Max	-	-	8.79	-	-	9.68	8.55
	Mean	-	-	5.76	-	-	5.41	5.07
Tm [s]	**Min**	4.8	7	1.49	5.11	4.49	3.18	2.74
	Max	9.6	13.3	8.03	9.4	9.64	9.06	8.26
	Mean	6.33	8.96	4.12	6.55	6.21	5.07	4.72
Peak Direction [°]	**Min**	52.42	-	2.17	2.66	1.1	0.46	0.09
	Max	342.33	-	355.67	359.44	358.56	359.94	359.63
	Mean	258.04	-	203.14	200.38	238.75	133.9	124.75
Peak Spread [°]	**Min**	21.12	-	16.57	14.45	25.44	27.02	30.47
	Max	92.74	-	79.9	94.47	94.71	94.78	95.04
	Mean	52.23	-	41.85	47.58	52.98	49.63	54.24
Temperature [°C]	**Min**	14.64	-	12.81	11.21	15.32	11.99	11.06
	Max	19.38	-	18.97	13.38	19.59	16.72	12.7
	Mean	17.11	-	15.61	12.1	17.06	14.35	11.98
Power [kW/m2]	**Min**	0.32	-	0.7	1.22	0.02	1.26	0.85
	Max	143.62	-	151.43	62.16	200.66	406.81	148.19
	Mean	15.82	-	16.61	14.06	19.64	12.72	6.34

The wave climate in Banks Strait is quite energetic with an average significant wave height of around 1.4 m and average mean period of 6.4 s. There are 2 main seas WNW and SE with WNW sea tending to be slightly more energetic. The relatively small mean period is representative of wind seas. Furthermore, strong wave-current interactions were experienced in Banks Strait. Such data are of great importance for companies seeking to deploy tidal devices in this location so as to evaluate fatigue level on the devices as well as installation and maintenance time windows and costs.

Figure 11 is a map that summarises the major trends of the waves in the Banks Strait from measurements taken between March and October 2018.

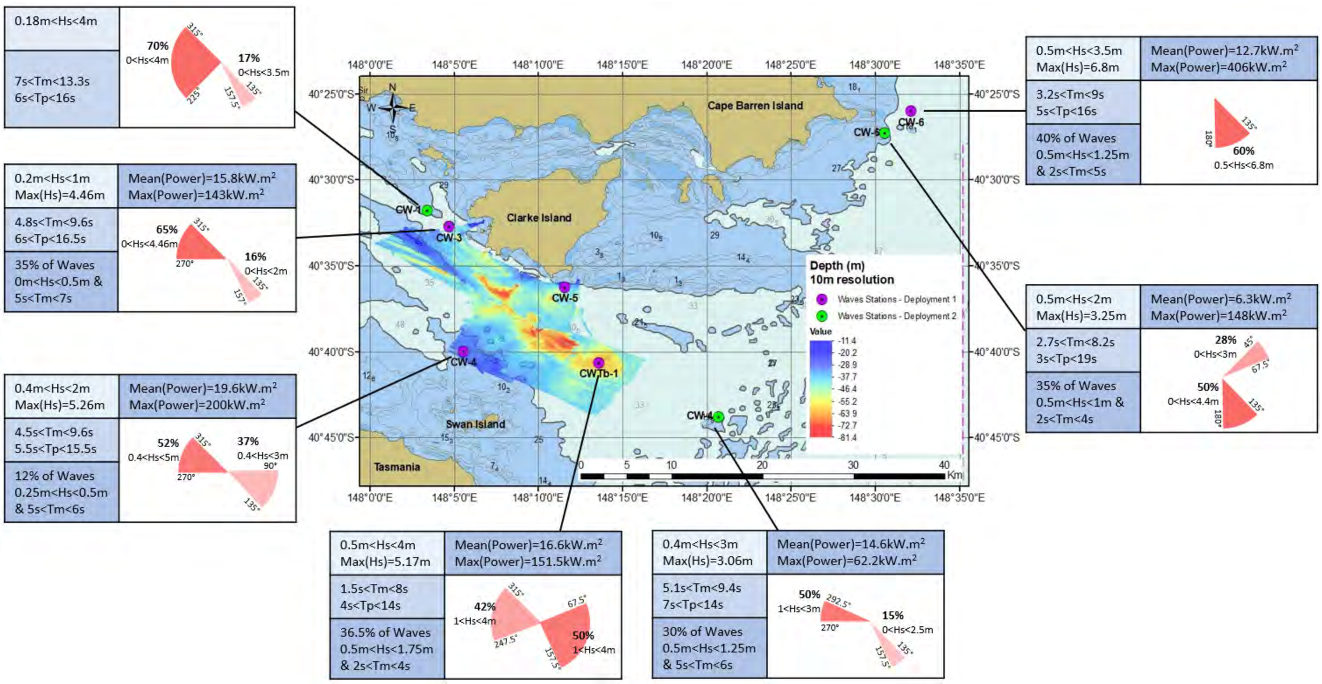

Figure 11: Summary of wave measurements in the Banks Strait, March 2018 to October 2018. Note that wave directions follow the standard "coming from"

Turbulence

Observation of processed turbulence data has demonstrated the strong wave-current interaction throughout the water column at both measurement stations. That is confirmed by the comparison to wave data collected by CWTb1 and CW4 (see Figure 5 for location). Therefore, in order to avoid overestimation of values, estimation of turbulence parameters has required prior wave-turbulence decomposition techniques to be applied to beam velocity signals.

Streamwise turbulence intensities estimated from measurements of instrument CTb3 vary mostly between 13 and 19% as seen in Table 7, with higher values happening during flood tide, when average velocities were slightly lower. Total turbulent kinetic energy was estimated from instrument CTb3. Total TKE routinely reaches 0.02 m^2s^2 during fully developed tides, with maximums reaching approximately 0.04 m^2s^2. As expected, higher results were found during ebb tides, when currents were stronger. Reynolds stresses tend to be very proximate to zero, with sudden increases during fully developed tide, when average velocities are higher.

Since instrument CWTb1 was measuring turbulence strictly with its vertical beam, streamwise parameters could not be estimated. Vertical TKE reach a maximum of approximately 0.0045 m^2s^2 and vary mostly around 0.002 m^2s^2. Similarly to instrument CTb3, higher values are commonly observed during ebb tide.

Table 7: Average streamwise turbulence intensities for ebb and floods tides from selected periods in each month from instrument CTb3 measured 15 m above the bottom

Month	Tide	Ebb (%)	Flood (%)
March	Neap	-	-
	Spring	12.69	16.01
April	Neap	18.35	23.64
	Spring	13.50	16.68
May	Neap	13.98	16.77
	Spring	11.63	13.61
Jun	Neap	13.15	15.23
	Spring	13.46	16.72
Jul	Neap	11.83	15.25
	Spring	-	-

Water Column Properties

Conductivity, Temperature and Depth (CTD)

Figure 12 shows the location of of all RBR Concerto CTD casts taken in Banks Strait where Table 13 returns the monthly statistics for each of the five sub-areas in the Banks Strait. Areas and time periods for which there is no data are greyed out.

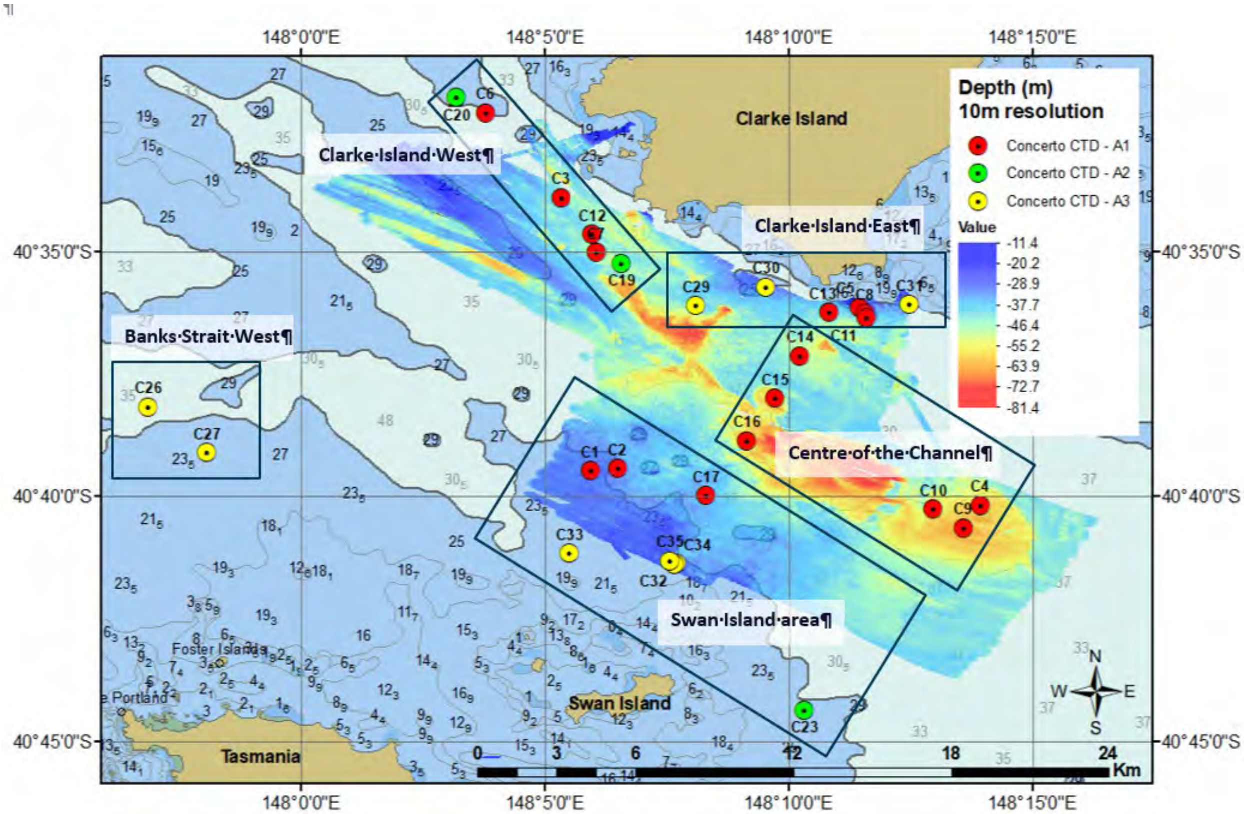

Figure 12: Map of all RBR Concerto CTD casts taken at Banks Strait and the five sub-areas chosen for this report

Table 8: Monthly statistics of casts taken with the RBR Concerto CTD, organised by area.

Date (UTC)		Mar-18			Jul-18			Dec-18		
Parameter		Temperature (°C)	Salinity (PSU)	Turbidity (NTU)	Temperature (°C)	Salinity (PSU)	Turbidity (NTU)	Temperature (°C)	Salinity (PSU)	Turbidity (NTU)
Clarke Island West Area	min	18.52	35.59	3.23	12.26	35.77	3.23			
	mean	18.85	35.63	3.39	12.5	35.79	3.28			
	max	19.7	35.65	3.64	12.75	35.8	3.37			
Clarke Island East Area	min	18.13	35.59	3.3				16.35	35.49	3.21
	mean	18.63	35.68	3.43				16.55	35.5	3.25
	max	19.42	35.83	3.72				16.67	35.52	3.35
Centre of the Channel	min	18.32	35.55	3.25						
	mean	18.71	35.67	3.47						
	max	19.64	35.76	3.87						
Swan Island Area	min	18.26	35.6	3.27	12.53	35.48	3.23	16.5	35.41	3.24
	mean	18.97	35.67	3.35	12.53	35.49	3.26	16.54	35.43	3.29
	max	19.47	35.77	3.86	12.54	35.5	3.34	16.58	35.44	3.44
Banks Strait	min							16.6	35.42	3.24
	mean							16.63	35.42	3.29
	max							16.65	35.42	3.38

Overall, the water column appears very well mixed in all the sub-areas of the Banks Strait. There is very minimal variation of temperature, salinity and turbidity between sub-areas which is as expected for an area with a strong current.

Within this small variation and within each season, Clarke Island West and Banks Strait West present the highest temperatures, and Clarke Island East present the lowest temperatures. The salinity ranges between 35.42 and 35.80; the turbidity ranges from 3.21 NTU to 3.87 NTU, this maximum being reached in the centre of the cross transect between Swan island and Clarke Island.

Temperature Station

The comparison of the temperature station data measured with sensors spaced 5 m along the water column showed that at Clarke Island’s Lookout Head (40° 34' 14.231'' S; 148° 7' 1.776'' E), the temperature does not vary considerably with depth correlating the results from the CTD casts around Banks Strait. During the 5 months of measurement (March to July 2018). The temperature decreased from 19.6° C to 12.2° C. In average, the temperature decreases between 1 and 1.5° C every month.

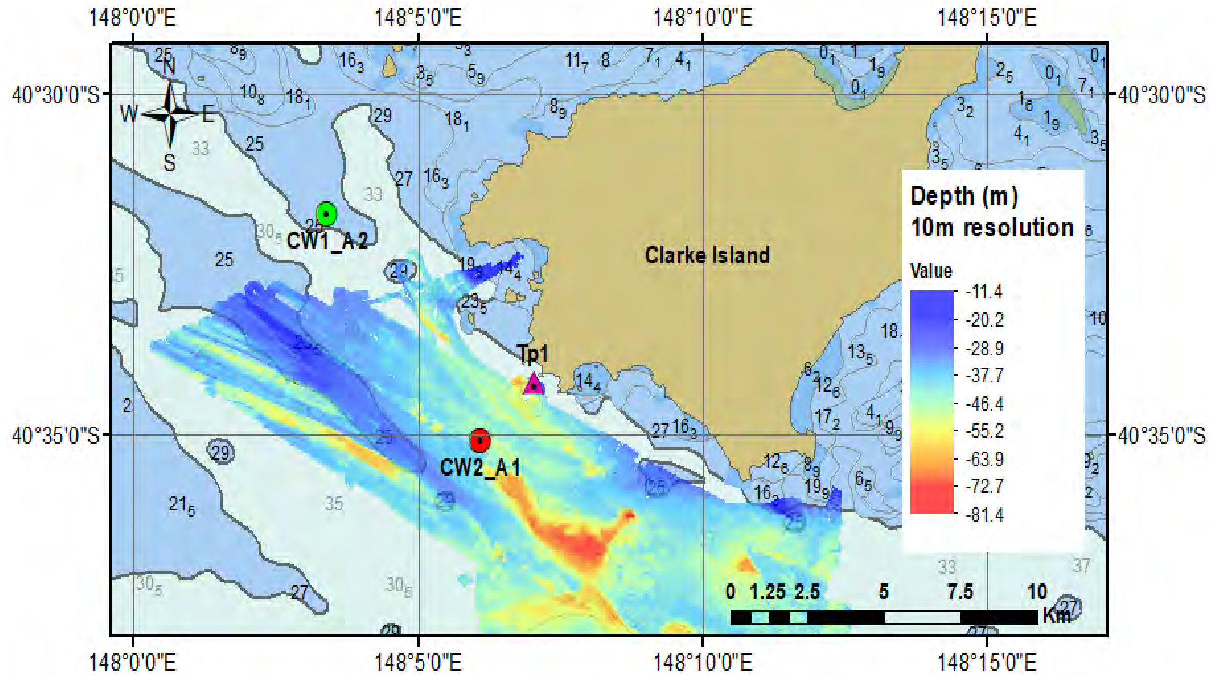

Figure 13: Map with the Temperature Station Tp1 and the two ADCP stations deployed nearby, CW2_A1 and CW1_A2

The data from Tp1 was compared with data from the ADCP temperature sensors deployed 2 km southwest of Tp1 from March to July 2018 (CW2_A1) and 7 km northwest of Tp1 from July to August 2018 (CW1_A2). See map of these three stations in Figure 13.

These three sources showed a similar trend with only a difference of 0.5° C between the ADCPs and the Temperature station, Tp1 being slightly lower overall which is attributed to the distance between the sources (see Figure 14).

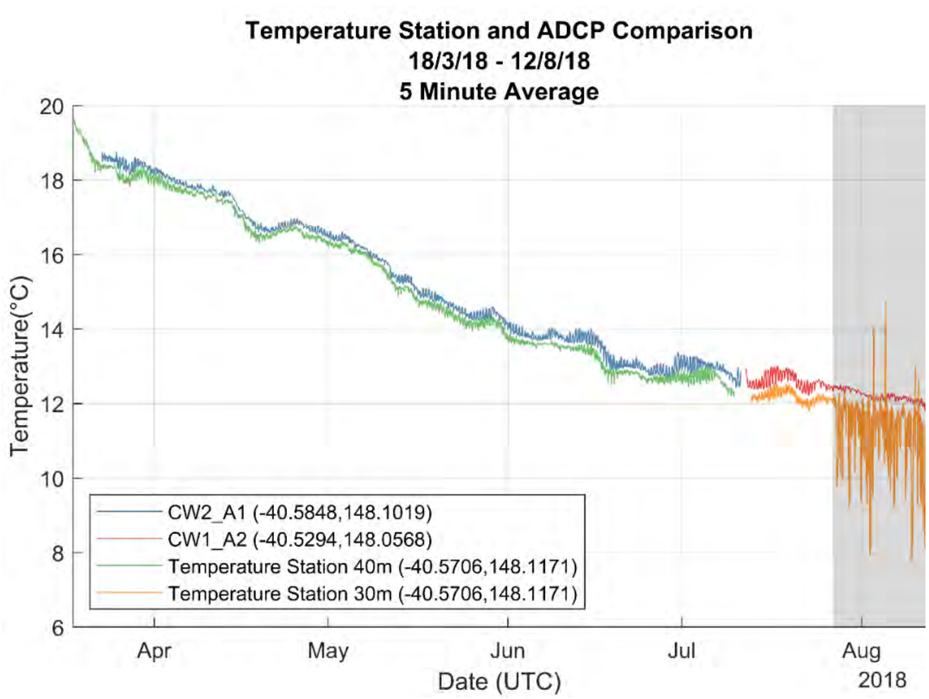

Figure 14: Comparison of the water column average temperature from Tp1 (green and orange lines) with data from two ADCPs' temperature sensors: stations CW2_A1 (blue line) and CW1_A2 (red line) from March 2018 to August 2018

Biological and Nutrient Information

The Seabird Rosette carousel was used for casts during the March 2018 field campaign in the Banks Strait. This rosette was equipped with 5 sensors that measured temperature, conductivity and nitrogen saturation, as well as optically derived biological and nutrient information including dissolved oxygen, coloured dissolved organic matter (CDOM), chlorophyll α fluorescence, and photosynthetically available radiation (PAR) (Table 9).

Table 9: Sensors included on Rosette casts.

Sensor	Property measured	Purpose of measurement	Sampling rate	Units
CTD	Temperature	Determine temperature profile of water column.	2 Hz	°C
CTD	Conductivity	Measured to determine salinity.	2 Hz	S/m
ECO triplet	Coloured dissolved organic matter (CDOM) fluorescence	Proxy for dissolved organic carbon and indicates the availability of organic matter for biogeochemical processes.	4 Hz	mg/m^3
ECO triplet	Chlorophyll-a (chl α) fluorescence	Measures fluorescence of chlorophyll-a pigments in phytoplankton to indicate phytoplankton biomass.	4 Hz	mg/m^3
SUNA V2	Included on instrument but not operational. Theoretical limit of nitrogen saturation is given instead.	Theoretical saturation limit of nitrate in water given measured temperature and salinity. Nitrate is an essential component in the ocean's biogeochemical cycle.	N/A	ml/L
Seabird SBE 63 Optical DO	Dissolved oxygen (DO)	Suitable DO conditions are required for organisms undergoing aerobic respiration. DO is added to the water by atmospheric exchange and photosynthesis.	1 Hz	ml/L
PAR	Photosynthetically active radiation	Measure of solar radiation in the spectral range (400 to 700 nm). Electromagnetic energy contained within these wavelengths is used by primary producers for photosynthesis.	100 Hz	$\mu mol/m^2/s$

The Rosette was programmed before each cast to ensure that the appropriate depths were targeted for the water sampler. All sensors began to measure once the instrument was programmed and armed for deployment. Once lifted into the water, the Rosette was kept just under the water surface for two minutes to ensure that all sensors had stabilised. Next, the instrument was lowered at an even pace until encountering the sea floor, at which point the instrument was retrieved onto the vessel. All sensor data was downloaded as .asc files following each cast.

A total of 22 casts were performed during the March 2018 field campaign using the Rosette carousel (Figure 15, Figure 16). Each cast computed a vertical profile for each sensor measurement throughout the water column.

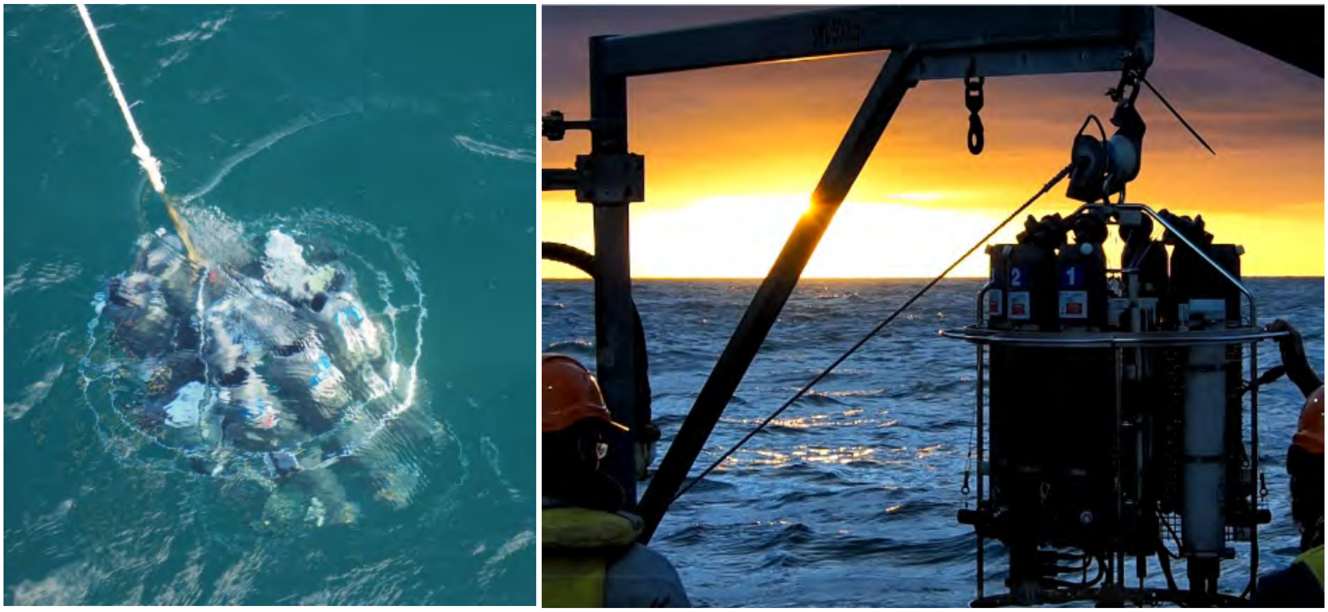

Figure 15: Left: Rosette being lifted with the crane; Right: Rosette underneath the surface for two minutes before being lowered to the seabed

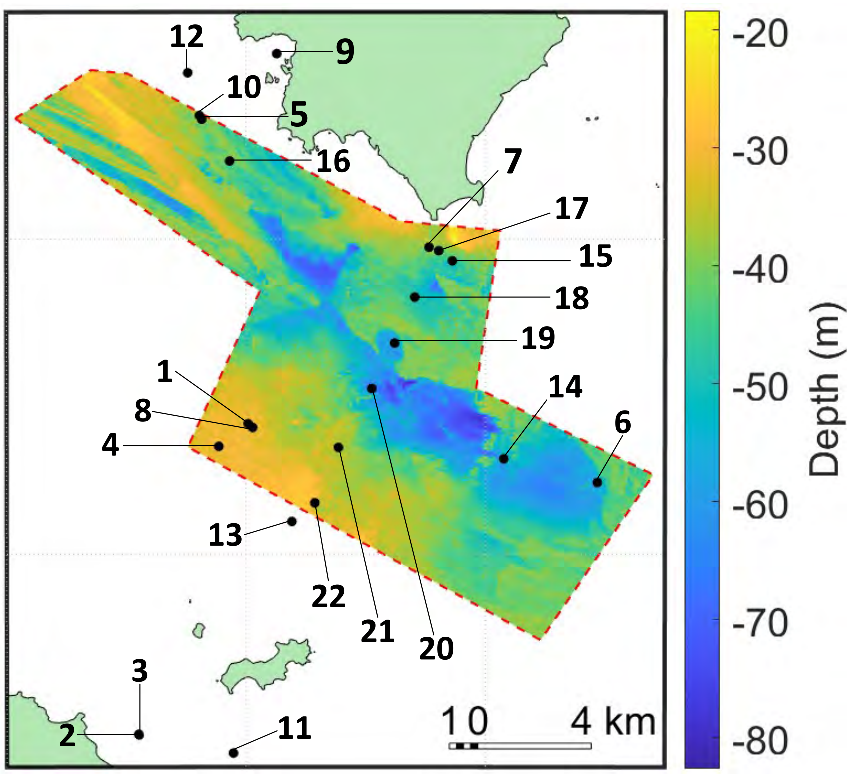

Figure 16: Rosette cast locations plotted with bathymetry of surveyed region in the Banks Strait

Water properties measured varied by location and time of cast (Figure 17). Vertical differences within each cast were minimal for temperature and conductivity (< 5%).

Oxygen concentration was significantly increased in the surface layer, but after 5 m depth had minimal variance (< 5%).

CDOM, chl α, and PAR experienced some vertical variation, where PAR, a measure of irradiance was expected to be significantly increased at the surface. Despite vertical differences in CDOM and chl α, no consistent vertical trend was identified where either water property would dominate a specific region of the water column.

In conclusion, all these parameters indicate that the water column at all locations sampled undergoes significant mixing due to the intensive current, turbulence, and wave activity present at this site.

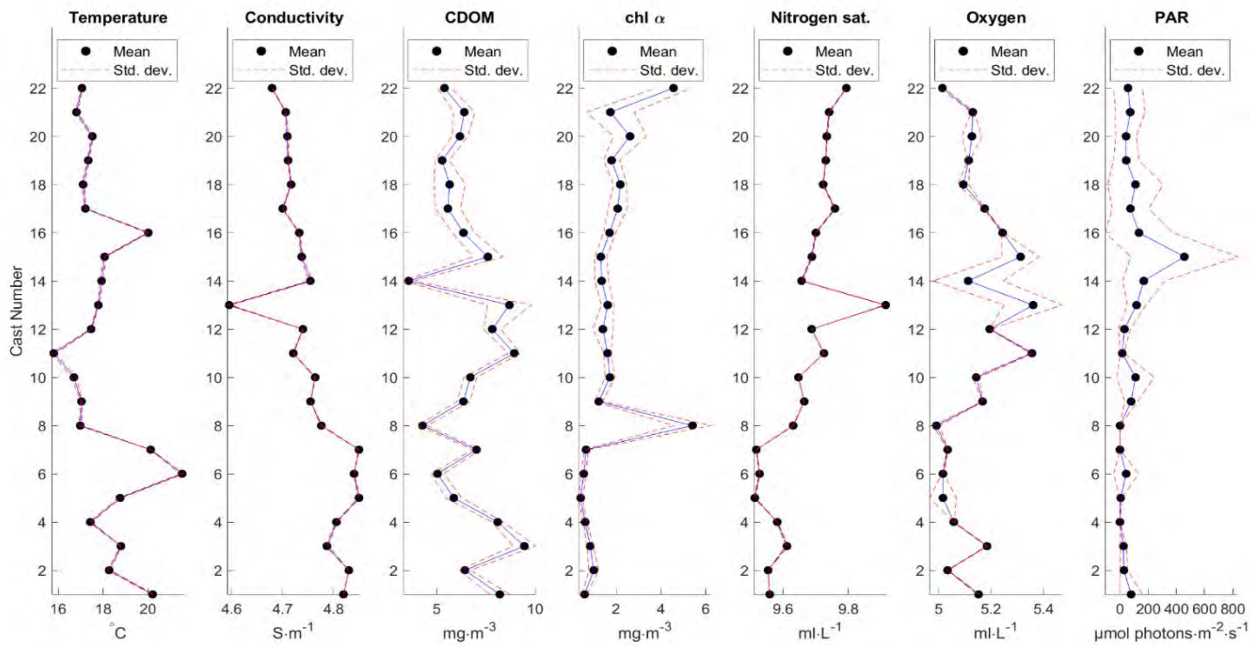

Figure 17: Mean and standard deviation values for each cast and sensor. Black circles indicate the water column mean for each cast and the red dashed line the standard deviation

Environmental Assessments

A general environmental impact assessment. This report aims to summarize the key reports and studies that detail the biotope, fish and bird habitat and marine mammals that occupy or are known to frequent the Clarence Strait, and its surrounding regions in the Vernon Islands. With the current field campaign to characterize the Clarence Strait underway, environmental parameters relevant to this assessment such as water properties (temperature, conductivity, salinity, turbidity, etc.), echograms, photos and video will be added to this literature.

The following key data sources and studies performed were noted:

- Biological and sediment studies[15]
- Fish assemblage[16] [17]
- Environment Protection and Biodiversity Conservation (EPBC) act
- Marine Mammal studies[18]

[15] Passlow, V., O'Hara, T., Daniell, T., and Beaman, R. (2004). Sediments and benthic biota of Bass Strait: an approach to benthic mapping.Geoscience Australia 2004/23.

[16] Hill, N.A., Barrett, N., Lawrence, E., Hulls, J., Dambacher, J.M., (2014). Quantifying Fish Assemblages in Large, Offshore Marine Protected Areas: An Australian Case Study. PLoS ONE 9(10): e110831. doi:10.1371/journal.pone.0110831

[17] Edgar, G.J., Barrett, N.S., Last, P.R., (1999). The distribution of macroinvertebrate and fishes in Tasmanian estuaries. Journal of Biogeography, 26: 1169-1189

[18] South-east Marine Region profile: A description of the ecosystems, conservation values and uses of the South-east Marine Region, Commonwealth of Australia 2015.

Further work around sediment transport[19] [20] [21], turbulence[22] [23] [24] and biophysical coupling of hydrodynamics and fish distribution[25] [26] [27] [28] are being investigated using Banks Strait field data.

Clarence Strait Site Characterization

The Clarence Strait as shown in

Figure **18** is located 50 km northeast of Darwin, Northern Territory, Australia. This approximately 24 km wide strait forms channels located between Mainland Australia and Melville Island which separates the Beagle Gulf on the West from the Van Dieman Gulf on the East. The Clarence Strait is composed of three channels that are formed between the Vernon Islands; the North Channel, Howard Channel and the South Channel.

Figure 18: Map of Australia and a zoomed-in map of the Northern Territory showing the Beagle Gulf, Van Dieman Gulf and Darwin. Image credit: Google Earth

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[19] Auguste, C., et al., (2020). Towards a tidal farm in Banks Strait, Tasmania: Influence of tidal array on hydrodynamics [Under Review]. Energies.

20 Auguste, C., et al., (2020). Influence of tidal energy converters on sediment dynamics in tidal channel. in 13th European Wave and Tidal Energy Conference (EWTEC2019). Napoli, Italy.

21 Auguste, C., et al. (2020). Investigation of Sediment Transport Processes near Tidal Stream Devices in Australia. in 2018 Australian Ocean Renewable Energy Symposium. Perth, Australia.

22 Perez, L., et al., (2020). Wave-Turbulence Decomposition Methods Applied to Tidal Energy Site Assessment. Energies. 13(5): p. 1245.

[23] Perez, L., et al. (2019). A case study of high frequency AD2CP measurements for tidal site characterization in Banks Straits, Tasmania, Australia. in Proceedings of the European Wave and Tidal Energy Conference, Naples, Italy.

[24] Perez, L., et al. (2018). On measurements to estimate turbulence for tidal turbines using new generation ADCPs in Banks Strait, Australia. in 2018 Australian Ocean Renewable Energy Symposium. Perth, Australia.

[25] Scherelis, C., et al., (2020). Relating fish distributions to physical characteristics of a tidal energy candidate site in the Banks Strait, Australia. International Marine Energy Journal. **3**(2): p. 111-118.

[26] Scherelis, C., et al., (2020). Investigating biophysical linkages at tidal energy candidate sites; A case study for combining environmental assessment and resource characterisation. Renewable Energy.

[27] Scherelis, C., et al., (2020) Dataset for concurrent echosounder and ADCP measurements at a tidal energy candidate site in Australia. Data in Brief. **31**: p. 105873.

[28] Scherelis, C., et al., (2018). Biophysical coupling of hydrodynamics and fish distribution at promising tidal energy candidate sites. in 2018 Australian Ocean Renewable Energy Symposium Perth, Australia.

Seabed Characterisation

The heterogeneity and variation of the seafloor has to be put into the geological context and prevailing environmental conditions in the Vernon Islands. Whilst narrow passages (channels in between the islands) promote strong tidal currents with erosion potential, the less constricted areas east and west of the islands group have more open sea character associated with relatively weaker ocean currents and with less sediment transport capacity. Erosion and scour processes are more prominent in areas of concentrated flow which leads to hard (sediment depleted) substrate, typically rock and reef structures. The shallow areas show distinct characteristic of cohesive sediments coverage which suggests transport from and interaction with the vast intertidal mud banks located around the islands.

Bathymetry

The bathymetry survey covered an area of approximately 63 km2 with depths ranging from 10 m to depths exceeding 70 m (Figure 19, Figure 20). Based on the bathymetry results the area around the Vernon Island Group can be classified into two zone:

- Tidal channels with deep areas (exceeding 60 m and deeper) to the east with a seabed that slopes towards the west; these two channels are the South Channel located between South Vernon Island and the Mainland Australia and the Howard Channel located between Northwest and East Vernon Island to the North and South Vernon Island to the South. Especially Howard Channel is larger and exhibits a 400-600 m wide plateau at the bottom.
- The outer areas to the North and East. North of Northwest Vernon Island there is another deeper (potentially also scoured) deep pocket (> 60 m water depth) but in all other parts west of the Islands the seafloor is more shallow with various plateaus around 20 m -30 m of water depth.

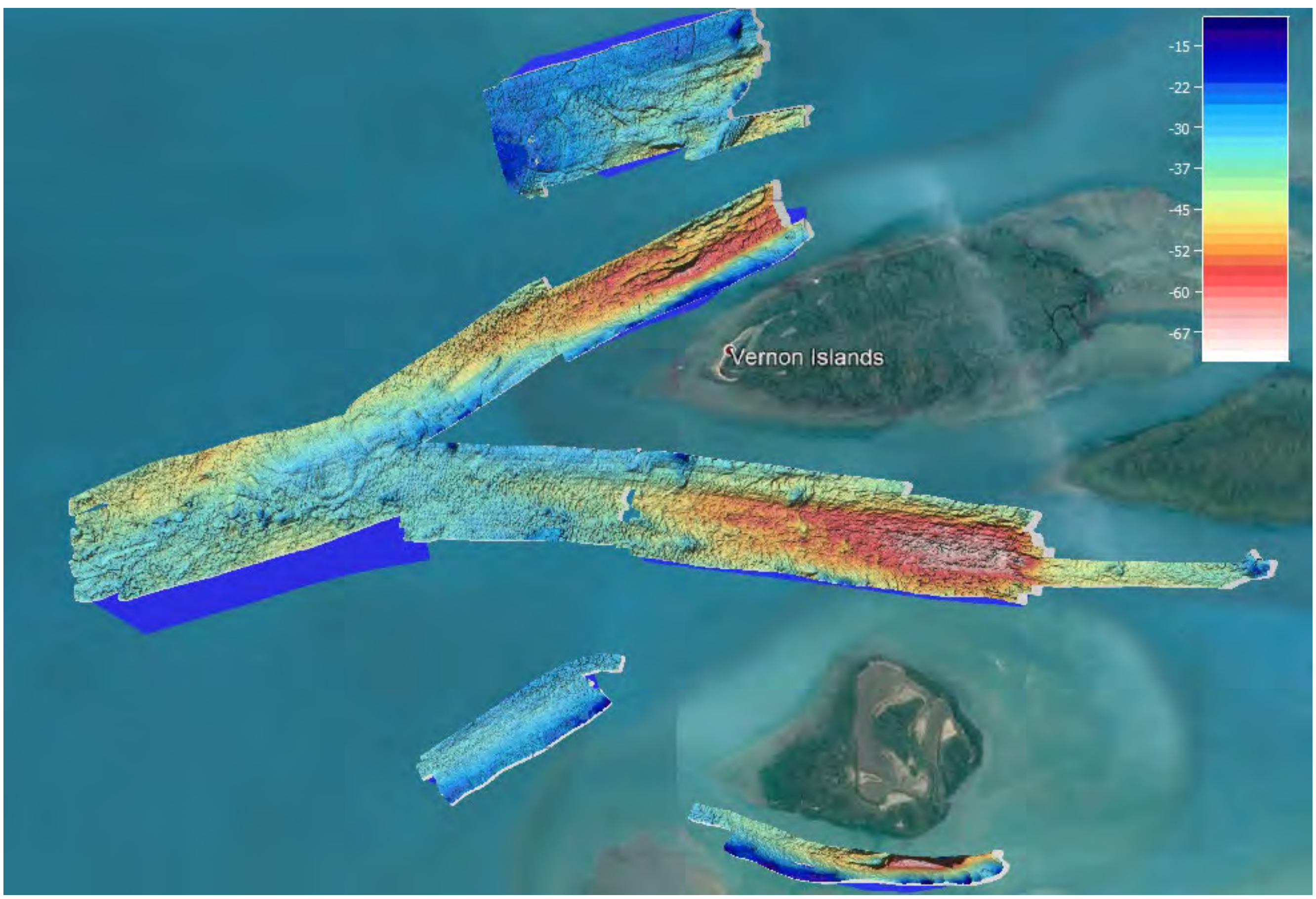

Figure 19: Overview of collected bathymetry superimposed on Satellite Image. Units of the colour bar is in meter

Sub-bottom

The seabed surrounding the Vernon Islands is very variable, exhibiting muddy deposits in shallow regions whilst deeper constricted passages consisting of largely rock, rubble and bedrock. The western Howard Channel region consists of shallow sediment bedforms suggesting both stability and sediment transport with no dominant current direction. The central region continues the trend of largely symmetrical bedforms in the deeper part of the channel (60+ m). The eastern region of Howards Channel does not reveal any bedforms, but rather is characterised by a bedding plane, possibly a shallow sediment layer.

The transect in the South Channel is mostly homogeneous bedrock. However, there is a small section of shallow bedforms that appears to correspond with a widening of the channel.

The variability within the whole region, and even within a few hundred meters is substantial. The penetrometer drops and sediment grabs in the South Channel along with little in the way of acoustic reflectors suggest the constricted water flow has eroded the seabed down to the bedrock.

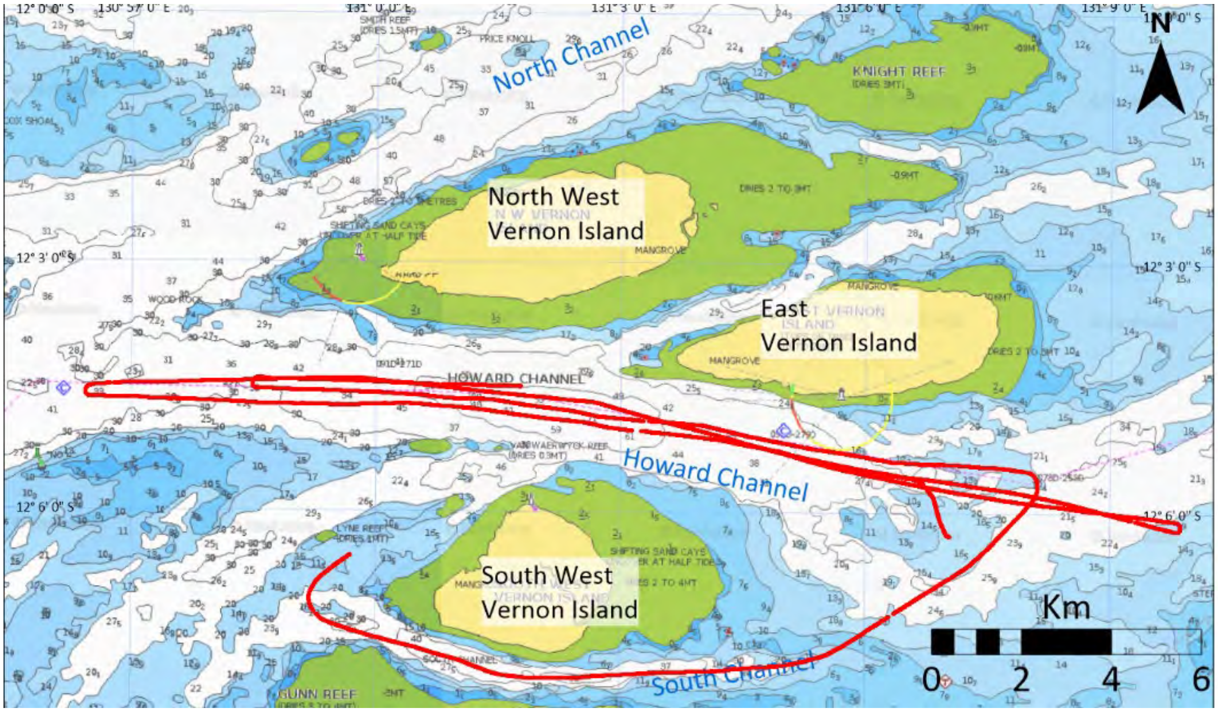

Figure 20: Vessel tracks indicating the areas of Sub-bottom survey

Penetrometer

The analysis of the seafloor is further corroborated by surficial sediment data from penetrometer drops which exhibit characteristics for non-cohesive sediments in the channels. The majority of penetration depths range between 0.01 and 0.05 m which is typical in coastal areas dominated by bedrock. However, several drops in shallow areas towards the west and also southeast of the Island group revealed penetration depths (> 0.1 m) and were carried out over softer and muddier seafloor.

Bottom Grabs

Twenty-one bottom grabs were conducted of which 8 were successful, and 13 were rejected from the analysis as the grabs did not catch enough bed material. Unsuccessful grabs are usually associated with hard substrate, typically rocks and reefs with no sediment coverage. Mud was the dominant fraction in all successful samples which had a d50 value of approximately 4-6 µm. Some grabs (particularly Grab 3 and Grab 14) contained coarser material, mainly coarse sand and smaller gravel particles. These coarser materials are associated with fragments of the reef structures at the bottom which are not linked to homogenous areas of coarse and loose particles.

Waves, Tidal Currents and Turbulence Characterisation

A total of 5 frames were deployed during the first campaign in May 2019 and 3 in September 2019 (Figure 21). The ADCPs on these moorings were set to collect Currents, Waves, Turbulence and/or Echosounder data.

For analysis purposes the channel was divided in 4 sub-areas and results will be presented referring to them as:

- The North Channel, with one ADCP deployment covering May 2019 to August 2019;
- The Howard Channel, with 4 ADCP deployments covering May to January 2020;
- The South Channel with 1 ADCP deployment covering May to September 2019; and
- The Cape Hotham, with 1 ADCP deployment covering May to September 2019.

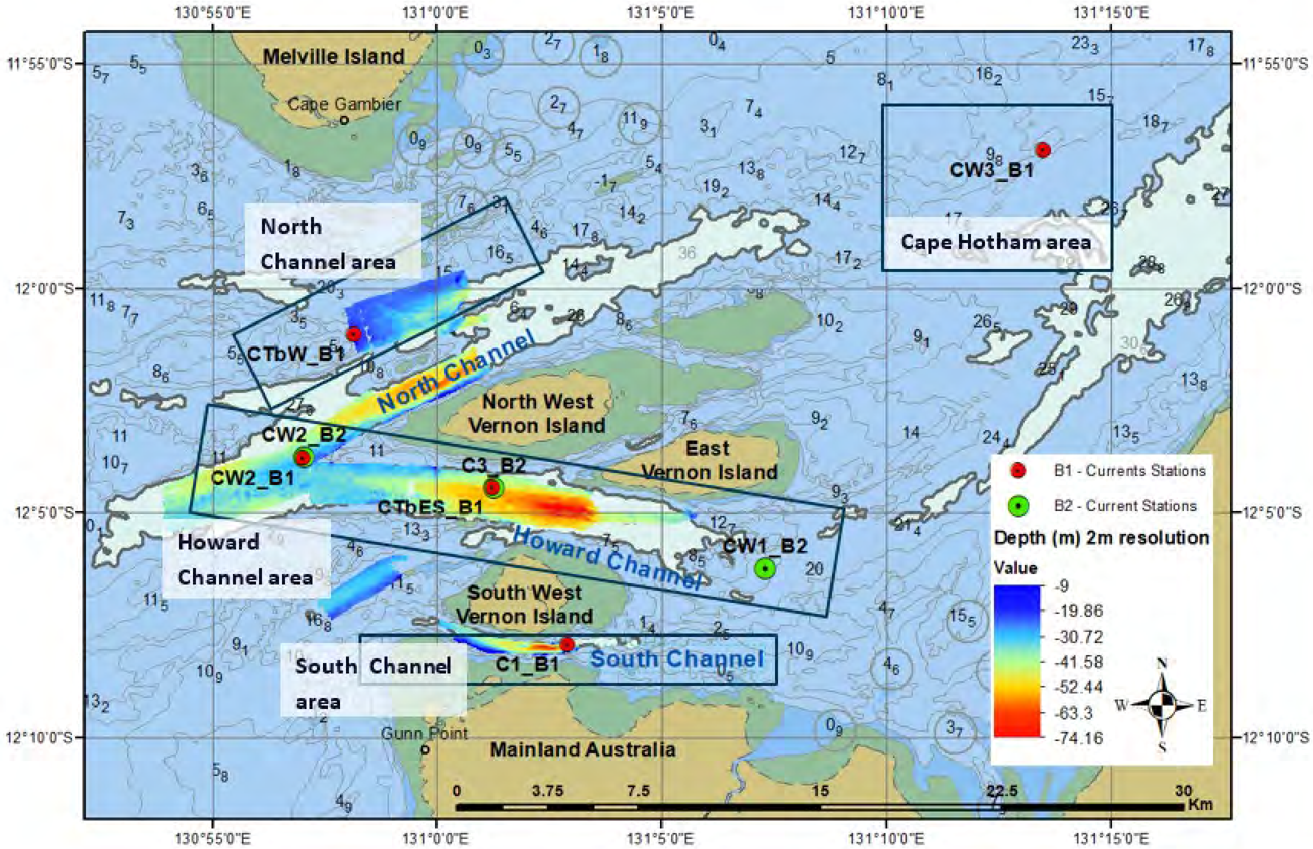

Figure 21: Map of all the ADCP stations measuring Currents deployed in the Vernon Islands from May 2019 to January 2020. Note that the icons for the first deployment (red circles) are smaller than the second deployment (green circles) to better visualize stations deployed in very similar positions such as CW2_B1 and CW2_B2, and CTbES_B1 and C3_B2

Currents

For each ADPC station, tidal range, current magnitude, current direction and vertical plots for flood and ebb plots were generated, an example of which for station CTbW_B1 for May 2019 is shown in Figure 22. Table 10 shows the statistics for all current data measured in the Clarence Strait. The highest currents speeds were found in the centre of the Howard and South Channels with a dominant East-West flow axis and maximum speeds of up to 2.8 m/s measured. Stations outside of these channels were found to have lower velocities due to their more exposed offshore location without any channelling effect.

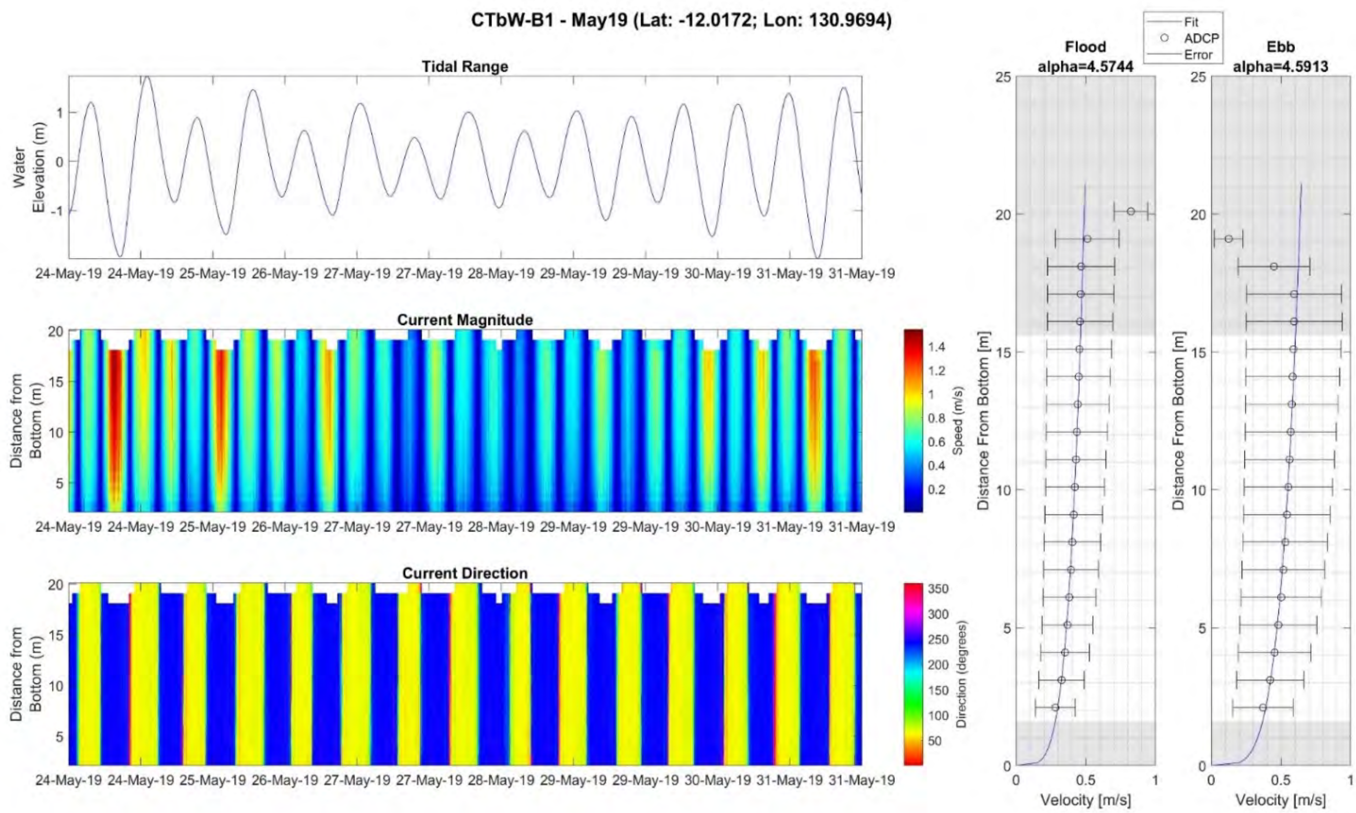

Figure 22: Tidal Range, Current Magnitude, Current Direction and Vertical Plots for Flood and Ebb for Station CTbW, Deployment 1, for the month of May 2019

<u>The highest currents speeds two found in two areas:</u>

- In the centre of the Howard Channel, around 12° 4' 26.435'' S; 131° 1' 16.355'' E, with a maximum current speed of 2.67 m/s, mean speeds of 1.03 m/s and Ebb/Flood asymmetry ranging 176.27°;
- In the centre of the South Channel, at 12° 7' 55.29'' S; 131° 2' 56.148'' E, with a maximum current speed of 2.8 m/s, mean speeds of 1.13 m/s and Ebb/Flood asymmetry of 174.3° (station CW1_B1);

All other stations outside of these channels in the Vernon Island have lower velocities due to a more exposed location. This is also corroborated with a stronger ebb/flood asymmetry below 170°.

Table 10: Statistics of ADCP Current Data over the full measurement period

Area	Station	Sensor	Depth (m)	Dates of data collected (UTC)	Tide	Velocity			Directionality	
						Mean Speed (m/s)	Maximum Speed (m/s)	Standard Deviation (cm/s)	Principle Axis (°)	Ebb/Flood Asymmetry (°)
North Channel	CTbW_B1	Nortek Signature 1MHz	22.4	24/05/2019	Flood	1.4	0.61	3.98	69.54	168.51
				4/08/2019	Ebb	1.91	0.63	5.18	238.05	
Howard Channel	CW2-B1	Nortek AWAC, 1MHz	31.7	22/05/2019 18/09/2019	Flood	1.87	0.68	5.2	83.53	160.2
	CW2-B2	Nortek AWAC, 1MHz	33.6	21/09/2019 5/01/2020	Ebb	**1.61**	**0.53**	**3.46**	**243.73**	
	CTbES_B1	Nortek Signature 500kHz	53	23/05/2019 26/07/2019	Flood	2.67	1.03	6.37	91.63	176.27
	C3_B2	RDI WorkHorse, 300kHz	55.6	21/09/2019 16/12/2019	Ebb	**2.26**	**0.86**	**3.96**	**267.9**	
	CW1_B2	Nortek AWAC, 1MHz	21.6	20/09/2019	Flood	2.08	0.81	4.74	105.21	150.77
				5/01/2020	Ebb	2.36	0.77	5.04	255.98	
South Channel	C1_B1	RDI Sentinel V50, 500kHz	52.3	24/05/2019	Flood	2.8	1.13	5.1	81.57	174.32
				15/09/2019	Ebb	2.52	1.04	5.31	255.88	
Cape Hotham	CW3_B1	Nortek AWAC, 1MHz	22.4	24/05/2019	Flood	1.62	0.64	2.27	64.4	146.2
				19/09/2019	Ebb	1.23	0.47	2.64	210.6	

Figure 23 summarises the general trends of the currents in the Clarence Strait, extracted from ADCP measurements from May to January 2020 and shows the different flow areas in the channel.

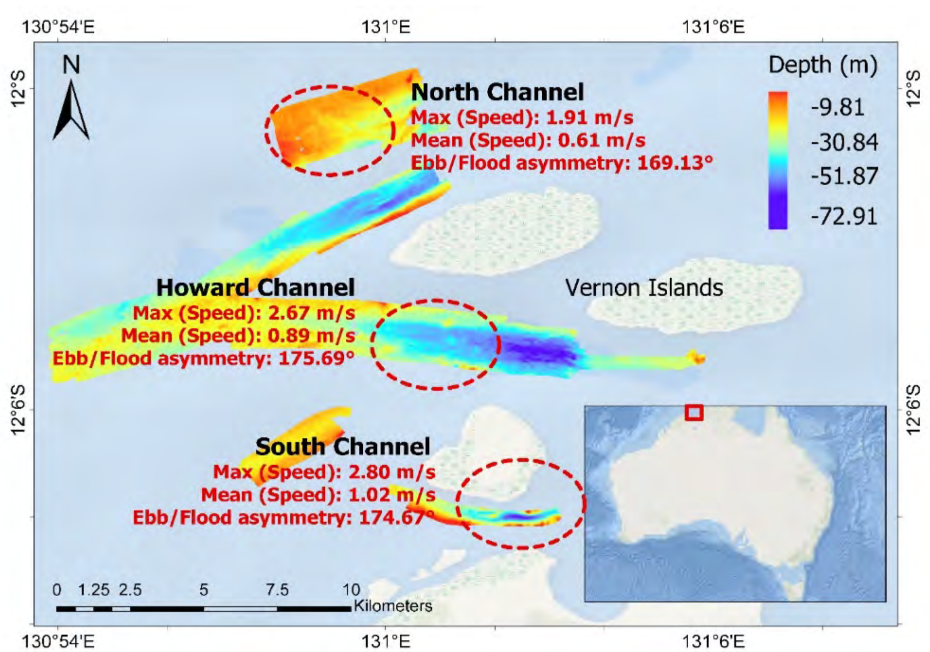

Figure 23: Summary of the Current trends in the Clarence Strait from measurements taken from May to January 2020

Waves

Three waves stations were deployed in May 2019 (Deployment 1) and two were deployed in September 2019 (Deployment 2). See map in Figure 24.

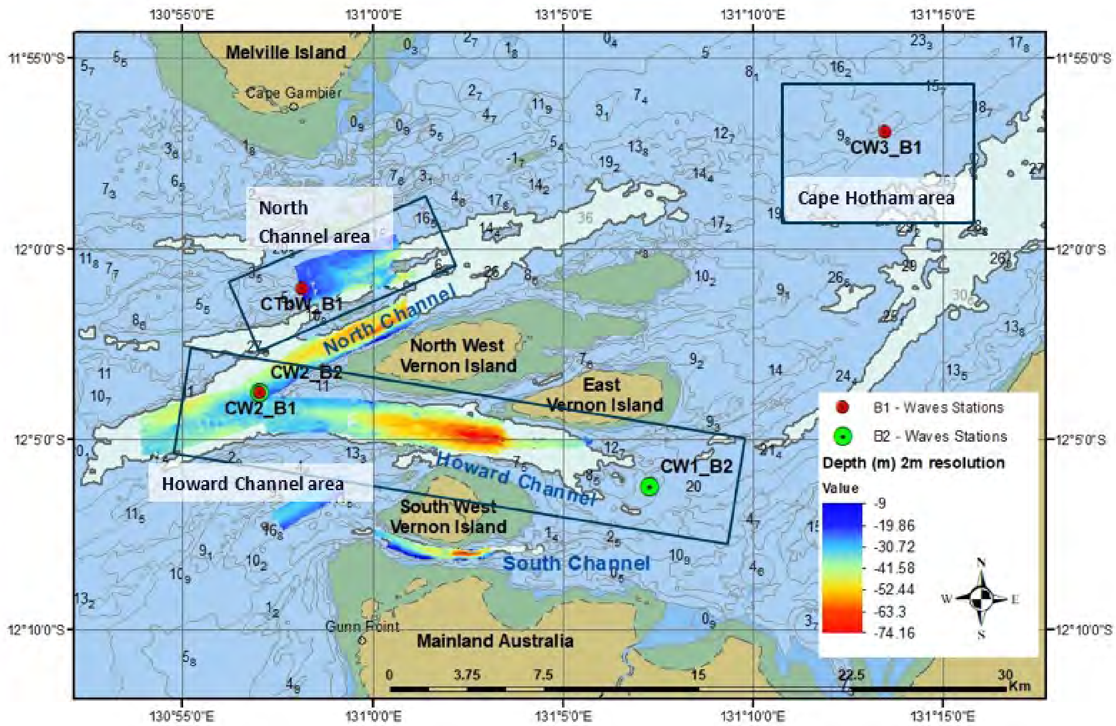

Figure 24: Map of all the ADCP stations measuring Waves deployed in the Vernon Islands from May 2019 to January 2020. Note that the icons for the first deployment (red circles) have been made smaller than the second deployment (green circles) to see stations deployed in very similar positions such as CW2_B1 and CW2_B2

For each station, significant wave height, mean period, peak period, mean direction, peak direction, wave rose and power distribution were derived. An example of wave rose and power distribution for CW2-B1 is presented in Figure 25 and Figure 26.

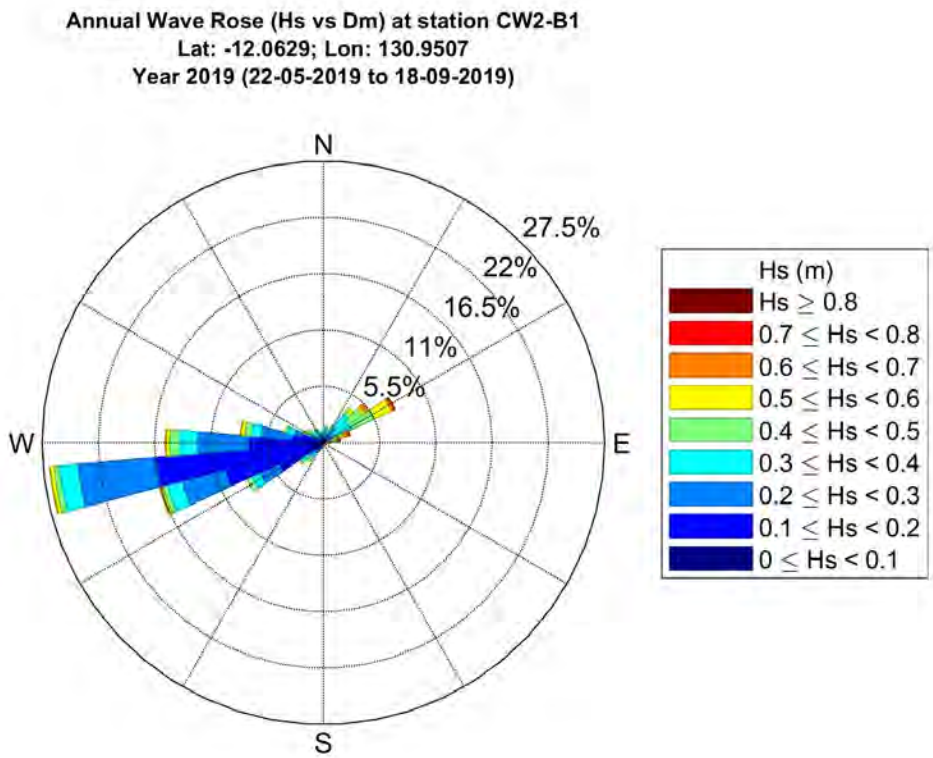

Figure 25: Annual Wave Rose at Station CW2, Deployment 1, from 22-5-2019 to 18-9-2019

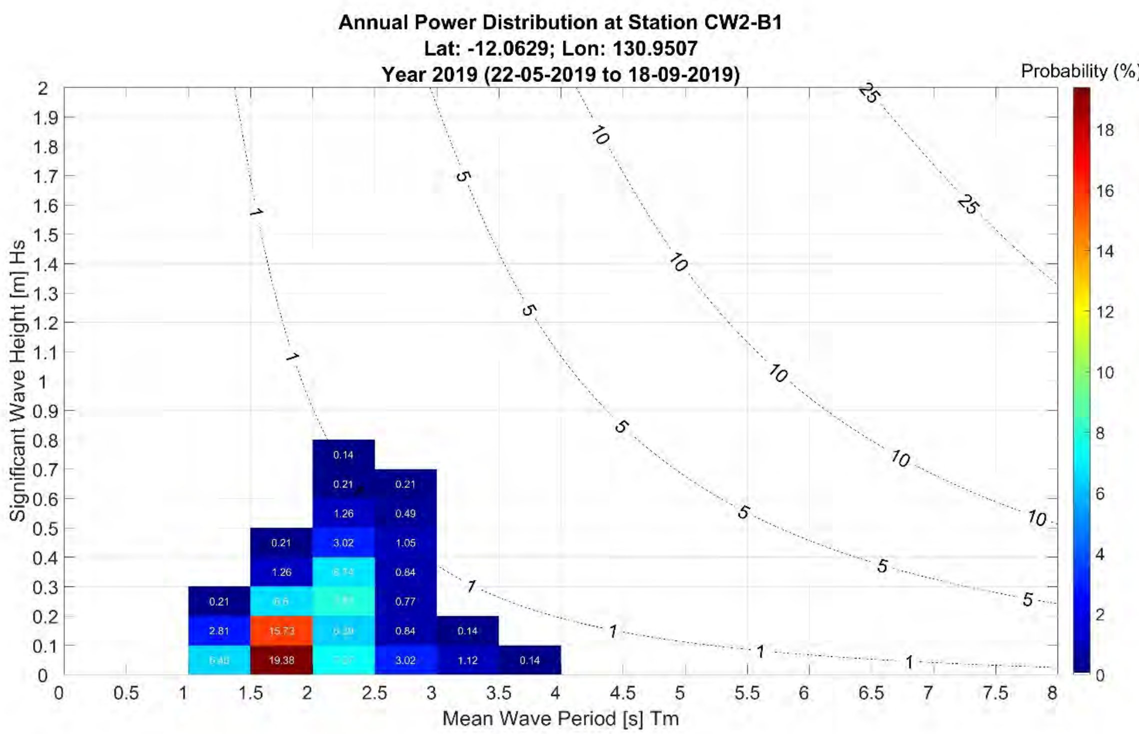

Figure 26: Annual Power Distribution (kW/m2) at Station CW2, Deployment 1, from 22-5-2019 to 18-9-2019

Table 11 shows the minimum, maximum and average values of the Significant Wave Height Hm0, Mean Zero crossing period Tz, Mean Period Tm, Peak Direction, Peak Spread, Temperature and Power density at the seven ADCP stations that were measuring waves in the Clarence Strait, from May 2019 to January 2020.

Table 11: Statistics of ADCP Wave Data over the full measurement periods

Area		North Channel	Howard Channel			Cape Hotham Area
Station		CTbW_B1	CW2_B1	CW2_B2	CW1_B2	CW3_B1
Sensor		Nortek Signature 1MHz	Nortek AWAC, 1MHz	Nortek AWAC, 1MHz	Nortek AWAC, 1MHz	Nortek AWAC, 1MHz
Depth		22.4	31.7	33.6	21.6	22.4
Dates of data collected (UTC)	Start	24/05/2019	22/05/2019	21/09/2019	20/09/2019	24/05/2019
	End	4/08/2019	18/09/2019	5/01/2020	5/01/2020	19/09/2019
Hm0 [m]	Min	0.07	0.05	0.05	0.05	0.03
	Max	1.01	0.88	1.02	1.03	1.48
	Mean	0.39	0.26	0.33	0.19	0.53
Tz [s]	Min	2.77	1.79	2.16	1.68	1.68
	Max	7	5.68	4.83	4.56	4.69
	Mean	3.52	2.71	2.92	2.53	2.84
Tm [s]	Min	1.37	1.52	1.87	1.57	1.56
	Max	4.67	5.05	6.28	4.24	4.63
	Mean	2.19	2.48	2.5	2.32	2.57
Peak Direction [°]	Min	0	2.22	0.21	0.19	0.08
	Max	359.46	359.59	359.83	359.1	359.94
	Mean	186.69	238.56	251.16	220.4	117.52
Peak Spread [°]	Min	12	21.81	26.38	33.82	32.72
	Max	81.03	83.52	83.49	83.52	83.55
	Mean	55.51	71.15	65.28	73.64	62.52
Temperature [°C]	Min	25.16	25.03	26.6	26.59	25.1
	Max	28.68	28.61	32.35	32.5	28.6
	Mean	26.55	26.41	29.9	30.04	26.46
Power [kW/m2]	Min	0.01	0.01	0.01	0	0
	Max	2.05	2.22	3.47	4.19	8.3
	Mean	0.38	0.23	0.32	0.13	1

Two major seas are found in this area which are picked up at different locations: The East North East and West South West seas. They are characterised with small Wave Heights of maximum 1.48m and average at around 0.3m. They have small Mean Period of average 2.35s and can be assumed to be related to small wind intensity fetch limited seas.

Figure 27 is a map that summarises the major trends of the waves in the Clarence Strait from measurements taken between May 2019 and January 2020.

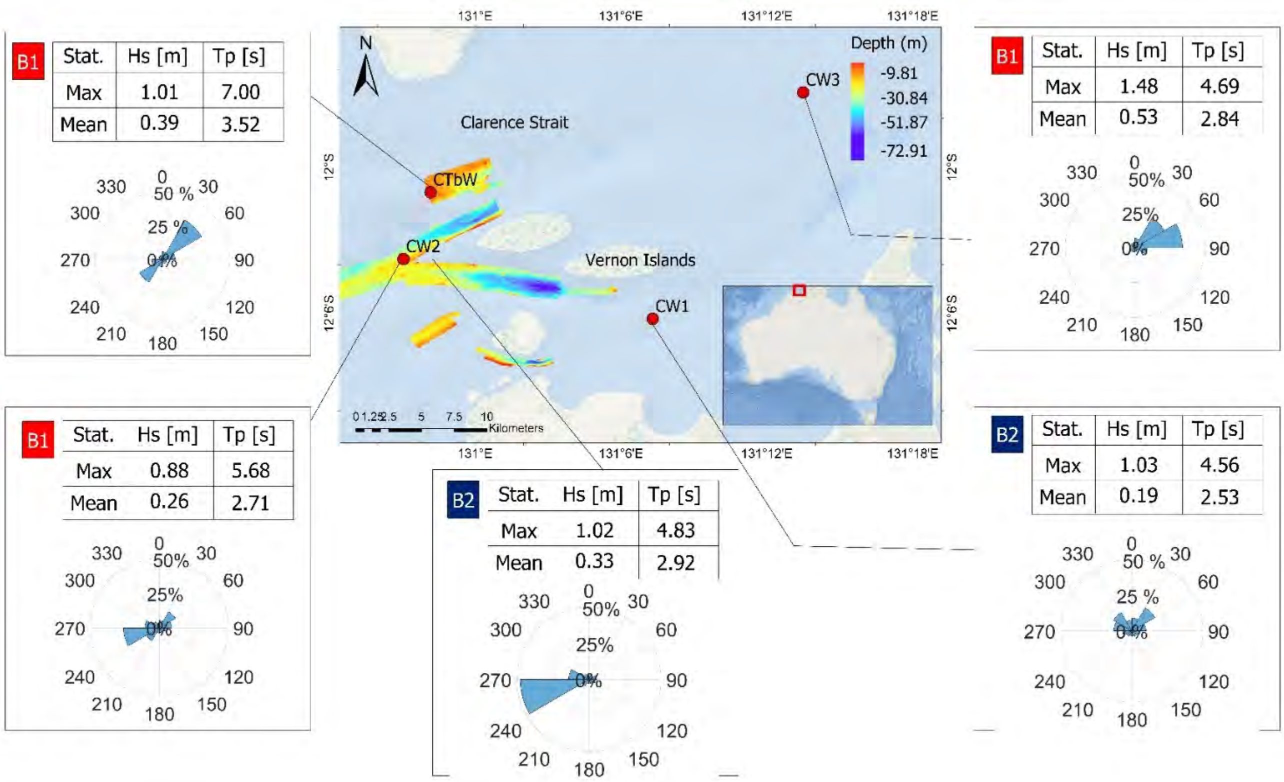

Figure 27: Summary of wave measurements in the Clarence Strait, May 2019 to January 2020. Note that wave directions follow the standard "coming from"

Turbulence

The velocity spectra obtained at both locations indicate that surface gravity waves rarely interfere with turbulence measurements at mid-water column. Therefore, no wave-turbulence decomposition technique is required.

Turbulence characteristics encountered at station CTbW and CTbES differ significantly. Mean streamwise TI at CTbES in the Howard Channel vary mostly between 10 – 13%, whilst CTbW in the North Channel presents mean TI varying mostly between 15 – 18%. TKE densities at CTbW were also larger than those measured at CTbES, despite of its faster current speeds. Integral length scales remain below 8 m most of the time. Both sites present some level of tidal asymmetry in turbulence parameters. At CTbW ebb tides showed larger TKE densities than flood tides. In contrast, at station CTbES flood tides reveal larger TKE densities up until approximately 5 m above the seabed and tend to decrease towards the surface, becoming lower than ebb tides at approximately 18 m above the seabed. Generally, turbulence quantities agree well with those observed in other tidal energy sites.

Table 12: Average streamwise turbulence intensities for ebb and floods tides from selected periods in each month from instrument CTb3 measured 15m above the bottom

Month	Tide	Ebb (%)	Flood (%)
March	Neap	-	-
	Spring	12.69	16.01
April	Neap	18.35	23.64
	Spring	13.50	16.68
May	Neap	13.98	16.77
	Spring	11.63	13.61
Jun	Neap	13.15	15.23
	Spring	13.46	16.72
Jul	Neap	11.83	15.25
	Spring	-	-

Water Column Properties

CTD

Table 13 presents the monthly statistics of casts taken with the RBR Concerto CTD and Maestro CTD, organised by area. Key findings from the CTD data collected at Clarence Strait are given below. A total of 34 CTD casts were taken during the 3 campaigns at Clarence Strait. Eleven casts were taken in the North Channel, 13 casts in the Howard Channel, 5 casts in the South Channel, 2 casts in the far east South Channel and 2 in the Cape Hotham area.

In the three channels, North Channel, Howard Channel and South Channel, temperature and salinity results are alike. The temperature plots indicate that there is little difference in temperature during the dry season (May to September), with a mean temperature of around 28.5° C and 26.5° C in May and September 2019 respectively. During the wet season, the mean temperature rises to 31.7° in January 2020. Also, the variation in temperature throughout the water column is close to zero, which implies that the water column is well-mixed. The thermocline cannot be seen in any of the casts as they are taken at depths greater than 50 m. Also, the salinity results also show little seasonal difference between the three channels, with salinity ranging from 34.8 to 35.4 PSU. In the South Channel, the salinity is generally lower by 1 PSU and show some variation with depth based in particular casts taken to the eastern side of the South Channel where the depth is greater than 70 m.

Table 13. Monthly statistics of casts taken with the RBR Concerto CTD and Maestro CTD, organised by area

Date (UTC)		May-19			Sep-19			Jan-20		
Parameter		Temperature (°C)	Salinity (PSU)	Turbidity (NTU)	Temperature (°C)	Salinity (PSU)	Turbidity (NTU)	Temperature (°C)	Salinity (PSU)	Turbidity (NTU)
North Channel	min	28.5	34.49	4.06	26.43	35.02	4.06	31.74	35.14	
	mean	28.539	34.703	4.49	26.515	35.075	4.49	31.75	35.16	
	max	28.64	34.89	4.92	26.59	35.13	4.92	31.84	35.16	
Howard Channel	min	28.37	34.66	4.47	26.32	35.14		31.78	35.2	
	mean	28.433	34.783	4.9267	26.488	35.24		31.83	35.357	
	max	28.54	34.89	5.81	26.66	35.32		32.22	35.42	
South Channel	min	28.31	33.96	5.66	26.71	35.41				
	mean	28.36	34.57	6.305	26.81	35.5				
	max	28.47	34.77	9.63	26.87	35.59				
East of South Channel	min	28.33	34.3	6.24						
	mean	28.335	34.41	6.63						
	max	28.37	34.5	7.21						
Cape Hotham	min	28.41	34.52	4.36						
	mean	28.42	34.66	4.53						
	max	28.42	34.8	5.56						

Turbidity measurements were only taken in the three channels in May 2019 using the RBR Concerto CTD. Turbidity results in all three channels indicate they are susceptible to noise and increasing turbidity near the seabed. In the South Channel turbidity showed the largest variation with depth, when compared to the North and Howard Channel's. The turbidity results taken on the east side of the South Channel is 9 NTU near the surface decreasing to 6 NTU at depth. The South Channel indicated the highest turbidity of all sites casts were taken in the Clarence Strait, NT.

Two casts were also taken with both the RBR Maestro and RBR Concerto CTD's further east of South Channel area and Cape Hotham area respectively. The further east of South Channel area, results show an average temperature is 28.3° C and average salinity of 34.5 PSU. The turbidity results indicate they are susceptible to noise variation and showing turbidity increasing with depth. This location is also more turbid than its neighbours in the channels (North, Howard and South Channels). The Cape Hotham area results show an average temperature is 28.4° C and average salinity of 34.6 PSU. The turbidity results indicate they are susceptible to noise variation and showing turbidity increasing with depth.

The above results also agree well with the temperature loggers mounted to the ADCP frames.

Temperature Station

A mooring with a surface buoy and five temperature loggers was deployed as shown in Figure 28, west side of the South West Vernon Island to measure the variation of temperature along the water column.

Because the water column appears well mixed, the data can be averaged over the water column. Table 14 shows the minimum, average and maximum temperatures measured by all temperature sensors on Tp1 averaged over the water column. At the beginning of the measurement campaign at Clarence Strait, the average temperature in May 2019 was 28.2° C, and at the conclusion of the campaign in January 2020 the average temperature was 31.8° C. The temperature dropped approximately 2.8° C from May to July 2019 then increased by 1.5° C from July to September (during the dry season), then in the period from September to October and then October 2019 to January 2020 (during the wet season) had a cumulative increase of 2° C respectively.

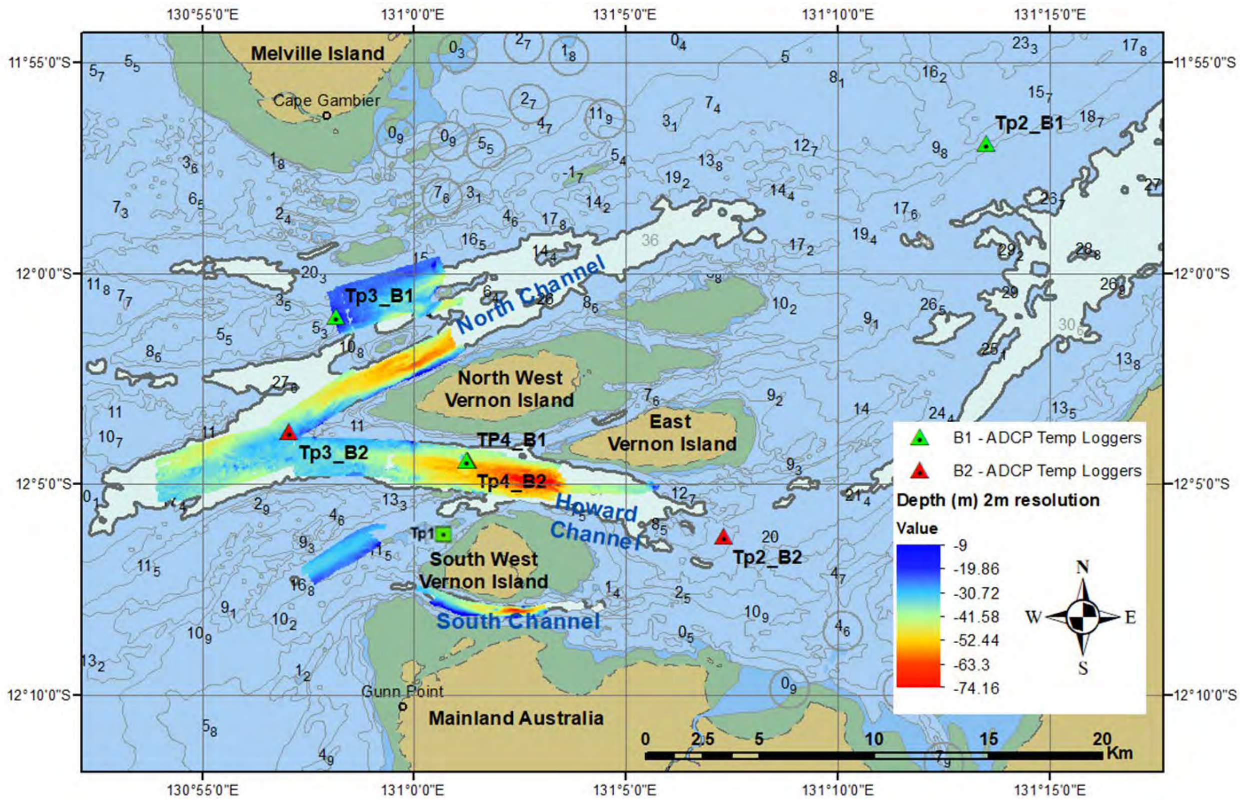

Figure 28: Temperature station and SoloT Temperature loggers deployed on ADCP moorings from May 2019 to January 2020

Table 14. Monthly minimum, average and maximum temperature at the Temperature Station Tp1, deployed at 12° 6' 21.779'' S; 131° 0' 34.236'' E and measuring valid data from 23-5-2019 to 3-1-2020

	Temperature (°C) - Full Water Column		
Month	**Min**	**Mean**	**Max**
May-19	27.29	28.19	28.72
Jun-19	24.63	25.75	27.75
Jul-19	24.96	25.37	25.95
Aug-19	25.31	25.88	26.4
Sep-19	26.06	26.77	28.17
Oct-19	27.77	29.01	30.23
Nov-19	29.71	30.44	31.67
Dec-19	31.12	31.86	32.61
Jan-20	31.71	31.83	32.05

The temperature was not only monitored at the location where the Tp1 station was deployed, but at many other locations around Clarence Strait, thanks to an array of temperature loggers deployed ADCP moorings.

ADCP mounted Temperature loggers

A total of 6 RBR Solo T sensors were deployed on ADCP moorings from May 2019 to January 2020. Results as shown in Figure 29 indicate that the temperature in the North Channel (Tp3_B1) has bigger variations than the other locations and seems to increase or decrease before the temperature at other locations. The temperature in the Howard channel (Tp4_B1 and B2) is generally lower than the other locations by 0.03 to 0.1° C, and the second lowest temperature can be found north of Cape Hotham (Tp2_B1). Temperature at Tp1 (west of South West Vernon Island) presents the higher variability: it has the lowest temperatures of all sensors from May 2019 to August 2019, and the highest temperatures from September 2019 to January 2020.

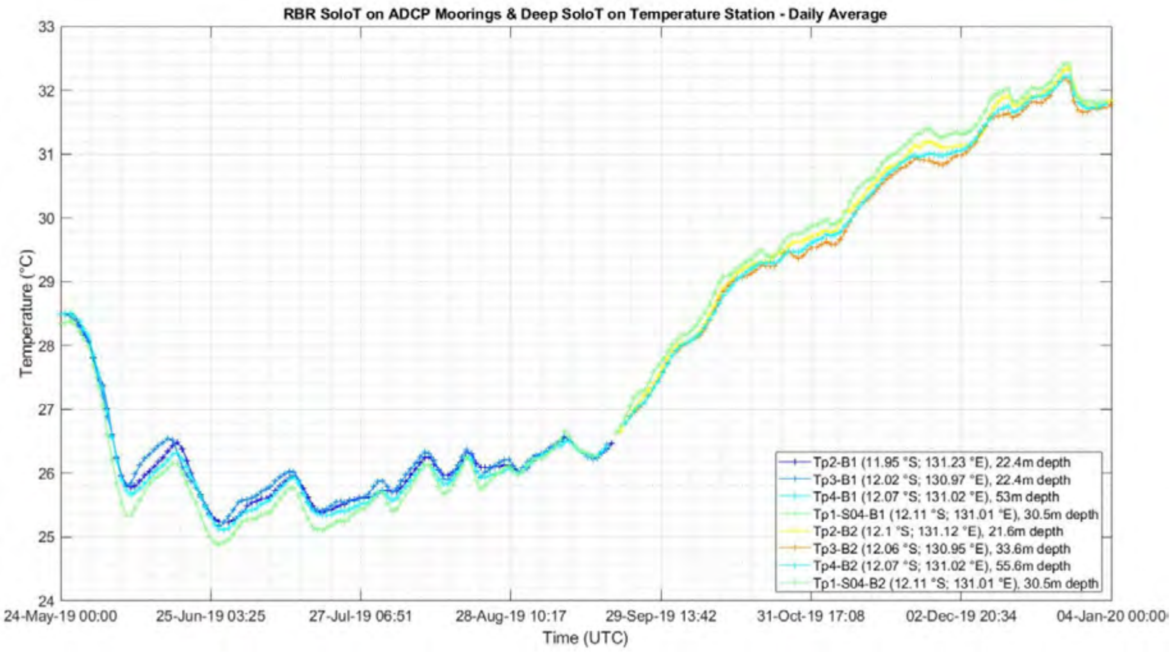

Figure 29: Time series of RBR SoloT loggers placed on ADCP moorings from 24-5-2019 to 5-1-2020. Top: Original sampling rate (2Hz); Bottom: Daily average. Note that data from the same location have the same colour: Tp4_B1 and Tp4_B2 in cyan; Tp1_S04_B1 and Tp1_S04_B2 in green

Environmental Assessments

A general environmental impact assessment. This report aims to summarize the key reports and studies that detail the biotope, fish and bird habitat and marine mammals that occupy or are known to frequent the Clarence Strait, and its surrounding regions in the Vernon Islands. With the current field campaign to characterize the Clarence Strait underway, environmental parameters relevant to this assessment such as water properties (temperature, conductivity, salinity, turbidity, etc.), echograms, photos and video will be added to this literature.

The following data sources and studies performed were noted:

- Fish and benthic studies[29] [30]
- Water column properties[31]
- NT artificial reefs and fish attracting devices, fish and benthic studies[32]
- Vernon Islands recreational fishing fish catch studies[33]

Comparisons Between Banks and Clarence Strait

Part of AUSTEn project, two promising sites for tidal energy applications were characterized through fieldwork, Banks Strait, Tasmania and Clarence Strait, Northern Territory. Through multiple campaigns, measurement related to seabed, currents, waves, turbulence as well as water column properties were performed. The findings showed that although some similarities exist, these two Straits are very different in nature.

The Banks Strait forms a large 14 km wide channel between Swan whereas Clarence Strait is composed of multiple smaller with the 12.5 km wide North Channel between n Melville Island and North West Vernon Island (although only the southern half part of the channel presents bathymetry over 10 m), the 4 km wide Howard Channel between South West Vernon Island, North West and East Vernon Island and the 1.5 km wide South Channel between Mainland Australia and South West Vernon Island. Both sites present scoring of the seafloor due high flow velocity in the area and the bathymetry varies from 10 to 60 m in Banks Strait and 10 to 70m in Clarence Strait. Banks Strait is mostly composed of hard substrate, typically rock and reef structures with some sandy areas located in the region near Clarke Island and some areas in the southwest towards Swan Island. On the other hand, Clarence Strait presents mostly muddy deposits in shallow regions whilst deeper constricted passages consist of largely rock, rubble and bedrock.

Tidal range in Clarence Strait is much larger (~4 m) than in Banks Strait (~1.5 m). Current speed in Clarence Strait were also found to be slightly higher with maximum speed measured at 2.8 m/s with mean speed of 1.13 m/s compared to a maximum of 2.3 m/s with mean speed of 1 m in Banks Strait. Clarence Strait has a completely different wave climate to the one experienced in Banks Strait. The wave heights are considerably smaller, with maximum significant wave heights of 1.48 m and an average of 0.3 m measured compared to 6.83 m maximum and average of 1.25 m in Banks Strait with the presence of strong wave-current interactions. Furthermore, Banks Strait is prone to large storm whereas no extreme events were particularly measured in Clarence Strait, however, the area is prone to cyclones which can produced extreme wave conditions. Unfortunately (or fortunately), such events did not occur during the time of measurements.

Notable variations in temperature, salinity and turbidity when comparing the results from the Banks Strait, with those from the Clarence Strait, Northern Territory. Overall, the water column appears very well mixed in all the sub-areas of the Banks Strait as in the Clarence Strait respectively but there are significant variations in temperature(BS: 12.2° C - 19.6° C, CS: 28.2° C - 31.8° C), salinity (BS: 35.42-35.80 PSU, CS: 34.3-35.59 PSU) and turbidity (BS: 3.21 - 3.87 NTU, CS: 4.06 - 9.63 NTU) between these two sites and at depth. This is expected given Banks Strait is a temperate location unlike Clarence Strait which is a tropical location. Both sites also have very different biotope and habitats as well as biofouling type and rate (experienced when retrieving the moorings in the two sites).

These results demonstrate the diversity in properties of potential tidal sites in Australia. Such information are vital for companies in evaluating resource, feasibility, planning, maintenance and potential environmental impact for the deployment of tidal energy converters in promising sites. Such field campaigns in such highly energetic tidal sites were a first in Australia. Many lessons were learnt, the bigger one being that further such site characterizations is needed in other promising sites around Australia.

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[29] https://apps.aims.gov.au/metadata/view/d89470cd-891b-495b-9840-09180ee39fb0

[30] https://researchdata.edu.au/evaluating-monitoring-status-continental-shelf/661443

[31] https://portal.aodn.org.au/search?uuid=8af21108-c535-43bf-8dab-c1f45a26088c

[32] https://dpir.nt.gov.au/__data/assets/pdf_file/0010/616591/NT_AR__FAD_Design_and_Site_Selection.pdf.

[33]http://www.territorystories.nt.gov.au/bitstream/10070/262893/91/Northern%20Territory%20News_20160624_section_NTNewsFeatureC_Lifestyle_page10_NTNewsFeatureC_Lifestyle_10.PDF

4. Australian National and Regional Models

Australia exhibits some of the largest tidal ranges in the world, with water level fluctuations of up to 11.8 m on Australia's north-west shelf. The National Tidal Centre tidal model (presented in the CSIRO 2012 Ocean Energy Report) already demonstrated that several prospective sites for tidal energy exist in Australian shelf waters[34]. The results estimated high energy densities of up to 3.4 MW/m2 but due to the coarse grid size (~10 km) many tidal flow areas are insufficiently resolved. This could lead to potentially overlooking yet unknown high energy sites as well as returning large uncertainties (>50%) for the energy assessment of the identified potential sites.

A new high resolution national tidal model was developed to improve the existing national model for tidal energy resources and to produce a robust tidal resource database similar to the Atlas of UK Marine Renewable Energy Resources (e.g., www.renewables-atlas.info). The AUSTEn national tidal model was also used to evaluate the national tidal energy resource and hence assess the geographic technical and economic feasibility of tidal energy in Australia.

Two new fine-scale regional models were also developed to model the tidal resource in two promising areas, the Banks Strait, Tasmania, and Clarence Strait, Northern Territory, Australia. These models used an unstructured mesh ocean model developed as part of this project to allow determination of the tidal resource at both national and regional scales. To update and validate the hydrodynamic models, results were compared to the extensive field campaigns performed at the two candidate sites.

COMPAS Development

To adequately resolve tidal flows in more prospective locations across Australia, a hydrodynamic model with high spatial resolution and with national extent is required. To simulate the hydrodynamics across the full Australian marine domain at a uniformly high resolution using a structured mesh is a very large computational task. In recent years, hydrodynamic models have been developed that use an unstructured format that allows variable resolution across the domain, with highest resolution in areas of most interest. CSIRO O&A have recognised these benefits for a range of marine applications, and hence have focused hydrodynamic model development on an unstructured modelling infrastructure - COMPAS (Coastal Model Prediction Across Scales).

COMPAS is an open-source coastal ocean model developed at CSIRO Oceans and Atmosphere, designed to be used at scales ranging from estuaries to regional ocean domains. It is a three-dimensional finite volume hydrodynamic model based on the three-dimensional equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq assumptions.

National Model

A national tidal model was developed to identify prospective tidal energy resource sites. An unstructured model mesh is used, achieving high resolution (~500 m) in most prospective regions to meet EMEC Stage 2a assessment criteria[35]. This model is national in extent, configured to quantify Australia's national scale tidal energy resource (stream and range) and identify the most promising regions for potential future tidal energy extraction. The model outputs are used to support characterisation of the resource performed by examining tidal energy, amplitude, tidal current velocity and associated kinetic energy, at multiple levels for selected regions. The model was run in 2D (vertically-integrated) mode to enable very high horizontal resolution to be used. During model development, simulations spanned a neap-spring cycle only, to allow many testing runs to be completed within computational constraints. Once model calibration and validation are complete, a 59-day simulation was completed to exceed IEC TC114 standards for tidal energy resource assessment purposes.

Bathymetry, Mesh and Forcing

Bathymetry for the national model was sourced from the Geosciences Australia (2002) database, with regions outside its extent filled using the dbdb2 (Naval Research Laboratory Digital *Bathymetry* global database[36]. This was supplemented with high

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[34] CSIRO Ocean Energy Report (2012). Retrieved from https://publications.csiro.au/rpr/download?pid=csiro:EP113441&dsid=DS2

[35] EMEC, (2009). Assessment of Tidal Energy Resource. Retrieved 30th September 2020, from http://www.emec.org.uk/assessment-of-tidal-energy-resource/

[36] Naval Research Laboratory, (n.d.). Global 2 Minute Topography. Retrieved from https://www7320.nrlssc.navy.mil/DBDB2_WWW/)

resolution datasets in the Great Barrier Reef[37] and the North West Shelf[38] regions. A minimum bathymetry of 4 m was imposed nationally, with some local adjustments along the North West Shelf coastline. Bathymetry was also median filtered to remove sharp gradients.

The national model mesh (Figure 30) was generated using a dual weighting function dependent on bathymetry and tidal current speed, such that those regions with shallow water and high tidal velocities receive high resolution and vice versa. The tidal current speed weighting was derived from an initial run, where high resolution as a function of tidal amplitude was prescribed. This initial grid resulted in some areas with moderate tidal range but high velocity due to tidal flows through relatively narrow constrictions (e.g. Banks Strait) receiving moderate resolution. The use of tidal velocity in preference to tidal amplitude in the weighting function circumvented this dependency. The model mesh has 183810 2D cells with a minimum resolution of ~64 km and maximum resolution of ~395 m. The mean distance between cell centres in this mesh was 2100 m and the mean length of edges in the mesh was 3680 m. An example of the transition of resolution this achieves around Flinders Island is shown in Fig. 1.

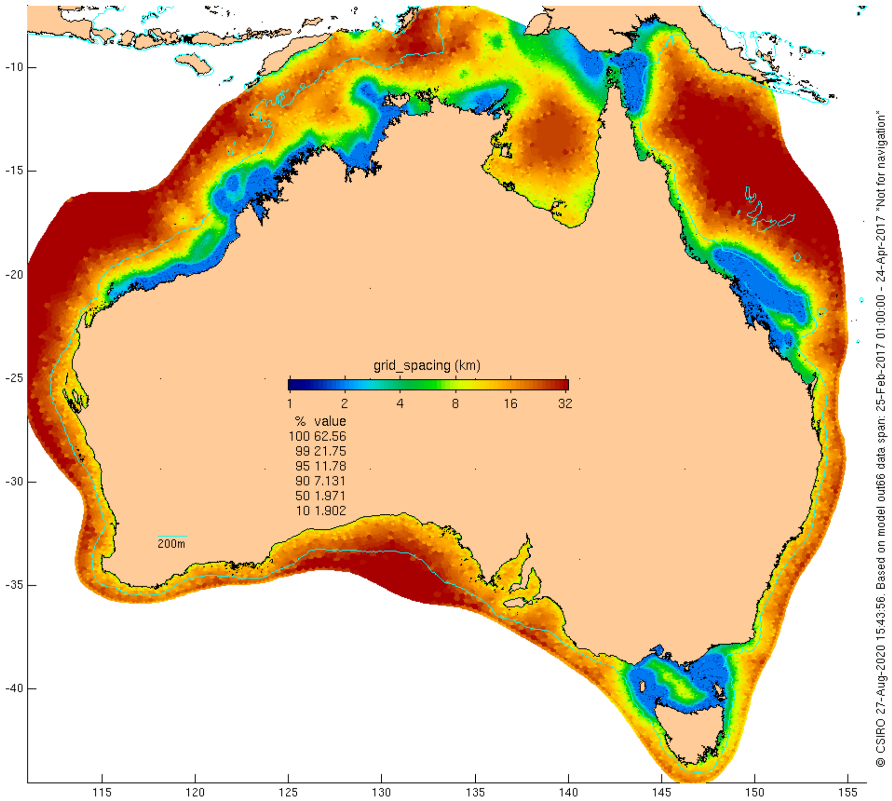


Figure 30: Resolution of the 2D ARENA mesh

The tide was introduced through 8 tidal constituents (M2 S2 N2 K2 K1 O1 P1 Q1) from the TPXO9v1 1/6° global model[39] applied at the boundary of the regional model using the open boundary condition described by Herzfeld et al.[40], which is a normal and tangential velocity Dirichlet condition, with a local flux adjustment on normal velocity to maintain volume continuity. Importantly, the surface elevation is unconstrained and is computed via volume flux divergence as is done in the model interior. To account for bathymetry differences between our model and the TPXO model, the depth averaged forcing velocity was computed from TPXO tidal transports (interpolated onto the model cell faces) divided by the model depth. A spatially constant bottom drag coefficient of 0.003 was used to compute bottom stress. The model started from rest and was run for 59 days from 24 Feb to 24 Apr 2017, including a 1-day ramp period.

[37] Beaman, R. 2010. Project 3DGBR: a high-resolution depth model for the Great Barrier Reef and Coral Sea. Final Report to Marine and Tropical Sciences Research Facility Final Report, June 2010

[38] Beaman and Spinoccia (2018). High-resolution depth model for Northern Australia - 30 m. https://cmi.ga.gov.au/high-resolution_depth_model_for_northern_australia_-_30_m

[39] Egbert, Gary D., and Svetlana Y. Erofeeva. (2002). Efficient inverse modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology 19.2: 183-204.

[40] Herzfeld, M., Engwirda, D., Rizwi, F. (2020) A coastal unstructured model using Voronoi meshes and C-grid staggering. Ocean Modelling, 148, 101599. https://doi.org/10.1016/j.ocemod.2020.101599

Model Validation

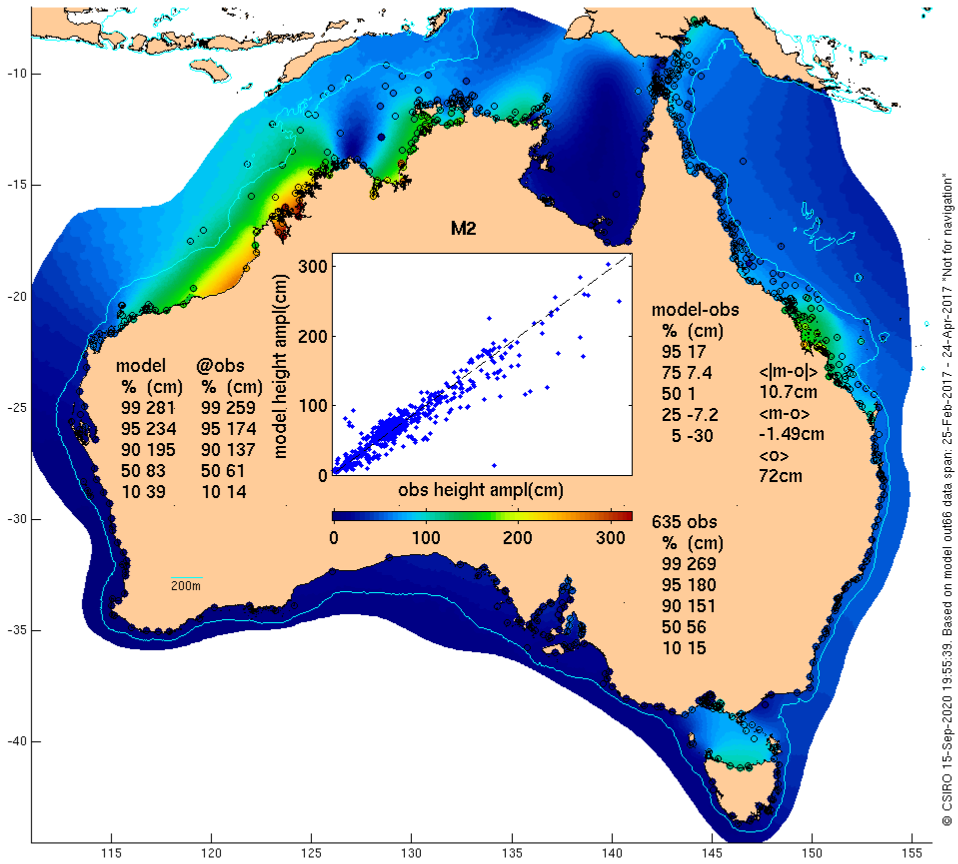
The Performance of the final model solution – The AUSTEn national tidal model – has been measured relative to a large database of observed tidal elevations and velocities across the national domain. These data are largely pre-existing 'opportune' data available as a result of previous national and regional observational campaigns, and include 683 tidal elevation gauges and 96 current meters. Model results were also compared to field data collected in Banks and Clarence Strait as part of this project. Validation of tidal height data are carried out according to the IEC-TC 114 Technical Specification 62600-201[41], compared on the basis of harmonic constituents of amplitude and phase. Additionally, comparisons of time-series between numerical model simulated tidal elevation and tidal elevation reconstructed from observed tidal constituents were completed. Observational records all exceed the 59 days duration of the numerical model, to enable comparison of equivalent tidal constituents.

Comparisons of tidal constituents from the AUSTEn National Tidal Model were performed by comparisons of tidal harmonics from the numerical model with that obtained from observations. Results were found for 5 variables (tidal elevation amplitude, h and phase, hg; and tidal velocity semi-major axis, maj; inclination, inc; and phase, ug), for 11 tidal constituents (M2, S2, N2, K1, O1, Q1, M4, MS4, M6, 2MS6, 2N2), across 18 regions/sub-regions, making a total of 990 comparisons. Comparisons between model and observations for the M2 lunar semi-diurnal tidal constituent, as the dominant constituent, are displayed for elevation amplitude and phase in Figure 31, and the semi-major axis of the tidal velocities in Figure 32. Model Bias statistics for all constituents are presented in Table 15: Summary of model performance, reflecting tidal constituents comparisons. Bias (model – observed) between national model and observed tidal constituents

Table 15: Summary of model performance, reflecting tidal constituents comparisons. Bias (model – observed) between national model and observed tidal constituents

Constituent	Elevation (N=635)		Velocity (N=95)
	Amplitude Bias (cm)	Phase Bias (degrees)	Major-Axis Bias (cm/s)
M2	-1.5	3.4	1.2
S2	5	1.9	2.4
N2	-0.52	3.9	0.14
K1	-9	4.6	-2.3
O1	-0.44	2.1	-0.46
Q1	0.38	7.5	0.22

[41] International Electrotechnical Commission, (2015). Technical Specification IEC TS 62600-201: Marine energy – Wave, tidal and other water current convertors – Part 201: Tidal energy resource assessment and characterization.



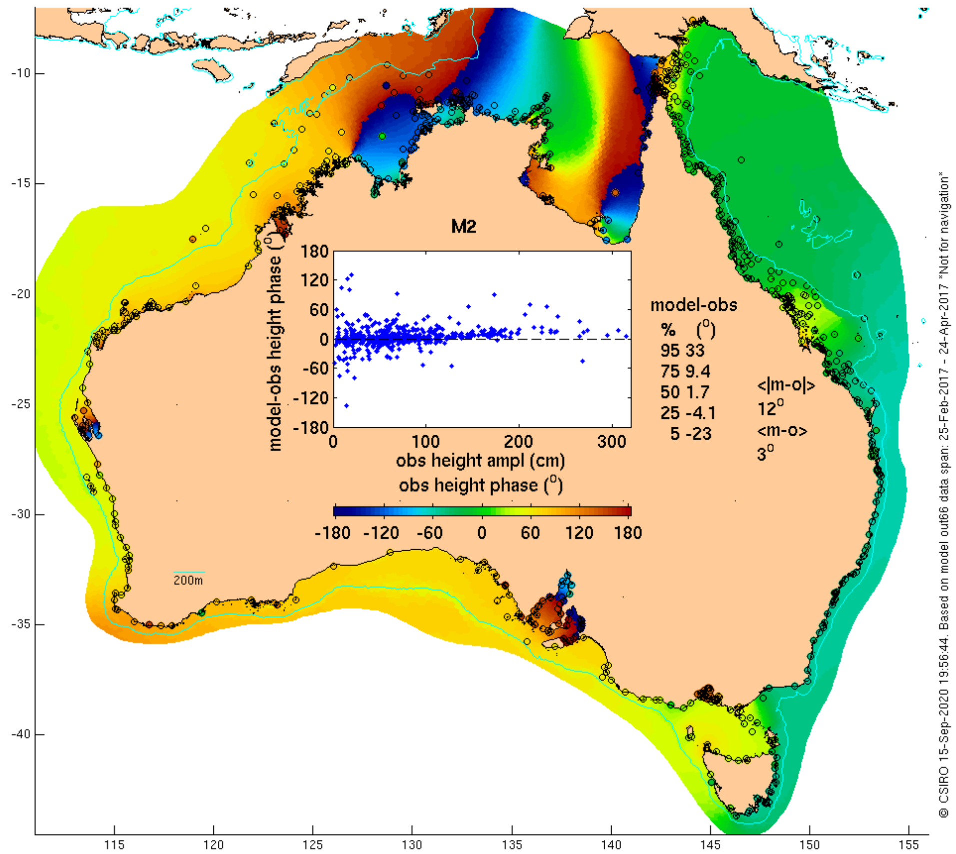


Figure 31: Map of Tidal Elevation Constituents. A) M2 Amplitude (m) and B) M2 Phase (degrees). The model extent is displayed with the model solution displayed. The overlain circles display corresponding observed values. The inset scatter diagrams display the agreement between observed (x-axis) and modelled (y-axis) constituents

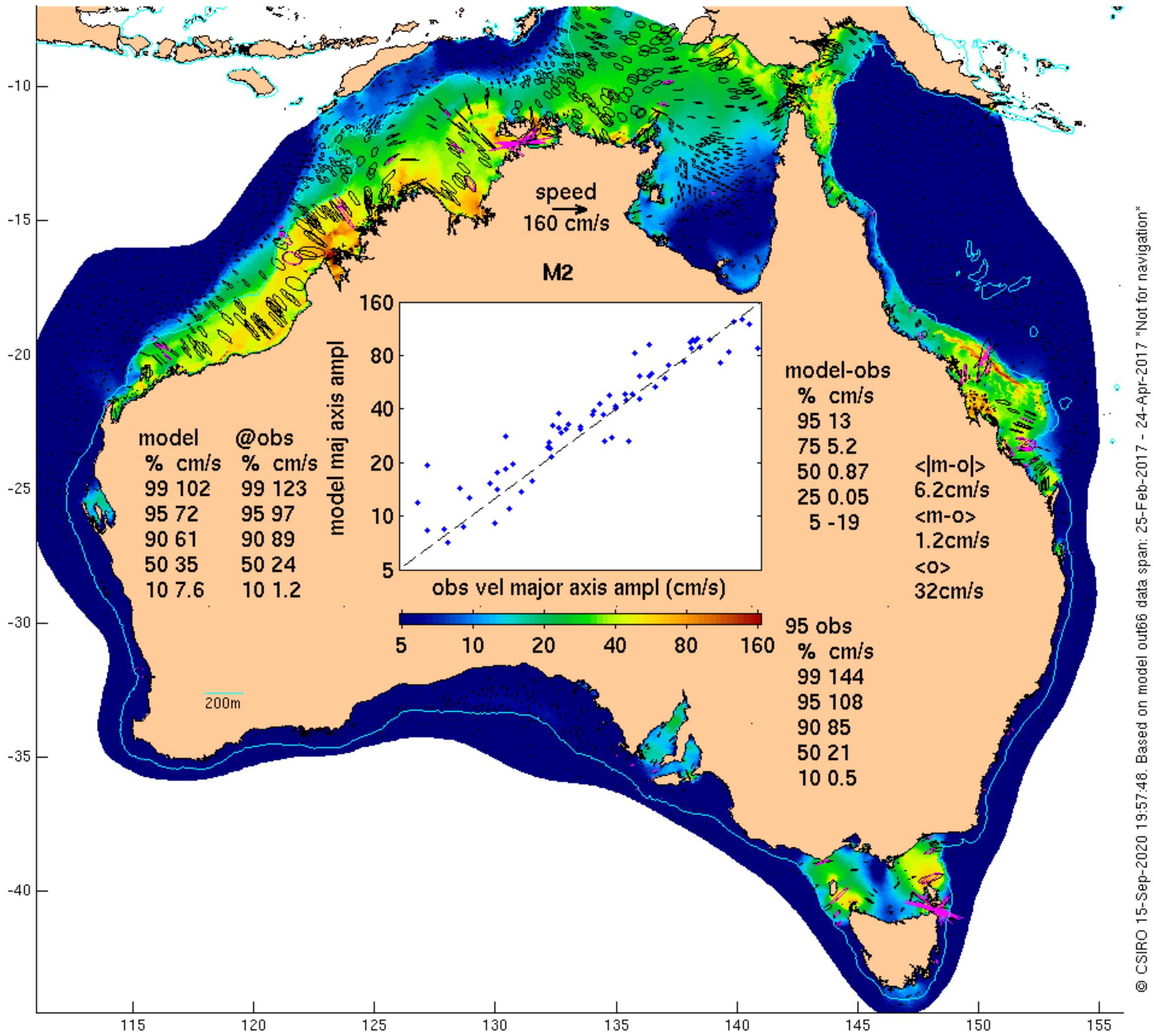


Figure 32: Map of Semi-major axis of the M2 tidal velocity constituents. The model extent displays the magnitude of the M2 semi-major axis from the modelled solution. Overlain black ellipses display modelled M2 tidal ellipses. Overlain pink ellipses display corresponding observed M2 tidal ellipses. The inset scatter diagram displays the agreement between observed (x-axis) and modelled (y-axis) M2 semi-major axis of the tidal velocities

Time-series comparisons of numerical model and observed tidal elevations and velocities were also performed at each site, with an example elevation time-series comparison presented for Darwin in Figure 33, An example velocity time-series comparison is presented for Darwin CW2 current meter, collected as part of the AUSTEn campaign in Figure 34

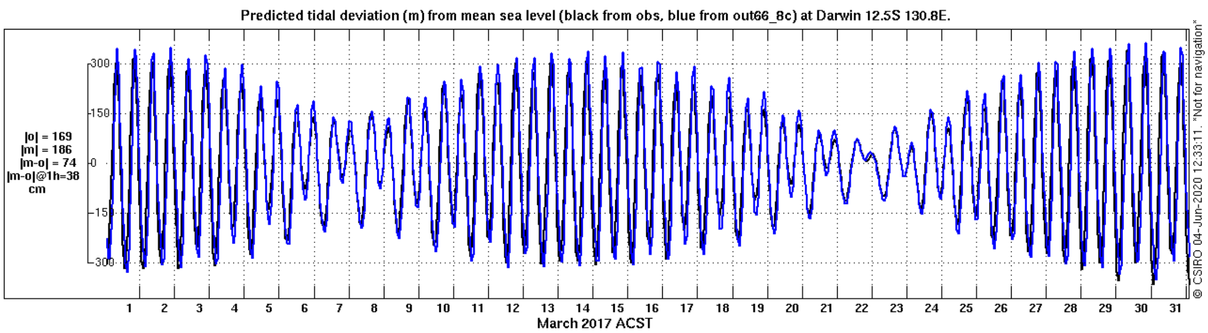


Figure 33: Time-series comparisons of observed (black) vs model (blue) tidal elevations at Darwin

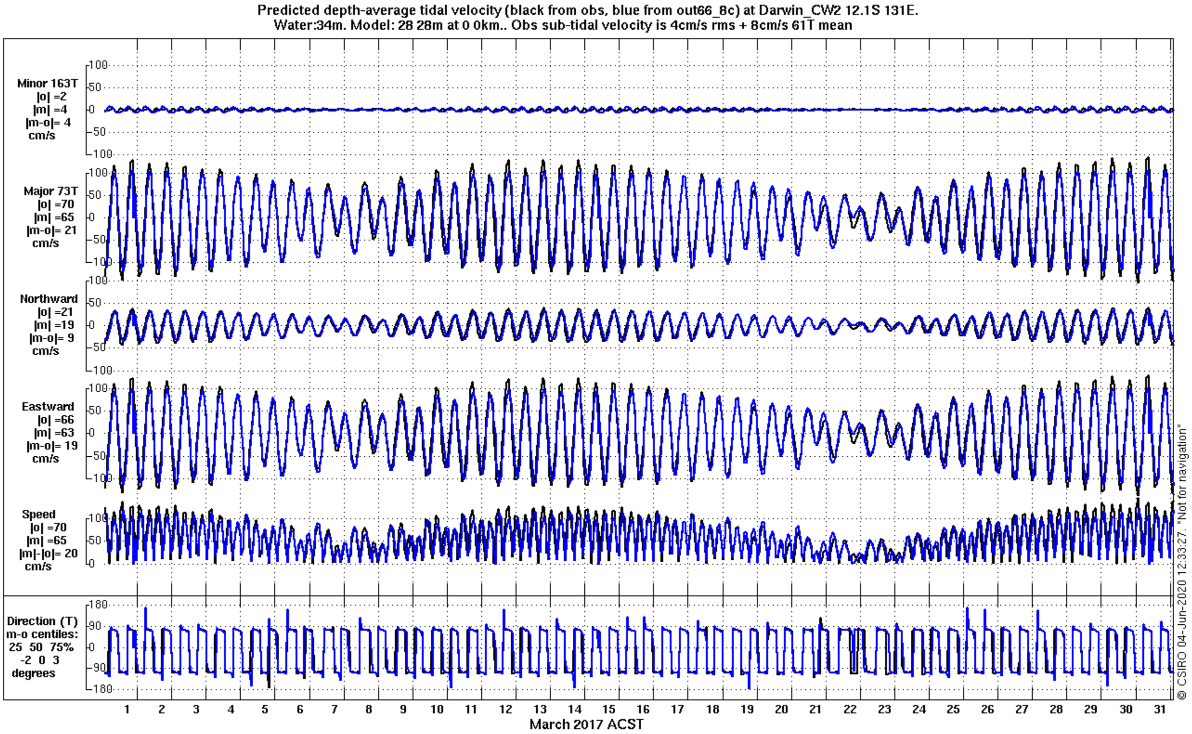


Figure 34: Time-series comparisons of observed (black) vs model (blue) velocities at the AUSTEn Darwin_CW2 site

Overall summary statistics of model-based vs observation based predictions are presented in Figure 35.

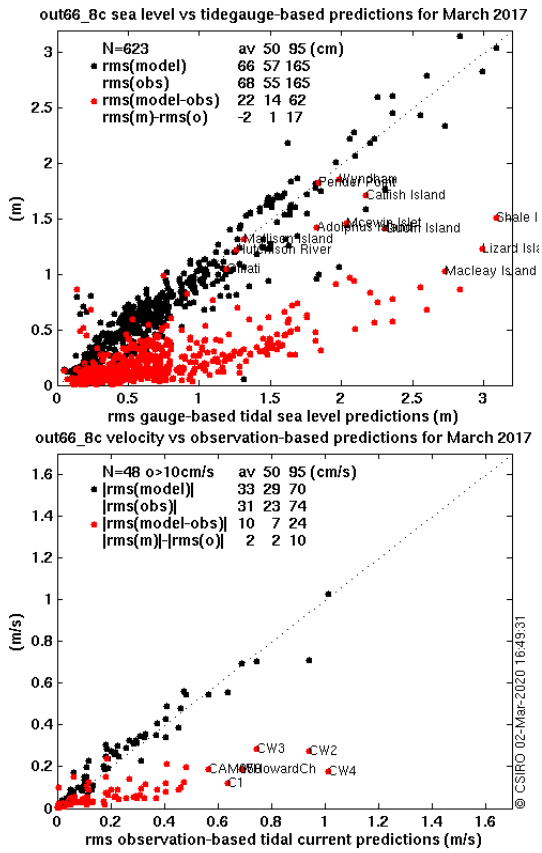


Figure 35: Statistics of model-based and observation-based predictions. Top presents comparison of tidal elevation statistics, bottom presents comparison of tidal velocity statistics. Black dots present the rms of numerical model values (y-axis) relative to the rms of the observation based predicted values (x-axis). Red dots present the rms of model error (y-axis) relative to the rms of observation based predicted values

Summarising, the performance of the AUSTEn national model is equivalent to the forcing model (TPXO9v1) when assessing tidal elevations (Table 1). Mean/Median elevation performance is within 2-3 cm of the TPXO model. For high tidal range areas (95th percentile), the AUSTEn model has a better fit with observed values. Given the TPXOv9 model assimilates tidal elevation data into the final solution (limiting independence of data and model), this illustrates the high performance of the AUSTEn model. As a consequence, the AUSTEn national tidal model performance exceeds that of previously available models when assessing tidal current speeds.

Resource Summary

The Australian national tidal energy resource is summarised via a number of parameters, following the IEC TC-114 TS 62600-201 for a Stage 2a tidal resource feasibility assessment. Using 30-min archived output from the AUSTEn national model simulation, the following parameters have been computed to summarise the Australian national tidal resource and made available via the Australian Renewable Energy Mapping Infrastructure (AREMI).

Figure 36, as example, presents the maximum tidal current speed (SPPC_100) in m/s. This figure illustrates the localisation of prospective tidal stream energy sites, with high tidal streams identified in localised regions across the North-West of the continent, and sparse sites elsewhere, as explored further in Component 3.

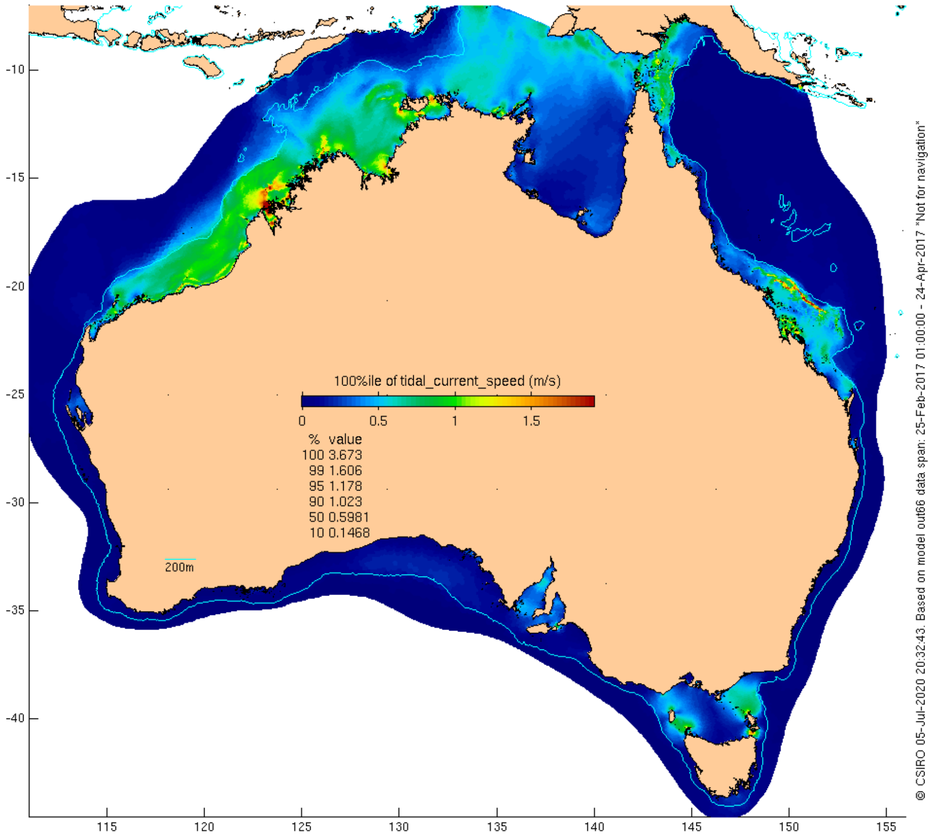


Figure 36: The Maximum Tidal Current Speed (100th Percentile) (m/s) computed from the AusTEN national tidal model simulation. The table of values displays spatial percentile values – the maximum (100th percentile) of 3.673 m/s occurring on the Kimberley coast

The AUSTEn National Tidal Model data is made available via CSIRO's Data Access Portal. Metadata is available at https://data.csiro.au/collections/collection/CIcsiro:45584 with all data served via CSIRO Thredds & OPeNDAP data services.

http://data-cbr.csiro.au/opendap/OA_SLE_processed/ARENA_tide/contents.html

http://data-cbr.csiro.au/thredds/catalog/catch_all/OA_SLE_processed/ARENA_tide/catalog.html

This data, which includes the 59 day model output, including hourly archives of tidal elevation and velocities, and tidal constituents, is made available under a Creative Commons Attribution-ShareAlike 4.0 International Licence.

Banks Strait, Tasmanian and Clarence Strait, Northern Territory Fine-Scale Models

Research conducted by the Australian Maritime College, University of Tasmania used the COMPAS ocean modelling software to determine the magnitude of tidal currents and elevations, enabling the assessment of the tidal resource characteristics of the Banks and Clarence Strait regions. To ensure the accuracy of these developed models, results were compared to field measurements performed using Acoustic Doppler Current Profiler (ADCP) field data collected as part of the AUSTEn project and outlined in the previous section. These resource assessments were completed to meet the international standards for performing resource assessments of tidal currents (IEC 114:60201) to ensure their accuracy.

Bathymetry, Mesh and Forcing

Models for Banks and Clarence Strait were developed using 2D and 3D unstructured hexagon-dominated meshes, with a graduated mesh refinement based on distance from the key region of interest: Banks and Clarence Straits, an example of which is shown in Figure 37. Bathymetry data for the Banks and Clarence Strait models was collated from three sources: the Geoscience Australia 2009 bathymetry dataset[42], AHS charts[43], and multibeam conducted as part of the AUSTEN project, and for the Clarence Strait from the Northern Australian 30 m bathymetry dataset. The multibeam survey results from the AUSTEn field campaign were used for high resolution modelling accuracy across the Banks and Clarence Strait. The coastline data used to develop the COMPAS model domains was collated from the high-resolution dataset of the Global Self-Consistent, Hierarchical, High Resolution Geography Database (GSHHG)[44].

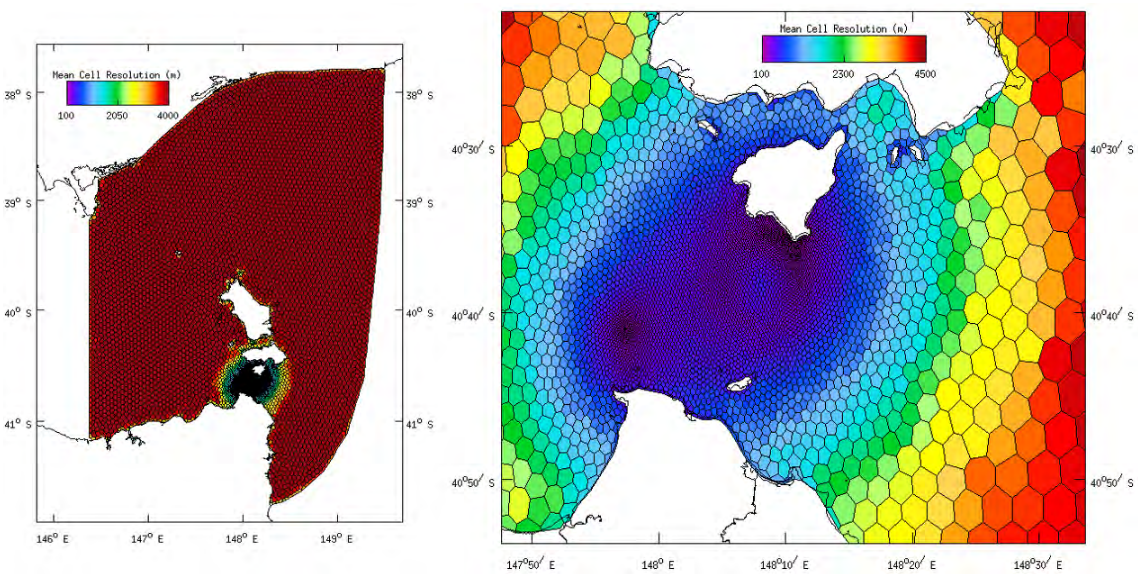


Figure 37: Example of COMPAS simulation model mesh domain showing (left) full domain and (right) closeup of Banks Strait region where the highest mesh density was located

The lateral boundaries were of the developed COMPAS models were forced using a normal and tangential Dirichlet boundary condition which uses a flux adjustment time scale to prevent total volume drift over time[45]. This forcing used predictions of elevations generated by the OSU TPXO9v1 tidal data inversion model, which used eight primary harmonic constituents (M2 S2 N2 K2 K1 O1 P1 Q1) applied as transports at the boundary edges[46].

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[42] Whiteway, T. G. (2009). Australian bathymetry and topography grid. Geoscience Australia, Canberra, Australia

[43] Australian Hydrographic Office Charts, (n.d.). http://www.hydro.gov.au/prodserv/paper/auspapercharts.htm

[44] Wessel, P., & Smith, W. H., (1996). A global, self-consistent, hierarchical, high-resolution shoreline database, Journal of Geophysical Research: Solid Earth, vol. 101:B4, pp. 8741-8743

[45] Herzfeld,M., & Waring, J.R., (2020). SHOC Sparse Hydrodynamic Ocean Code / COMPAS Coastal Ocean Marine Prediction Across Scales User Manual V6527, CSRIO Marine Research, Hobart, Australia

[46] Egbert, Gary D., and Erofeeva, S.Y., (2002). Efficient inverse modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology 19.2: 183-204.

Model Calibration and Validation

Tidal current validation was performed by comparing the COMPAS simulation surface elevation and depth-averaged 2D current velocities with the ADCP field data collated as part of the AUSTEn field campaign as outlined in Section 3. The simulation models were calibrated by varying bottom friction, horizontal viscosity and diffusion until good agreement was found with the AWAC field survey data. Given the difficulty in calibrating simulation results against up to five widely spaced ADCP stations, considerable effort was placed in model calibration and validation, with examination of harmonic coefficients, statistical metrics using Taylor diagrams, probability exceedance distributions and resource area determinations were performed, with the methodology following IEC standards. All calibration runs were performed for 36 days to meet IEC standard simulation time guidelines, with an additional initial 7 days of simulation results removed to avoid any start-up transients. Once completed the successfully calibrated model was then run for longer time frames corresponding to the long-term deployments in Banks and Clarence Strait to ensure model accuracy in capturing the tidal resource at these sites over these timeframes. Results indicated that 2D simulation models offered comparable accuracy to 3D simulation models but at significantly reduced computational cost, and hence the 2D models were used for all resource assessments and turbine modelling simulations.

The high level of agreement between the COMPAS model and the ADCP field data demonstrates that the developed numerical models are accurately simulating both the continuity and momentum / advection processes driving the current flow in the Banks and Clarence Strait region, confirming the models suitability for determining power density and AEP estimates for tidal turbine deployment planning purposes.

Resource Summary

Using the validated models estimates of tidal current velocity, power density, probability distribution, exceedance probability and resource area determinations were performed for each strait. Possible locations for a tidal farm array were then investigated for each site, along with examination of influence of energy extraction on local and far-field surface elevations and currents due to the presence of TEC. This required the addition of turbine modelling parameters to the COMPAS model, which were calibrated against theoretical channel results[47] to ensure their accuracy.

Banks Strait

The tidal current resource in the Banks Strait identified by the tidal assessment was promising. The distribution of mean and maximum current velocities across the Banks Strait was consistent, with a large region across the Strait exhibiting good tidal resource levels for TEC installation, with maximum values found at the narrowest part of the channel as expected. Peaks in current velocity of approximately 3 m/s were found to the south near the Tasmanian mainland, and at the tips of Clarke Island as shown in Figure 38 located at (148°10’37.2”E, -40°35’50.28”S) with a maximum AEP of 20 MWh/m^2 found.

[47] Yang, Z., Wang, T., and Copping, A. E. (2013). Modeling tidal stream energy extraction and its effects on transport processes in a tidal channel and bay system using a three-dimensional coastal ocean model. Renewable Energy, 50, 605-613.

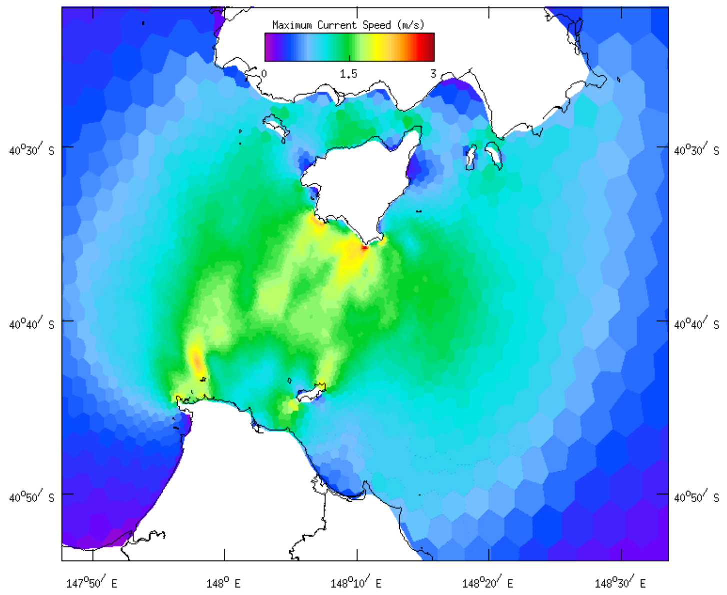

Figure 38: Maximum current velocities in the Banks Strait region, found using the developed 2D Cd=0.0185 COMPAS model over a 36-day period

Using the developed models, resource size at depth ranges can be extracted to obtain greater understanding of the distribution of the tidal resource as shown in Figure 39, with results indicating that the largest resource is found at water depths between 30 m to 50 m.

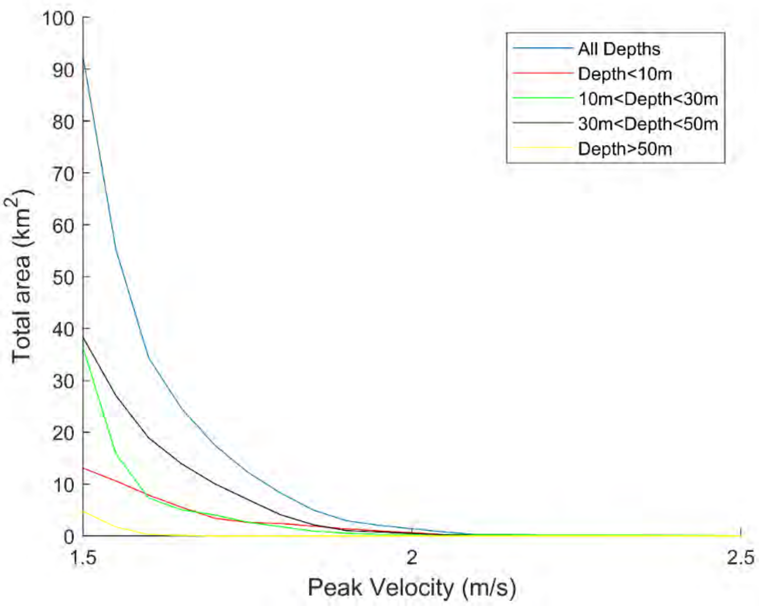

Figure 39: Potential tidal stream resource for Banks Strait for differing depths

Two regions in the Banks Strait are promising for TEC deployments with differing site characteristics. The first is an area of high current velocity located to the north of the Tasmania mainland as shown in Figure 40. Due to the rapid shelving in bathymetry and the restriction of the Banks Strait, peak velocities in excess of 2 m/s were found in this region along a roughly northern-orientated line. As the water depth was limited to between 6 to 10 m this site would suit the deployment of an array of small diameter TECS. The second site identified as promising is located south of Clarke Island as shown in Figure 40, where peaks in velocity over 2.5 m/s were found at water depths above 30 m, making this site suitable for the installation of large-scale TEC's. At both prospective sites low tidal direction asymmetry was found indicating that TEC with yaw control may not be required at these two sites, reducing TEC design complexity.

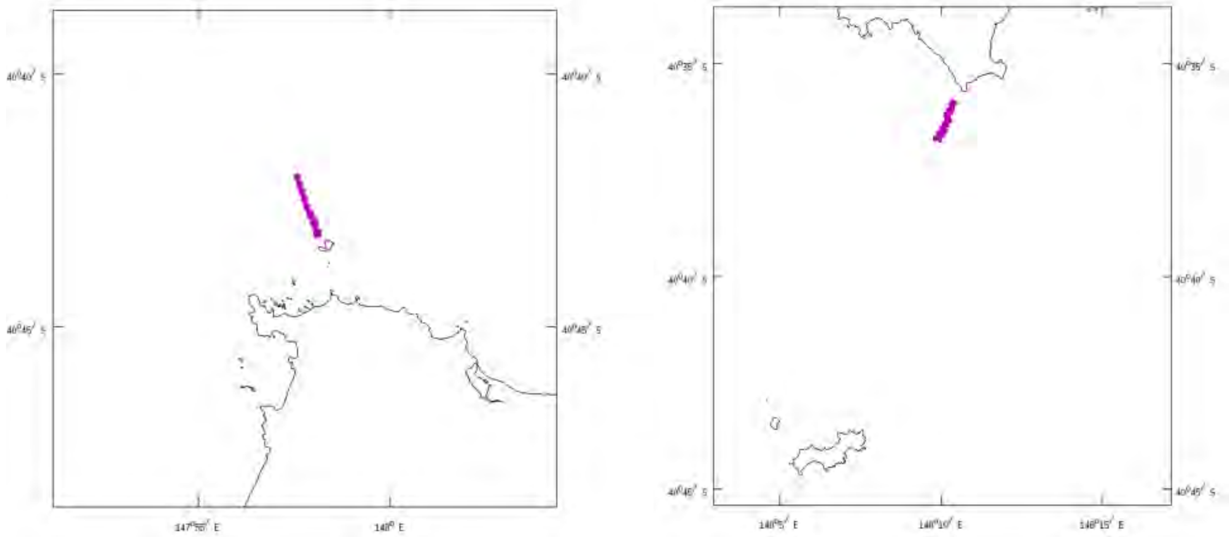

Figure 40: Location of TEC array (left) Farm 1 and (right) Farm 2 in Banks Strait

Energy Extraction Modelling

To simulate the energy production of proposed TECs two methods were used, the first following IEC Annex A (called IEC Annex A Model) of the IEC TS 626-201[48] and EMEC guidelines[49], the second by modelling the 2D energy extraction using a bottom friction energy removal approach (called 2D Bottom Friction Model)[50]. The first approach does not require any additional numerical modeling once the resource assessment has been completed, allowing for quick estimation of energy production for any given farm layout. The second approach requires the injection of modified bottom friction coefficients into the resource assessment to account for the presence of TEC arrays, and hence requires additional simulation runs. This bottom friction model was added to the COMPAS model as part of this project. Two TEC farms were simulated in each of the Banks and Clarence Strait, with rated capacities of up to 40 MW per farm as outlined in Table 16.

Table 16: Main farm parameters for Farms 1 and 2 in Banks Strait

	Farm 1	Farm 2
Turbine Diameter	3	20 (Twin Rotor)
Total Number of Turbines	295	40
Rated Velocity	1.5 m/s	1.6 m/s
Rated Power	4 kW	490 kW
Farm Rated Power	1.2 MW	19.6 MW
Average TEC AEP	6 GWh	52 GWh
Average TEC Capacity Factor	0.43	0.32

Using the developed turbine model the presence of both TEC farms has reduced the flow velocity in the TEC near-field as expected with reductions of up to 5 cm/s determined as shown in Figure 41. Given that the current regularly exceed 2.0 m/s in this region, this implies little minimal environmental disturbance is caused by the presence of the two TEC arrays. As expected, the larger TEC

[48] International Electrotechnical Commission, (2015). Technical Specification IEC TS 62600-201: Marine energy – Wave, tidal and other water current convertors – Part 201: Tidal energy resource assessment and characterization.

[49] EMEC, (2009). Assessment of Tidal Energy Resource. Retrieved 30th September 2020, from http://www.emec.org.uk/assessment-of-tidal-energy-resource/

[50] Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C., (2020. Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished)

array to the north of Banks Strait exhibits increased reduction in velocity, as the larger array extracts approximately 10 time more energy from the flow as shown in Figure 41.

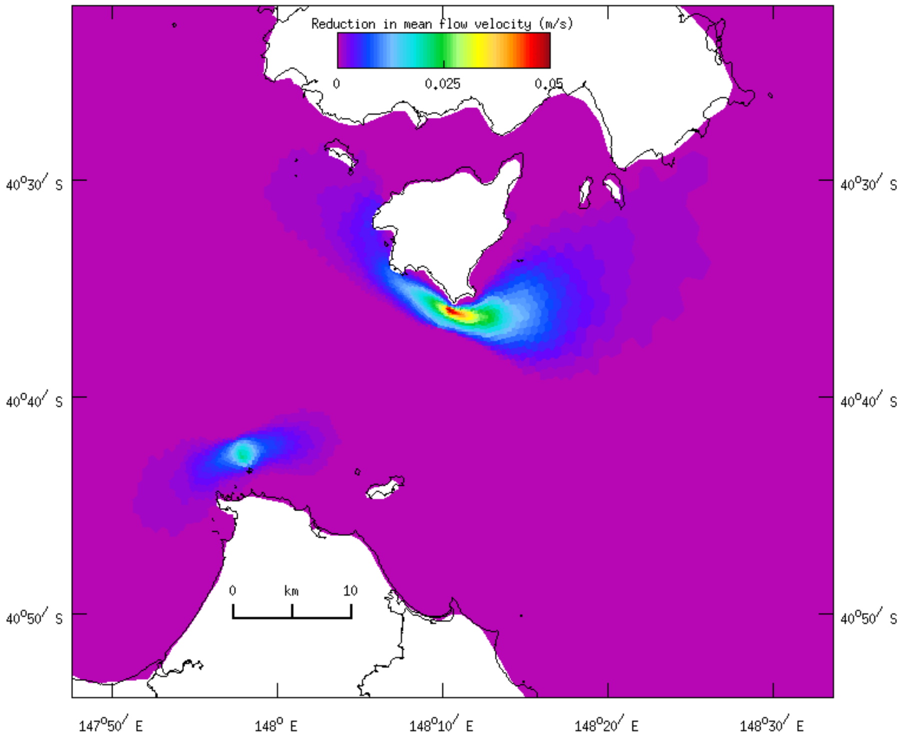

Figure 41: Changes in mean flow velocity over Banks Strait caused by the presence of Farms 1 and 2

Clarence Strait

The Clarence Strait tidal resource was found to be promising, with peaks in current velocity of up to 2.55 m/s predicted in the regions surrounding the Vernon Islands, confirming their suitability for TEC installations. Using the developed models the spatial distribution of mean and maximum current velocities across the Clarence Strait were found as shown in Figure 42, with large tidal current velocities consistently found in the channels that are aligned with the mean flow directions between the Vernon Islands. The formation of these channels results from considerable scouring by the high currents between the Vernon Island group. A maximum AEP of 12 MWh/m^2 was found for the Clarence Strait at the location of maximum velocity of 2.55 m/s.

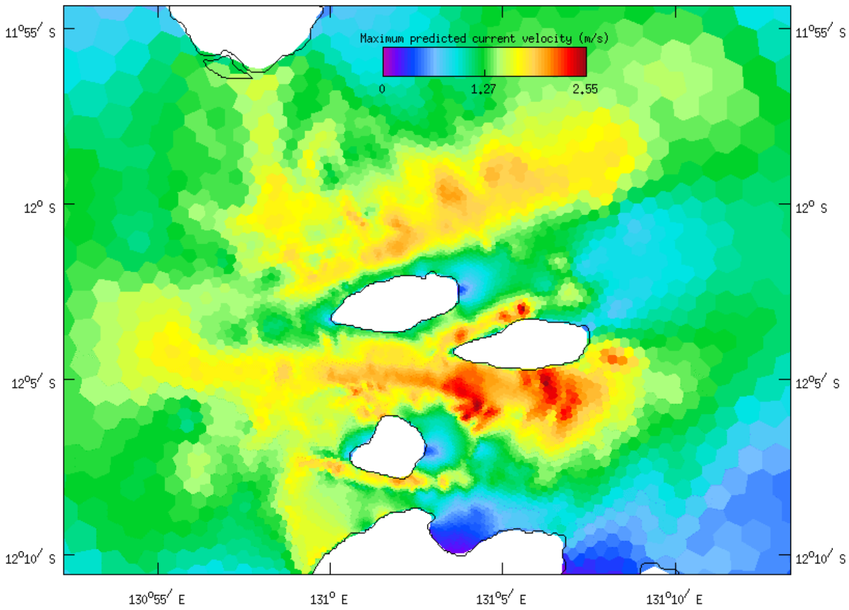

Figure 42: Maximum tidal current velocity found by the numerical models in the Clarence Strait around the Vernon Island group

Investigations of the spatial distribution of tidal current between 1.5 m/s and 3.0 m/s were performed for three depth ranges that cover a range of TEC operating design depths and blade sizes; less than 10 m, between 10 m and 30 m, and from 30 m to 60 m deep. Given the high tidal range in the region, depths of under 10 m may be problematic for TEC array installation if they are to maintain adequate top and bottom clearances for shipping and other users. The most promising regions for TEC placements were found to occur between the East and South East Vernon Islands, with current velocities of up to 2.55 m/s found over wide channel lengths of up to 2 km at water depths of between 30 m and 60 m as shown in Figure 43.

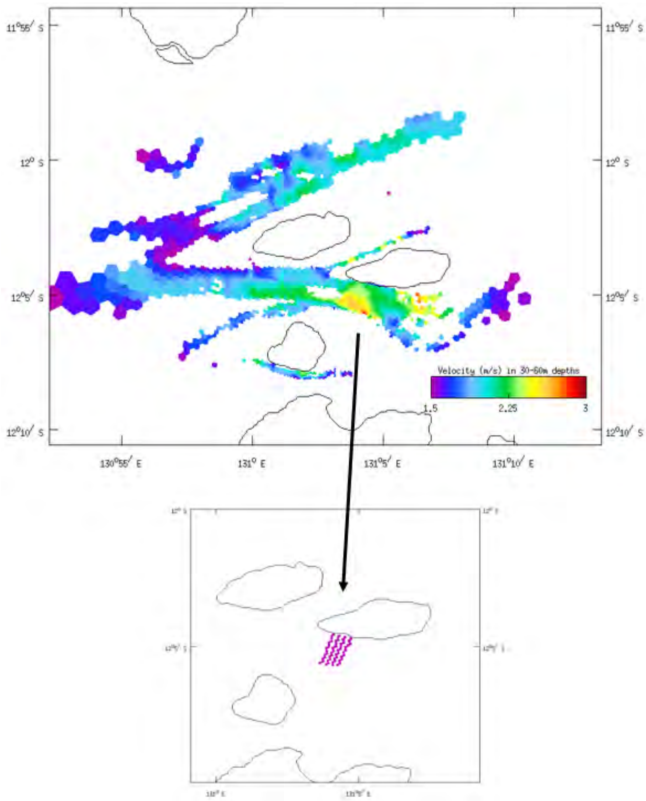

Figure 43: Example of location of simulated of TEC farm arrays compared to maximum velocity ranges at depths between 30 and 60 m

Using the developed turbine performance models, two TEC farms of differing turbine design were simulated in the location shown in Figure 43; one an array of 295 10 m diameter TEC's site in water depths greater than 30 m, the other at the same location using an array of 59 20 m diameter twin rotor TECs. The 10 m and 20 m turbine designs were based on EMEC guidelines driven by site characterisation and depth results from the numerical. The main TEC design characteristics of both turbines are outlined in Table 17, along with the average AEP and capacity factors determined using the two calculation methods.

Table 17: Main TEC design parameters and turbine farm outputs

	10 m Farm	20 m Farm
Turbine Diameter	10 m	20 m (Twin Rotor)
Total Number of Turbines	295	59
Rated Velocity	1.7 m/s	1.7 m/s
Rated Power	100 kW	700 kW
Farm Rated Power	35 MW	40 MW
Average TEC AEP	64 GWh	96 GWh
Average TEC Capacity Factor	0.28	0.27

Similar to the Banks Strait model, the presence of TEC farms has reduced the flow velocity in the TEC near-field as expected with reductions of up to 3 cm/s determined as shown in Figure 44 for the case of the 20 m Farm, implying minimal environmental disturbance due to the presence of the two TEC arrays as current speed regularly exceed 2.0 m/s in this region.

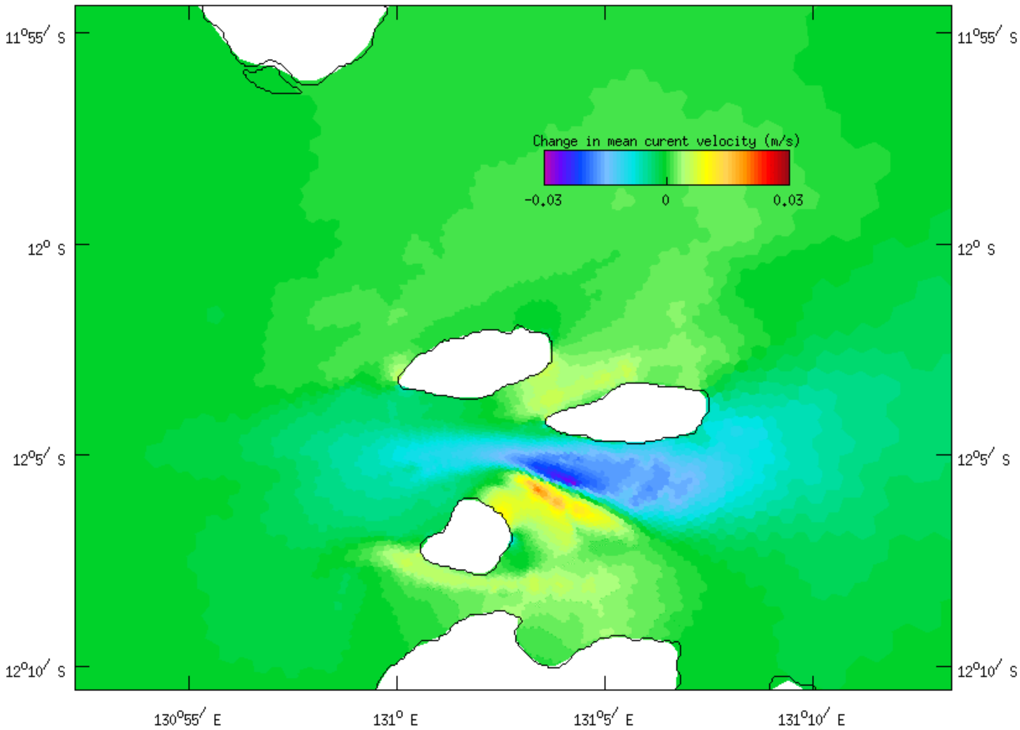

Figure 44: Example of changes in mean flow velocity over Banks Strait caused by the presence of two TEC farms in Banks Strait

Multicriteria Assessment Model

As part of the selection of the Clarence Strait field site a multi-criteria assessment of site suitability was performed. This study used a Multi-Criteria Assessment (MCA) approach using Geographic Information System (GIS) layers to determine a site suitability index and allows for the assessment of numerous factors that may influence site selection, including resource size, electrical grid proximity and size, water depth, environmental (marine parks and reserves) and other users, including fisheries, no anchor zones and other restrictions, with a summary of factors shown in Figure 45, with details of each outlined below.

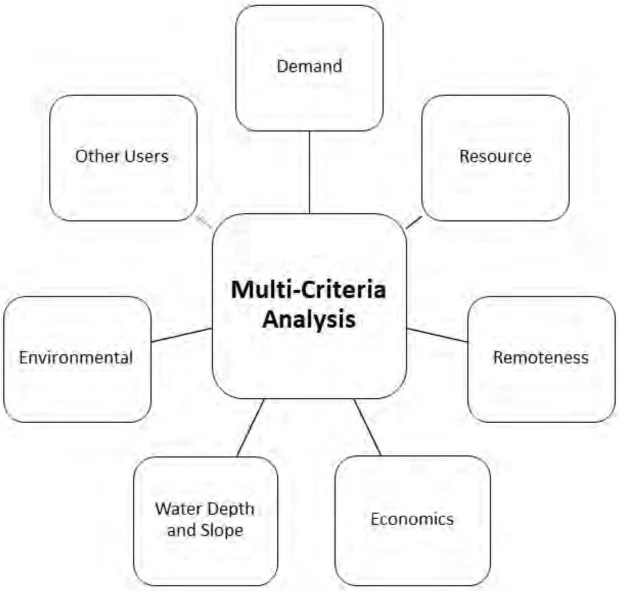

Figure 45: Examples of factors used in Multi-Criteria Assessment

The developed MCA model identified a number of promising locations in Australia, including the Banks Strait region northeast of Tasmania, regions to the north of Darwin, Northern Territory, and Backstairs Passage off Kangaroo Island, South Australia. Preliminary results from the MCA as shown in Figure 46 determined that the Clarence Strait, Northern Territory exhibited high suitability when measured using criteria including resource size, water depths and slopes suitable for tidal turbine deployment, suitable distances to coastline and ports to minimise capital and operational expenditure, proximity to grid substation connections at Gunn Point, with no major environmental restrictions identified.

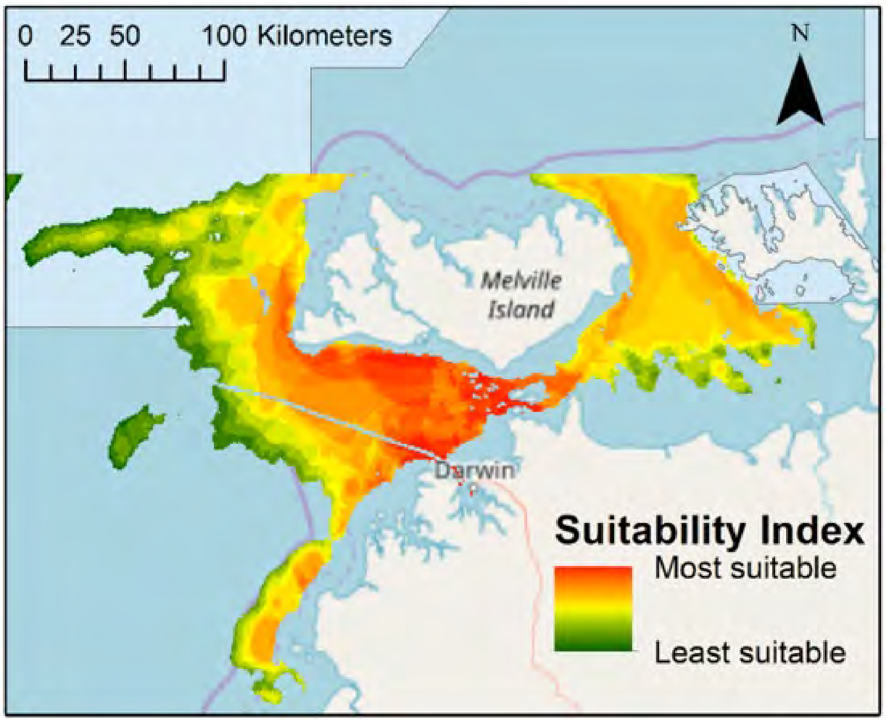

Figure 46: Preliminary tidal turbine site suitability index generated by Multi-Criteria Assessment model for Darwin, Northern Territory, determined using depths between 20 m and 60 m, with equal weighting for the national hydrodynamic model top 5% spring currents

Tidal resource layers in AREMI and Data Availability

Both the national and fine-scale models of Banks and Clarence Straits are made available on the Australian Renewable Energy Mapping Infrastructure[51]. This AREMI functionality includes the presentation of tidal resource variables as raster images via the Australian Marine Energy Atlas (Figure 47). AREMI provides the following spatial layers of national and regional tidal energy resource:

- Tidal Stream Kinetic Energy
  - Daily average Tidal Stream (0:10:100th percentiles)
    - National
  - Tidal stream Kinetic Energy Flux (0:10:100th percentiles)
    - National
    - Banks Strait
    - Clarence Strait

- Tidal Current Speed
  - Daily average Current Speed (0:10:100th percentiles)
    - National
  - Percentile Tidal Current Speed (0:10:100th percentiles)
    - National
    - Banks Strait
    - Clarence Strait
  - Tidal Current Exceeds (% occurrence speed exceeds 1.0, 1.5 and 2.0 m/s).
    - National

- Tidal Range
  - Percentile Tidal Range (0:10:100th percentile)
    - National
    - Banks Strait
    - Clarence Strait
  - Tidal Range Power Density (annual mean)
    - National

An example of the AREMI output is shown in Figure 47, which displays the 50th percentile of Daily Kinetic Energy Flux (W/m2).

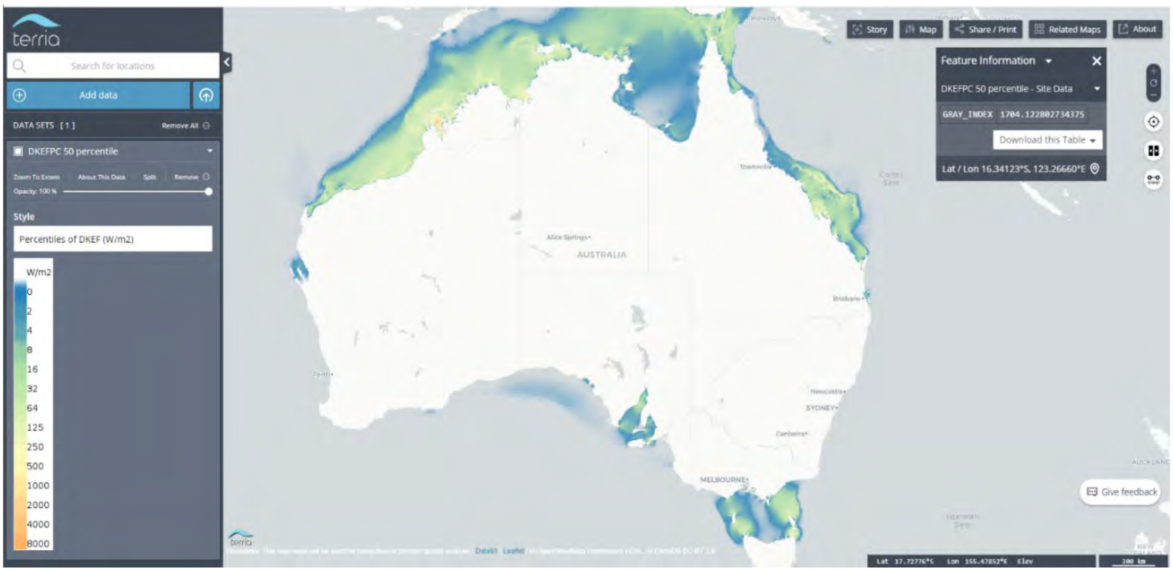

Figure 47. Example display of Tidal Energy Resource Layer in CSIRO development version of AREMI. Here, DKEFPC50 is displayed, according to the colour scale on the LHS. The Feature information box on top-right displays functionality to choose location to obtain layer value (GRAY_INDEX = 1744 W/m2) for chosen location.

[51] Australian Renewable Energy Mapping Infrastructure (AREMI). http://www.nationalmap.gov.au/renewables

Further to the display of spatial raster layers, a number of analysis tools have been developed by CSIRO OA for inclusion in the AREMI tools to assist with assessment of available tidal energy resource at selected locations. These include: Velocity and Kinetic Energy Flux probability distribution curves, Tidal roses, signifying speed and direction of tidal velocities at the specified location, Time-series extraction of tidal velocities (speed and direction) and elevations at the specified location. Each of these tools provides an on-the-fly data extraction, computation, figure output, and ascii table for download. If the specified location coincides with availability of observations, observed conditions will also be provided. Example output for each of the analysis tools is displayed in Figure 48.

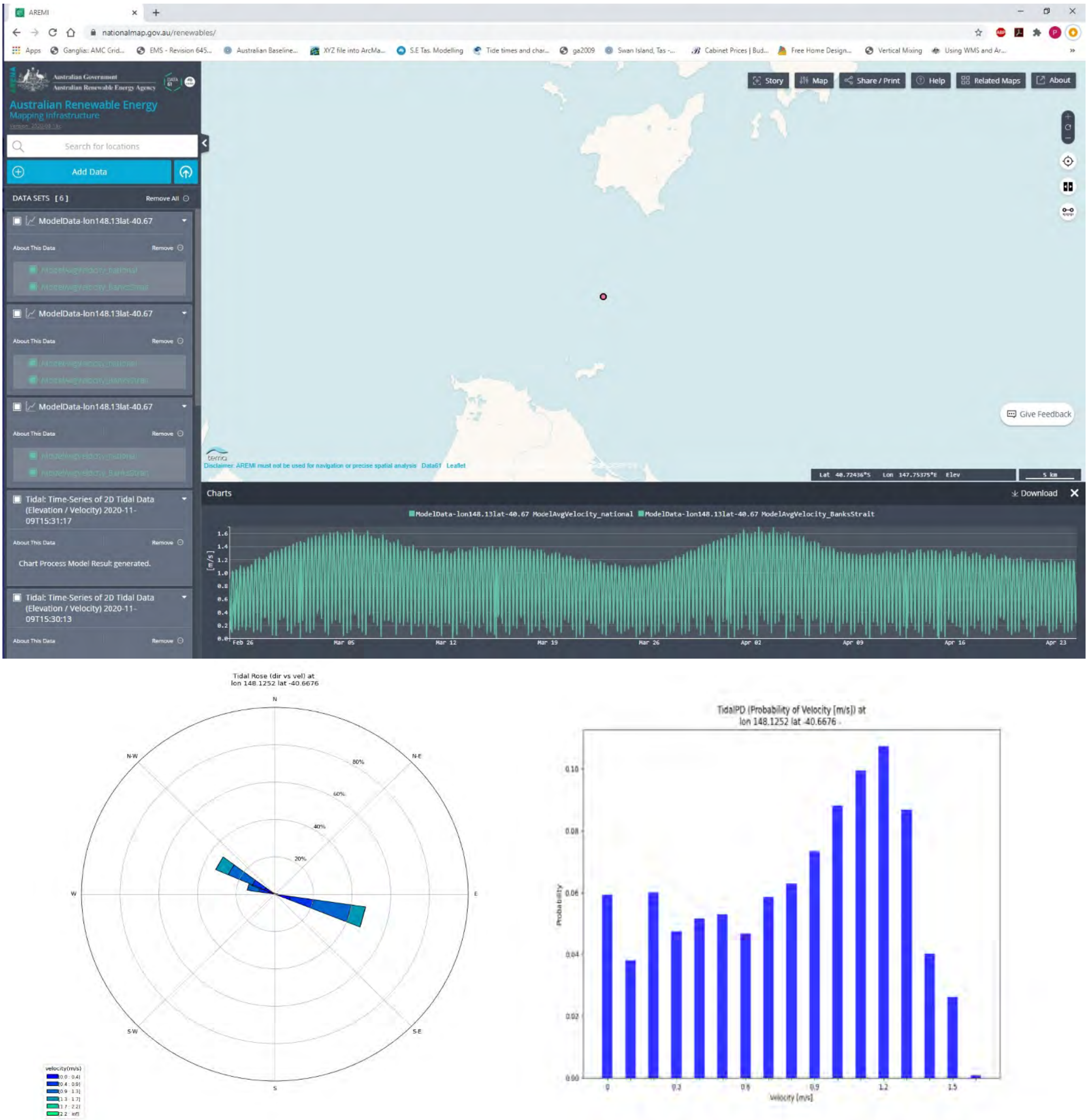

Figure 48: Example display of Tidal Energy Analysis tool output from development version of AREMI. Top image displays the time-series of velocity from the location 148.1251E, 40.6676S. Lower left displays the tidal velocity rose for this location, and lower right displays the distribution of tidal current speeds at this location

5. Identification of Promising Regions for TEC Deployments

The National Tidal Energy Model was used to identify regions in Australia with peak tidal flow rates greater than 1.5 metres per second within 100 km of a community or Industry with a significant electricity demand (Figure 49, Table 18). These regions were selected for further analysis to determine their suitability as TEC farm sites. The following TEC sites were identified and their tidal energy resource was assessed together with the household component of their potential electricity demand and actual electricity demand data, if it was available. Of these sites, Port Hedland and the Great Barrier Reef (GBR) were discontinued after a preliminary assessment due to lack of water depth (Port Hedland), sites over reef (GBR), and whale migration paths (Curlew-Middle Island Channel).

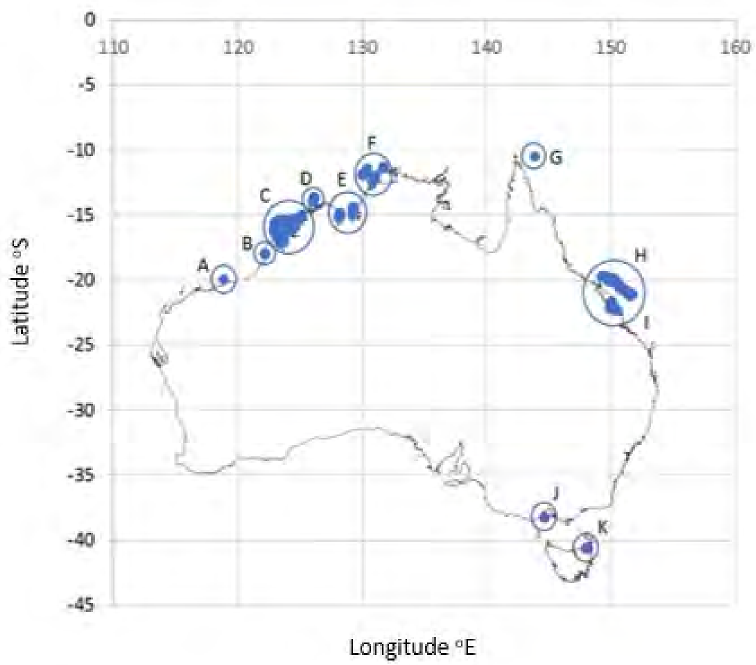

Figure 49: National distribution of tidal flow rates greater than 1.5 metres per second

Table 18. Key to candidate sites

A - Port Hedland (Little Turtle Islet)	G - Off-shore marine location
B - Broome (Gantheaume Point)	H – Great Barrier Reef
C - Ardyaloon and Derby (King Sound)	I – Mackay (Curlew and Middle Islands)
D - Kalumburu and Mungalalu-Truscott Airbase (Troughton Island)	J – Port Phillip Bay
E - Wadeye and Thamarrurr (Treachery Bay)	K – Banks Strait
F - Tiwi Islands, Vernon Islands and Darwin (Clarence Strait)	

Tidal energy converters expected performance in Identified Regions

The maximum extractable energy to be expected from an array of TECs subject to SIF constraints was assessed by setting up a transect orthogonal to the tidal stream and fitting an array of simulated TECs selected from commercially available designs into the transect cross-sectional area. Transects were identified from visual inspection of the tidal reference charts, considering tidal intensity, local average tidal direction and location of electricity demand. TEC packing fractions were determined for each datapoint from the depth, elliptical spacing, rotor diameter and significant impact factor (SIF)[52] . TEC rotor diameters were selected to match the depth and required clearances at each transect datapoint. TEC rotor spacings were determined at each transect data point, dependent on the SIF factor, the rotor diameter and the sea depth. Spacings typically ranged from four to five rotor diameters. The study focused on horizontal axis turbines as they are the most commonly available commercial units.

[52] Marine Current Resource and Technology Methodology, (2006). Significant Impact Factor (SIF) http://www.esru.strath.ac.uk/EandE/Web_sites/05-06/marine_renewables/envimpact/sif.htm. University of Strathclyde, Environment:

Designs from four TEC companies were used to set up a generic TEC model that included power curves over a range of rotor diameters from four to twenty-six metres. To determine the TEC outputs the power P(U) was read from the TEC power curves at hourly intervals using the results from the national and regional numerical models and annualised. Rated energy (Erated) was evaluated as the rated power in the power curve applied over a year and capacity factor (CF) was evaluated as the ratio of annual energy delivered to rated energy delivered over a year.

Initial studies were carried out to assess the potential for extractable power from Australian tidal energy sites using power curves obtained from the generic simulated TEC power curves. These studies were repeated after adjustments had been made to the power curves reducing the rated power of the TECs to more closely match the available tidal energy resources.

Currently available TECs with large enough rotors to take advantage of Australia's relatively low speed tidal currents have power ratings that are too high for them to operate near full capacity. A second assessment was therefore carried out with a modified set of power curves designed to keep rotor sizes as large as possible while reducing the power rating to match the available tidal current flow rates. A third assessment was carried out using the AUSTEn high resolution data focussed on the Tiwi and Vernon Islands, Northern Territory and on Banks Strait, Tasmania. Table 19 lists those sites that had sufficiently high capacity factors to justify further economic analysis.

Table 19: Sites near a generation capability sufficient to justify further economic analysis

Site	Capacity Factor	Annual electricity generation (GWh)	Rated Power (MW)
Ardyaloon	38%	669	199
Banks Strait	17%	155	111
Broome	9%	5	6
Derby (south beach)	17%	40	27
Dundas Strait	20%	325	188
Howard Channel , North Channel and Vernon Islands	29%	77	31
Port Phillip Bay	15%	3	2*
Wadeye & Tharramurr	18%	66	43

* The average power for Broome is for three data points only – a high resolution survey is needed to properly establish this site's capability

On and off- grid constraints on maximum tidal farm size

To investigate the power requirements for each identified region above, on and off-grid estimates of annual load were performed as shown in **Table 20**. For off-grid sites the total estimated loads were calculated from the fuel consumption for local communities close to identified tidal resources were based on an estimate. These estimates of electricity demand were used to limit further analysis on tidal regions if the demand is too low to be of practical use and too far away from the tidal resource. However, if actual annual load data was available, it was used instead of the household load data estimate.

For on-grid sites, a detailed review of the load data, generation data, substation data and network architecture has been made of the network in Tasmania and the Darwin-Katherine Interconnected System (DKIS) in the Northern Territory (NT). This review was used to develop a power system model of each of these networks using the DIgSILENT/PowerFactory software tool.

Table 20: Electricity grid data at communities located near suitable tidal locations

Community	Tidal region	Grid/off grid	Existing generation (MW)	Existing fuel use	Approx annual load (MWh)
Ardyaloon	One Arm Point	Off-grid	0.8	Diesel	1771
Broome	Gantheaume Point	Remote grid	39.6	Gas/diesel	130,332
Darwin	Clarence Strait	Grid	329.1	Gas/solar	286,567
Derby	King Sound North and South	Off-grid	12.53	Gas/diesel	33500
Kalumburu	Troughton Island	Off-grid	1.2	Diesel	540
Melbourne	Port Phillip Bay	Grid	-	Mix	304,937
Tasmania	Banks Strait	Grid	168	Mix	561
Wadeye/Thamarrurr	Treachery Bay	Off-grid	6.9	Gas	8,930
Wurrumiyanga	Bathurst Island/Tiwi Islands	Off-grid	5.6	Diesel	6,851

The integration of tidal into electricity networks

The capacity of the electricity networks near Banks Strait (the National Energy Market (NEM)) and near Darwin (the Darwin Katherine Interconnected System) to host tidal generation has been assessed using the developed DIgSILENT power system models. The focus of the assessment has been on quasi-dynamic simulation and limiting tidal farm capacity based on the thermal capacity and over-voltage constraints to find the maximum tidal farm that could be installed in a system from a static power perspective. Two main constraints that have been considered are the voltage of buses and the thermal capacity of lines and transformers. The voltage of buses should always be in the operational range and the loading of lines and transformers should always be lower than their rated thermal capacity. Therefore, time-series simulations are required to check the voltage and loading over a period. Figure 50 represents the algorithm to find the locational hosting capacity for tidal generators.

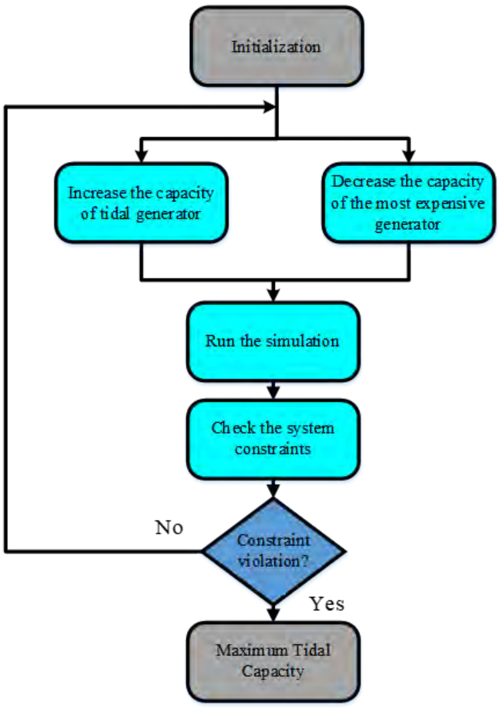

Figure 50: Methodology for finding the maximum hosting capacity of tidal generation

Factors that can affect the maximum tidal farm that could be installed in a system are the connection point of the tidal farm and the amount of dispatchable generation. For each region, the closest connection points and dispatchable generation were identified, with gas plants at Channel Island and Weddell for the Clarence Strait model and hydropower stations at Trevallyn, Paloona, Devils Gate, Cethana and Lemonthyme / Wilmot for the Banks Strait model. Results shown in Table 21 outline grid-base connection limits for each prospective site and what is causing the limitation. In the cases where transformer capacity is a limitation, upgrading the transformers removes this impediment.

Table 21: Maximum allowable tidal generation at different locations in Darwin-Katherine and Tasmanian networks

Resource	Substation Point of Connection	Maximum allowable capacity (MW)	Limitation
Clarence Strait	Darwin city	89	Line capacity
	Snell street (Woolner)	77	Line capacity
	Casuarina	104	Line capacity
	Frances bay	91	Line capacity
Banks Strait	Musselroe Bay WF	59	Line capacity
	Derby	24	Transformer capacity
	Scottsdale	65	Transformer capacity
	Starwood / Bell Bay	90	Line capacity
	St Marys	21	Transformer capacity

From examination of Table 21 it can be concluded that the DKIS can accommodate a higher level of tidal generation than the Tasmanian network. In fact, the maximum tidal generation for the DKIS is 60 % higher than that of the Tasmanian network for the Baseline scenario. It should be mentioned that this conclusion is limited to the chosen tidal farm sites.

Maximum tidal farm size

A summary of the maximum farm size considering both grid and resource is shown in Table 22. Where the grid is a limiting factor there is an opportunity to expand the grid or establish a new industry which will increase demand for electricity. For example, there has been some discussion around constructing solar farms in the Pilbara and Kimberley and exporting the power via HVDC to Asia[53] and/or using renewable energy to generate hydrogen in Western Australia for export to Asia[54]. These projects could take advantage of not just solar PV but also the large tidal resource in the Ardyaloon area.

Table 22: Summary of maximum tidal farm sizes taking all constraints into account

Community	Tidal region	Limitation on farm size	Maximum farm size (MW)
Ardyaloon	One Arm Point	Grid	0.8
Broome	Gantheaume Point	Resource	6
Darwin	Clarence Strait	Resource / Grid	104 (Dundas Strait), 31 (Howard channel and Vernon Islands)
Derby	King Sound North and South	Grid	12.53
Kalumburu	Troughton Island	Grid	1.2
Melbourne	Port Phillip Bay	Resource	2
Tasmania	Banks Strait	Resource	111
Wadeye/Thamarrurr	Treachery Bay	Grid	6.9
Wurrumiyanga	Bathurst Island/Tiwi Islands	Grid	5.6

[53] Mella, S., James, G. and Chalmers, K. (2017). Pre-feasibility Study: Evaluating the potential to export Pilbara solar resources to the proposed ASEAN grid via a subsea high voltage direct current interconnector. Pilbara Development Commission
[54] Department of Primary Industries and Regional Development, 2018). Annual Report. https://dpird.wa.gov.au/annual-report

The characteristics of an expected future electricity grid

The future Tasmanian and DKIS network capability for hosting tidal generation was examined in the developed DIgSILENT power system models by simulating potential future transmission lines and committed generations. This then allowed for identification of the future potential capacity for tidal energy converters that can be installed in these networks. The focus of the assessment has been quasi-dynamic simulation and limiting tidal farm capacity based on the thermal capacity and over-voltage constraints. The assessment showed that although both Banks and Clarence straits provide very good tidal resources, the network capacity to transfer the energy from those locations to load centres is limited. In other words, the network capacity is an immediate constraint on future massive tidal integration into these both networks.

Further, the sensitivity of the maximum allowable tidal generation to the capacity of a prospective wind and/or solar farm has been assessed. It was observed that a prospective wind and/or solar farm would not impact the locational tidal hosting capacity for some POC while they could decrease the maximum allowable tidal generation at other POCs. Another interesting point was that none of the projected transmission and distribution lines could improve the locational tidal hosting capacity for the considered tidal POCs. This is because the projected lines are either far away from the area of interest or they cannot release a limiting congested substation or line.

The calculation of the LCOE of tidal energy for different tidal energy converters in the prospective regions

Levelized cost of electricity (LCOE) is a widely used tool to evaluate and compare the cost of electricity from different types of generation. It is an economic assessment method which estimates the average total cost of constructing and operating an electricity generation asset over its entire plant life divided by the total electricity generated by the asset over that lifetime. To examine the economic feasibility of tidal energy the LCOEs of tidal energy under three scenarios in the year 2030 and 2050 at each farm location has been calculated. Graham et al.[55] developed cost and performance projections of electricity generation technologies under three global scenarios: Central, High Variable Renewable Electricity (VRE) and Diverse Technology, outlined as:

- Central – consists of 4 degrees of warming climate policies, moderate electricity demand and existing constraints on renewable technologies,
- High VRE – has a carbon price and climate policies consistent with a 2-degrees world. There are few VRE constraints and higher learning rates lasting longer for VRE technologies, and
- Diverse Technology – has a carbon price and climate policies consistent with a 2-degrees world. VRE is limited to 50% maximum per region. This allows for a greater diversity of technologies to contribute to electricity generation.

Tidal energy is considered to be a variable renewable, therefore, there should be greater uptake of tidal under the High VRE scenario and consequently lower capital costs compared to the other scenarios. The capital costs are projected using a learning by doing methodology, where the costs reduce with uptake of a technology. For more information see Graham et al (2020).

Other cost factors besides capital and operations and maintenance costs that have been included in the calculation of LCOE are regional factors and cabling costs. Generally, when LCOEs of different technologies are compared, the impacts of location are ignored and average values are used. However, the location-specific parameters including the renewable resources, capital cost, equipment freight cost, labour wages etc. may have significant impacts on the LCOE. Therefore, regional factors have been considered in this economic assessment study. The main data requirements include: equipment cost (in $/kW or $/TEC unit), installation costs of 20% of total capital costs, electrical connections of approximately $1 million per Km (Sabella, 2020), operations and maintenance cost ($/kWh and/or $/kW) estimated at 6% of capital cost, a lifetime (years) of 25 years, financial parameters of a discount rate of 6% and all costs are in AUD 2019, and a degradation in performance of 0.44% per year (Crabtree et al., 2015). Additional to these, rated power, turbine power curves, tidal resource data and tidal farm size included as outlined in the previous sections.

The rated power and capacity factor calculations in Table 23 were based on the National Model results. This did not have a significant impact on the results for Banks Strait, but the National Model has underestimated the tidal velocities that would contribute to electricity generation near Tiwi Islands/Darwin.

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[55] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

Table 23: TEC parameters by region used in the calculation of the LCOE

Location	Rotor diameter	Rated power per Turbine	Number of TECs	Distance to town	Capacity factor matched power curve cases
Unit	**metres**	**MW**		**Km**	
Broome	6.30	0.05	130	10	8.00%
Ardyaloon	26.00	0.78	213	28	37.00%
Ardyaloon	16.00	0.30	15	28	26.70%
Ardyaloon	10.00	0.12	222	28	52.00%
Ardyaloon	6.30	0.05	58	28	51.20%
Derby South	6.30	0.05	179	50	20.70%
Derby South	4.00	0.02	1,012	50	15.10%
Derby North	6.30	0.05	53	55	4.50%
Derby North	4.00	0.02	446	55	11.30%
Wadeye	10.00	0.12	316	40	15.90%
Wadeye	6.30	0.05	137	40	17.70%
Wadeye	4.00	0.02	113	40	17.80%
Troughton Island North	26.00	0.78	45	74	9.00%
Troughton Island North	16.00	0.30	39	74	9.50%
Troughton Island South	26.00	0.78	29	74	8.70%
Troughton Island South	24.00	0.67	17	74	10.80%
Troughton Island South	16.00	0.30	14	74	9.00%
Port Phillip Bay	4.00	0.02	112	59	15.80%
Banks Strait	26.00	0.78	41	25	16.60%
Banks Strait	16.00	0.30	93	25	16.90%
Banks Strait	10.00	0.12	249	25	13.80%

The capital cost of these modified TEC has been calculated from the bottom-up to take into account the differences in component sizes. Segura[56] published costs and sizing of TEC components for an 80 MW farm in the UK, as the proposed modified TEC have a smaller power take-off (PTO) system, smaller electrical equipment in the nacelle and transformation platform but larger rotor diameters than existing OTS designs. In order to project these capital costs into the future, the percentage change in costs over time for tidal energy determined in Graham et al.[57] have been applied to the adjusted capital costs. These are shown as unit costs in Table 24 under the Central scenario for the years 2030 and 2050 for Melbourne. For other city and regional locations capital cost adjustment factors/regional factors were sourced from GHD (2018). The regional factors represent the additional cost of installing equipment and operating it in a remote area.

Table 24. Adjusted TEC capital costs under the Central scenario for modelled years at Melbourne

Rotor diameter (m)	Power rating (kW)	Capital cost in 2030 ($)	Capital cost in 2050 ($)
4	18.5	2,520,820	2,221,385
6.3	45.9	2,611,211	2,301,039
10	115.6	2,681,585	2,363,055
16	296	2,882,180	2,539,821
24	666	3,294,821	3,041,628
26	781.6	3,426,081	3,019,116

[56] Sedura, E., and Morales, R. (2017). Coast Assessment Methodology and Economic Viability of Tidal Energy Projects, Energies 10(11):1806.

[57] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

Using the developed scenarios and collated datasets, the LCOE of each potential regional tidal energy farm was calculated using each region's rated power taken from Table X. Four cases were considered under the High VRE, Diverse Technology and Central scenarios for the years 2030 and 2050. This resulted in 24 different LCOE calculations per region. The four cases that were calculated are: LCOE of TEC with line connection costs for matched power curve cases; LCOE of TEC without connection costs for matched power curve cases, LCOE with the regional factor with line connection costs for matched power curve cases, and LCOE with the regional factor without line connection costs for matched power curve cases. The reason the LCOE was calculated under four different cases was to show the impact of uncertainty in line connection costs and the impact regional costs can have. The LCOE ranges under all scenarios, years and cases are listed in Table 25.

Table 25 LCOE range for different regions

Location	LCOE Range ($/kWh)
Ardyaloon	0.25-0.47
Banks Strait	0.98-1.60
Broome	8.38-15.52
Derby North	15.30-28.49
Derby South	8.42-15.52
Port Phillip Bay	11.21-17.04
Howard Channel , North Channel and Vernon Islands	0.96-1.75
Troughton Island North	0.79-1.61
Troughton Island South	0.70-1.50
Wadeye	2.54-3.92

The LCOE of all four cases increased slightly when the connection line cost was included. However, the impact on the LCOE of line connection costs varied by connection distance, as would be expected. Broome has the shortest connection distance (10 km) and the difference the connection cost made to the LCOE was an increase of less than 2% under the High VRE scenario in 2050 when regional factors are included. Troughton Island North has the longest connection distance (79 km) and the difference that made to the LCOE under the same scenario was 11%. After considering the regional factors in the LCOE calculation, the LCOE of most regions increased slightly. Ardyaloon has the lowest LCOE whereas the Derby North region still has the highest LCOE. The LCOE results in Broome, Ardyaloon, Derby and Troughton island regions have greater changes to the LCOE after including the regional factors as these generation sites are far from economic centres, which leads to higher costs. Port Phillip Bay is close to Melbourne and consequently the LCOE results were unchanged.

The LCOE results for all regions in 2030 scenarios are higher than 2050 scenarios. Moreover, the LCOE results under the High VRE scenario are the lowest compared to Central and Diverse Tech scenarios. The reason for this is because the capital cost of tidal under the High VRE scenario are the lowest and the Diverse Tech scenario has the highest capital cost as shown in Table 54. The Ardyaloon region has the lowest LCOE and is the most suitable location from an economic perspective, whereas the Derby North region has the highest LCOE and is not recommended as a site for tidal project installation.

Competitiveness of tidal with other forms of electricity generation based on current LCOE Projections

The competitiveness of tidal in remote off-grid communities, remote grids and the DKIS and NEM has been explored in this report using three different models: HOMER for off-grid and remote grids (Broome), Aus-TIMES for Darwin and Banks Strait, STABLE for Banks Strait. Each model used as input the resource assessments and LCOE calculations performed in the previous sections.

The Hybrid Optimisation of Multiple Energy Resources (HOMER) microgrid modelling tool, developed by the National Renewable Energy Laboratory was used to undertake the techno-economic optimisation of the off-grid and remote grid systems in Broome, Ardyaloon and the Tiwi Islands, enabling the determination of the least-cost technology mix to meet demand. For these regions HOMER modelling indicated that tidal is not part of the least-cost solution or of the lowest-cost 100% renewables solutions in the communities surveyed. The competitiveness of tidal is not impacted by fossil fuel price, but by the low cost of solar PV and battery storage. As the fossil fuel price increases the developed HOMER model installs more solar PV and batteries. In order for tidal to be competitive in one example community, the Tiwi Islands, it needs to reduce its capital cost by 50%, down to $1,509,558 per device or 1,930 $/kW in the year 2050.

The AUS-TIMES model satisfies energy services demand at the minimum total system cost, subject to physical, technological, and policy constraints. Accordingly, the model makes simultaneous decisions regarding technology investment, primary energy supply and energy trade (Loulou et al. (2016)). Using hourly generation data generated form resource studies performed in Section X, tidal energy was modelled using Aus-TIMES in both Darwin and Banks Strait out to the year 2050. However, there was no uptake of tidal energy in either location. A further run was made where the capital cost was halved, however, there was again no uptake of tidal. This modelling did not include connection/cabling costs, which would increase the capital cost significantly. The results demonstrate, that, on an annual timescale basis, tidal is not competitive with the other renewables, namely wind and solar PV, that are in those locations and connected to the NEM and DKIS electricity grids. However, tidal maybe viable for off-grid applications that are not accounted for in this model.

STABLE, an intermediate horizon model was used for modelling tidal in Banks Strait in the T1 REZ in the years 2030 and 2050 under all three scenarios. Unfortunately, there was no uptake of tidal even with a 50% capital cost reduction and a reduction in the O&M cost to 2.5% of the capital cost. The model run featured plenty of demand opportunities, especially in the year 2050 where the Marinus link was included between Tasmania and the mainland, which resulted in the ability to transmit an additional 1.79 GW along this line. Tasmania built up to its limit of wind (3.5 GW) in the south, a big battery for the whole state (415 MW capacity) and built wind and solar in the North West. These new additions, along with the existing wind and hydro, were enough to allow Tasmania to become a 100% renewable electricity state. There were no new capacity additions in the North East i.e. in the T1 REZ. Demand is relatively low in Tasmania, particularly so in REZ T1 where no new capacity was needed. If a new industry was located there that relied on renewable energy, demand for electricity would increase which may change the outcome for tidal in REZ T1, as long as wind capacity is saturated and the transmission from REZ T1 out is limited.

Since this modelling was completed, Tasmania has announced plans to rely on 200% renewable energy. This may provide an opportunity for tidal, in particular if other forms of renewables become saturated or if there are constraints placed on further wind farm development, for example a mandated requirement for dispatchable power such as was proposed by the National Energy Guarantee.

In all cases, tidal needs to achieve significant cost reductions, over and above those attributable to learning by doing based on global deployment of tidal projected in Graham et al (2020) and those obtainable by modifying TECs to better suit Australian conditions to be competitive with wind and solar PV. In order to assist with understanding why tidal is not competitive in the modelling results for Darwin and Tasmania and in the region of the most promising tidal resource, Ardyaloon, the LCOE of competing technologies in Darwin, Tasmania and Ardyaloon has been calculated, and compared with the LCOE of tidal. The LCOE of tidal is at least more than double the LCOE of both PV and onshore wind in all tidal regions. Even if two hours of battery storage or six hours of pumped hydro energy storage is added onto the LCOE of PV and wind, it adds less than 0.1 $/kWh[58] onto both technologies, which is still lower than tidal energy. The calculations of the LCOE of tidal in Banks Strait and Darwin used the tidal resource data from the high resolution, regional model. This resulted in an increase in capacity factor of tidal in Darwin.

Sensitivity Study on LCOE Parameters

In order to further understand what is driving tidal energy's high LCOE, a sensitivity analysis has been made on the key parameters behind the LCOE. The key parameters included were the capital cost, O&M cost, capacity factor and discount rate. Each key parameter had its value varied by ±50% and the impact that had on the LCOE is presented in the tornado charts, where the x-axis shows the impact of that variation on the LCOE. The results are presented for Ardyaloon in the year 2030 in Figure 51. It can be seen that LCOE is most sensitive to capacity factor, which is the case for the majority of renewable technologies. Capital cost is the next key parameter, where a 50% reduction in capital cost results in a 25% reduction in LCOE. However, even with a 25% reduction in LCOE, tidal is still not competitive with solar or wind. A 50% reduction in O&M reduces the LCOE by 23% - this has almost the same impact as a reduction in capital cost. A reduction in discount rate reduces the LCOE by 12-14%.

[58] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

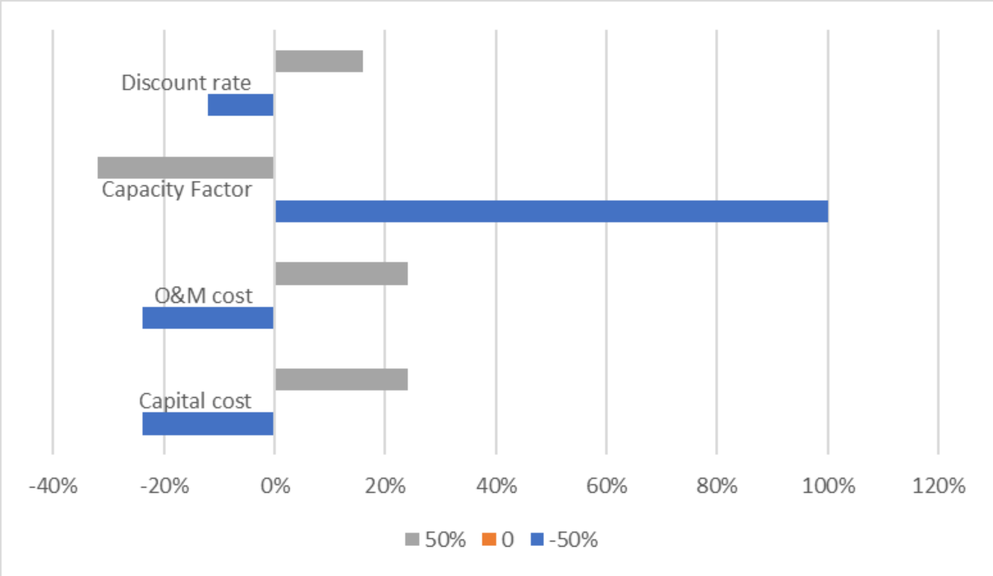

Figure 51 Sensitivity of the projected LCOE of tidal in Ardyaloon in the year 2030

It may be difficult to reduce the capital cost by 50% to 2,345 $/kW in Ardyaloon, including all regional factors. There may be more opportunities to reduce the O&M cost. For example, the O&M cost of both onshore and offshore wind has seen significant reductions over time (IRENA, 2012) and the current O&M cost of offshore wind in Australia is expected to be 2.5% of the capital cost (AEMO, 2019). In order for tidal in Ardyaloon to have the same LCOE as solar PV, with an O&M equal to 2.5% of the capital cost, the capital cost needs to be 1,256 $/kW or $982,000 per TEC with a rated capacity of 781.6 kW. In Darwin the capital cost needs to be even lower: 789 $/kW or $617,000 per TEC. These costs do not include cabling to connect to the grid.

Limitations of LCOE Modelling

There are limitations to the modelling presented here. For instance, the models have perfect foresight and have the ability to project exactly the cost and quantity of each source of electricity generation and optimize for the least-cost. In a real situation, while there is wind and solar forecasting, is not perfect and may miss sudden drops in wind, for example. Solar PV is subject to cloud cover and this can result in very fast changes in output. The generation from tidal on the other hand is forecastable years in advance. However, there is a need to develop methods for including the ability to account for sudden drops in wind or changes in cloud cover in models with perfect foresight.

If individual renewable energy farms needed to be able to provide some form of dispatchable power, for example, to increase grid reliability in a particular part of the network, then tidal may be able to assist as it has a component of dispatchable power. It would also be possible to size energy storage with tidal on a least-cost basis as the output of tidal is completely forecastable, which may be lower in cost than having to size energy storage with a wind or solar farm, where the storage has to have sufficient capacity to meet the farms' total capacity.

Tidal may be useful in cases where electricity is needed offshore and offshore wind has a weak resource. Electricity is needed offshore for offshore aquaculture and in future for offshore hydrogen production. Even in areas with a strong offshore wind resource, tidal energy could share some of the infrastructure and at the same time provide a dispatchable component to the offshore wind farm's electricity generation.

The communities modelled in WA and NT are subject to cyclones. It is possible to design PV systems to withstand cyclones, however, tidal, being installed in the water, would be immune to cyclones and would be able to continue generating whereas solar PV output would be reduced or non-existent. If the wind speeds are too high, wind turbines cut out so wind output would also be reduced. Therefore, there may be energy security reasons for installing tidal and not relying solely on PV, batteries and wind to increase renewable penetration in regions prone to cyclones.

6. Case Studies

The AUSTEn study has highlighted the strengths and weaknesses of tidal power and its importance in contributing reliability rather than capacity to electric power distribution. This reliability is quantified as dispatchability or the ability to provide continuous power. Dispatchable electricity is more readily achieved on large networks such as the national grid where the geographic diversity of renewable energy lowers the frequency of intermittent power loss. However, there are critical applications such as chemical processing, emergency power security or supplying small regional electricity networks, where an intermittent loss of power may be intolerable. This is the niche in which tidal energy can be valuable.

Assessing tidal energy's viability in the dispatchable energy niche requires a clear understanding of the need for continuous power, how much is required and the cost penalty of not having it. This should be included in the economic assessment along with capital and installation costs and the local costs of operations and maintenance. To this end a knowledge of the intermittency statistics of competing resources is essential. It is also necessary to examine the specifications generally given for TECs more comprehensively, for example rated power may be of much less importance than the average power a TEC generates in a particular environment.

In addition to the means of generating electricity its distribution must be accounted for. In the cases described here the assumption has been made that as the requirement for renewable energy generation increases, the investment in associated infrastructure will expand to match it. So, for example in a 200 percent renewable environment, such as that proposed by the Tasmanian government, it will be necessary to increase the capacity of substations and transmission lines to distribute and export renewable energy and support the necessary increase in generation capacity.

The hypothetical case studies that follow illustrate these approaches and demonstrate the potential of tidal power to guarantee electricity supply and reduce the cost of doing so.

Case Study: Banks Strait – A hybrid tidal/wind farm with dispatchable power

Executive summary

This case study describes a hybrid wind and tidal energy power station in Banks Strait that generates 569 gigawatt hours of renewable electricity per year. It takes advantage of tidal power's predictability to ensure 12 percent dispatchable power and a 27 percent ($250M) capital cost saving, by using tidal energy converters and a small battery to replace the much larger battery that would be required for wind energy alone. Dispatchable power is essential for grid stability and for running chemical plant. If this power station were combined with a hydrogen production and liquefaction plant it could produce 11 thousand tonnes of liquid hydrogen per year.

Background

Tasmania has set a goal to produce 200 percent of its energy from renewable resources by 2040 and has established a plan that draws on wind, solar, hydro and tidal energy resources[59]. However, as wind and solar energy become more widely used the land available for wind farms will become increasingly scarce and the intermittency of wind more problematic. A local wind farm can typically be unavailable for several consecutive days each month, for example Figure 52 shows wind speeds below 3 m/s (a common wind turbine cut in wind speed) for approximately 206 hours out of 744 hours of the month.

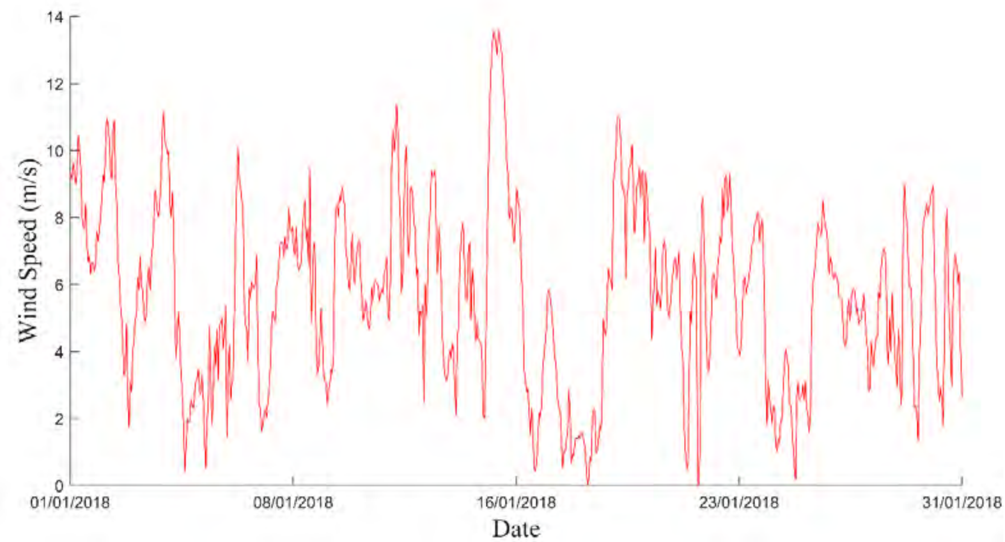

Figure 52: Wind speed (m/s) at Swan Island for January 2018 at 10 m height

A National Grid that runs entirely on renewable energy will need to provide a proportion of its rated capacity as continuous (dispatchable) energy. In 2018 a proposal 'The National Energy Guarantee' was prepared for COAG. It included a statement that: "*The Guarantee requires retailers to contract with generation, storage or demand response so that: • there are contracts in place to support a minimum amount of dispatchable energy to meet consumer and system needs*"[60]. The objective is to maintain National Grid stability as it moves to 100 percent renewable energy. This case study describes a scenario where at least ten percent of the energy that a generator supplies to the grid is required to be dispatchable.

Project Details

Overview

The power station described here has a peak power rating of 215 MW, an average power of 65 MW and dispatchable (continuous) power of 8 MW. To illustrate this the case study is based on a tidal energy farm located off Southern Point in Banks Strait together with a wind farm such as Musselroe Wind Farm. It combines 60 tidal energy converters each rated at 0.78 MW, and 56 on shore wind turbines each rated at 3 MW.

Location and the tidal and wind resource

Banks Strait is an approximately 15 km wide channel between the Furneaux Island Group and the north-eastern corner of mainland Tasmania. It connects the south-eastern region of Bass Strait with the Tasman Sea. Research conducted by the

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[59] Tasmanian Government, (2020). The Draft Tasmanian Renewable Energy Action Plan, accessed 5 September 2020

[60] COAG Energy Council, (2018). The Final Design - National Energy Guarantee - COAG Energy Security Board, 1 August 2018, accessed 5 September 2020, <http://coagenergycouncil.gov.au/

ARENA (Australian Renewable Energy Agency) AUSTEn (Australian Tidal Energy) project[61] [62], together with data from the nearby Musselroe Wind Farm[63], suggests an opportunity for the deployment of a hybrid tidal and wind turbine power station.

Three potential locations for tidal farms were found including: off Cape Portland on mainland Tasmania's north east, and from the middle of Banks Strait to either Lookout Head or Southern Head on Clarke Island (Figure 53). The ARENA AUSTEn project determined that the most powerful tidal energy resources were to be found at Southern Head and the case study focuses on this region. Power generation records for Musselroe Wind Farm were used[64] to illustrate the wind energy resource, its average value and intermittency. Together the tidal energy and wind energy farms were estimated to be capable of providing a rated power of 215 MW with a capacity factor of 30 percent [Tables 1,2,3].

The AUSTEn tidal farm model was distributed from Southern Head to the centre of Bank's Strait. It included depths varying from 29 m to 52 m with an average depth of 42 m, and tidal flow rates averaging 0.93 m/s with a mean peak rate of 2.0 m/s and a maximum peak rate of 2.9 m/s. To operate efficiently within this range, it will be necessary and feasible to use relatively low power tidal turbine generators rated at about 780 kW with large rotors between 20 m to 26 m diameter. A 60-unit tidal turbine farm of TECs with 26 metre rotors had a peak rated capacity of 47 MW and was capable of generating an average power of 8 MW in this location[61].

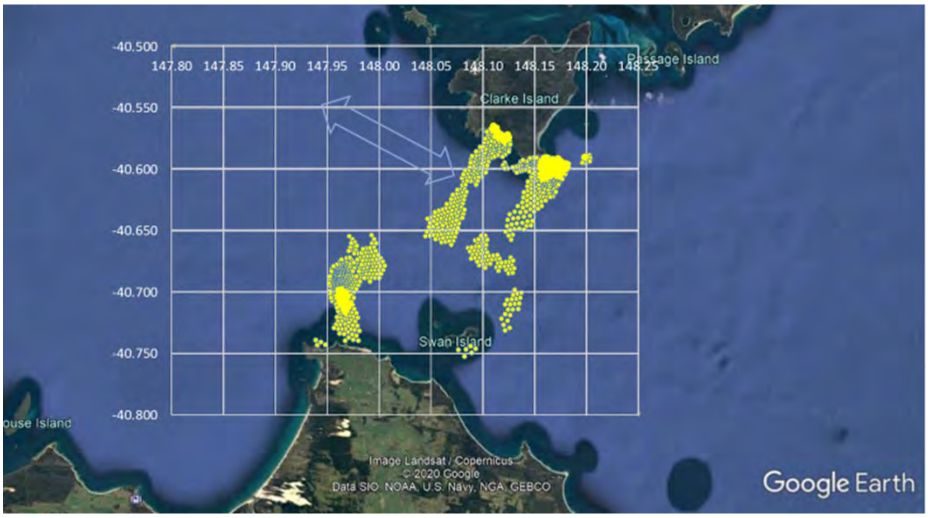

Figure 53: Regions of high tidal stream flow rate

Environmental constraints

Detailed environmental and user impact studies have yet to be carried out. However, there are no Marine Parks or Marine Nature Reserves in the immediate vicinity of the proposed tidal energy farm with the closest being the Swan Island Abalone Research Area 10 kilometres south of the tidal turbine farm[65]. A preliminary assessment by the AUSTEn study estimates that the tidal energy farm would have a minimal influence on surface elevation and current speed distribution in both the near and far-field regions. There is a 59 percent theoretical limit on energy extraction using unshrouded turbines and the assessment applied a further 12 percent significant impact factor to limit the extracted tidal energy to approximately six percent of the available tidal energy in Bank's Strait[66].

[61] Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C., (2020). Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished)
[62] Australian Energy Market Operator (AEMO), (2020). Market Data – NEMWEB, accessed 5 September 2020, <http://www.nemweb.com.au/>
[63] Miskelly, A., (2020). Renewable power in the Australian Energy Market, accessed 5 September 2020, <https://anero.id/energy/renewable-energy>
[64] Hydro Tasmania, (2018). Battery of the Nation Unlocking Tasmania's energy capacity, accessed 5 September 2020, <https://www.hydro.com.au/>
[65] Dep't of Environment and Primary Industries, Parks, Water and Environment, (2019). Marine Reserves, accessed 5 September 2020, <https://dpipwe.tas.gov.au/sea-fishing-aquaculture/recreational-fishing/area-restrictions/>
[66] Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C., (2020). Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished),

System Specification[67]

Wind Farm component

56		Wind turbines
168	MW	Rated power
500	GWh	Generated electricity per annum
57	MW	Average power
34	percent	Capacity Factor
1152	MWh	Battery used to provide continuous power of 8 MW for 6 days

Tidal Farm component

60		TECs 26m 0.782MW
47	MW	Rated power
8	MW	Average power
69	GWh	Dispatchable electricity per annum
17	percent	Capacity Factor
24	MWh	Battery for dispatchable (continuous) tidal power of 8 MW for 3 hours

Hybrid Farm Parameters

215	MW	Total Rated Power
65	MW	Total Average Power
65	GWh	Dispatchable electricity
569	GWh	Generated electricity per annum
10813	tonnes	Equivalent hydrogen
30	percent	Capacity factor
24	MWh	Battery for dispatchable (continuous) tidal power of 8 MW for 3 hours
47	AUDM	Annual value of generated electricity per year at $82.73/MWh
22	AUDM	Annual value of hydrogen at $2 per kg

Capital costs

Capital cost without tidal energy	AUDM	Capital cost with tidal energy	AUD
56x 3 MW wind turbines	$ 394M	56x 3MW wind turbines	$ 394M
1152 MWh battery	$ 469M	24MWh battery	$ 10M
		33km subsea power cables	$ 33M
		60x 0.78MW tidal turbines	$ 220M
Total	**$ 863M**	**Total**	**$ 657M**

[67] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

Opportunities

- Electricity production is at first sight the most attractive opportunity. At 47 million dollars the annual return on sales of electricity is about twice the return obtained by producing liquid hydrogen. It is also the most likely product to benefit from any policy or market strategy that requires electricity retailers to include a significant percentage of dispatchable power.
- Hydrogen production with an annual return of $22M dollars is a less attractive but potentially viable proposition. In a 100 percent renewable energy economy, the intermittency of wind energy may create significant issues when used to produce hydrogen or methane. The difficulty arises when matching the control of rates of production, liquefaction and methanation to the intermittent availability of wind energy. The use of tidal energy and a 24 MWh battery to help stabilise the power supply could be a very cost-effective solution.
- The tidal energy farm could be located at one of two potential sites. For this case study it was located off Southern Head on Clarke Island. A second power station could be located accessing the tidal resource off Lookout Head on Clarke Island.

Challenges, gaps and uncertainties

Tidal energy converter design

If full advantage is to be taken of Australia's limited tidal stream resource it will be necessary to develop custom designed TECs using large rotor blades and relatively low powered highly geared (x3) generators[68]. The 42 m average depth of the Banks Strait hybrid farm sites make them an ideal site for development of such TECs.

Tidal and wind Farm layouts

Preliminary assessments have been carried out on two farm layouts in the AUSTEn project, but further design is required with more detailed bathymetry. Likewise, checks are needed to confirm if any proposed installation would interfere with navigation channels or dredging operations, so that the hybrid farm layout can be adjusted accordingly

Environmental impact

Detailed environmental and multi-use impact assessments need to be carried out. Particular issues may include the abalone research station next to Swan Island, and bird life.

Hydrogen production

AEMO should be consulted on the level of dispatchable power required for a National Grid running on 100 percent renewables and the likely policies and strategies being considered for its implementation. The degree to which dispatchable power is required for hydrogen and methane production also needs to be further evaluated so that a better estimate can be obtained for the required ratio of tidal to wind energy if a fuel plant becomes a preferred option instead of electricity generation.

Cost benefit

- The estimates for submerged infrastructure: capital equipment costs are indicative and based on GenCost estimates for the tidal energy converter industry[69] they will need to be assessed in more detail. The operations costs remain to be determined as they are location specific. The costs of methane and hydrogen production from renewable energy are not included as this technology is rapidly developing.

Key findings and outcomes

Findings

- Tidal energy could have a significant role in adding dispatchability at relatively low cost to highly intermittent renewable energy resources, conditional upon there being a requirement that all renewable energy generators be contractually obliged to ensure a percentage of their energy is dispatchable.
- Tidal energy may have a similar role in stabilising renewable energy power supplies for applications such as chemical processing plant where continuity of supply is critical to efficient operation. For example, a potential role for tidal energy in wind powered hydrogen production has been identified that is related to the stability requirements of hydrogen or methane production and liquefaction.

Outcomes

[68] Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C., (2020). Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished)

[69] Dep't of Environment and Primary Industries, Parks, Water and Environment, (2019). Marine Reserves, accessed 5 September 2020, <https://dpipwe.tas.gov.au/sea-fishing-aquaculture/recreational-fishing/area-restrictions/>

- Locations have been determined for a hybrid tidal wind farm with a 215 MW rated capacity. The hybrid farm includes a 12 percent dispatchable energy to meet potential contractual requirements such as those proposed by the National Energy Guarantee submitted to COAG in 2018.
- A second site with similar capacity has also been identified extending from Lookout Head to the centre of Banks Strait
- The hybrid tidal-wind farm has been assessed as capable of generating 0.57 terawatt hours of renewable electricity per year with an annual value of 47 million dollars
- If combined with an electrolysis plant the power station could produce 11,000 tonnes of liquid hydrogen per year valued at 22 million dollars per annum [Table 4]
- A mechanism has been shown for reducing the capital cost of the wind turbine farm by 19 percent [Table 4] by reducing the energy storage capacity needed to provide dispatchable power.
- Preliminary estimates for the capital cost of the hybrid tidal and wind energy farm and its components have been determined. The capital cost without tidal energy converters is assessed as 863 million dollars. If twelve percent of the generated electricity is provided using tidal energy converters the cost reduces to 699 million dollars [Table 4].

Recommendations/next steps

The following are required prior to making a presentation to key stakeholders interested in the project:

- Community and stakeholder consultations together with more detailed environmental assessments are required as a first priority before further consideration of the project.
- A design should be developed for a 26 m rotor 0.8 MW tidal energy converter suitable for Australian tidal flow rates.
- The installation and operations costs per year for TEC should be determined and the capital costs assessed in more detail, in particular the costs of hydrogen production from renewable energy are not included as this technology is rapidly developing.
- A prototype hybrid wind and tidal energy converter with associated energy storage battery should be tested to confirm the performance of a future tidal stabilised wind farm in Banks Strait.
- A detailed process control analysis should be carried out to determine the feasibility of wind powered hydrogen / methane production and the role that tidal energy might play in process stabilisation and capital cost reduction.

Case Study: Broome - Tidal energy to supply high security energy

Executive summary

This case study discusses the potential for using tidal energy converters (TECs) to provide a secure and constant electricity supply during power outages and emergencies for key sites in Broome, for example the Kimberley Port Authority. Broome has been susceptible to power instability because of the high penetration of household solar electricity and because of damage to infrastructure during the cyclone and rainy seasons. A renewable energy resource could supply energy security for essential services during power outages. In particular the Port of Broome is a key Western Australia facility for exports and imports and its operator, the Kimberly Port Authority, is located within 1.5 kilometres of a strong tidal stream off Entrance Point.

Background

In reviewing the potential for renewable energy as an emergency power supply for Broome, wind turbines would be precluded because of their intermittency and low intrinsic capacity factor in the region. Solar and tidal power could provide complementary services with tidal contributing 23 percent continuous (dispatchable) electricity. A $(200m)^2$ solar farm together with a single 0.8-megawatt tidal turbine located off Entrance Point and a small battery may be capable of generating a rated power of 3.9 megawatts, with an average power of 870 kilowatts of which 200 kilowatts would be dispatchable power. This should be sufficient to supply continuous emergency power to the Kimberly Port Authority or Horizon Power.

Project Details

Overview

Location and the tidal resource

Figure 54 and Table 26 show the results of the AUSTEn tidal stream assessment. While there are strong indications of suitable tidal flow rates there is very little high-resolution data. This will be essential for detailed feasibility and cost assessments.

Table 26: Conservative assessment of tidal stream potential to supply electricity

Tidal electricity generated	4579	MWh/yr.
Modelled average power	0.5	MW
Rated power	5.9	MW
Capacity factor	8.8	%
Average tidal stream flow rate	0.7	m/s
Maximum tidal stream flow rate	1.7	m/s

Despite this conservative assessment The Kimberley Port Authority notes that Broome has a nine metre to ten metre tidal range and that tidal streams are complex and fairly strong in the port area[70] [71]. When the AUSTEn low-resolution survey was used in conjunction with Navionics data[72] it found a number of fairly high velocity tidal streams between Gantheaume and Entrance Point (Figure 54), including a deep channel south of Entrance Point with a 2 m/s to 2.5 m/s tidal stream that may be suitable for TEC electricity generation.

[70] Harbourmaster, Kimberley Ports Authority, (2010). Port of Broome Port and Terminal Handbook. Version 6.0 Reference: HBR025/177525 Original issue: February 2010 Last review: February 2020, accessed 12 Sept 2020, <https://www.kimberleyports.wa.gov.au/MediaLibrary/Documents/REC177525-KPA-Port-and-Terminal-Handbook-V6-0.pdf>

[71] AusTides - Australian Hydrographic Office

[72] Navionics, (n.d.).

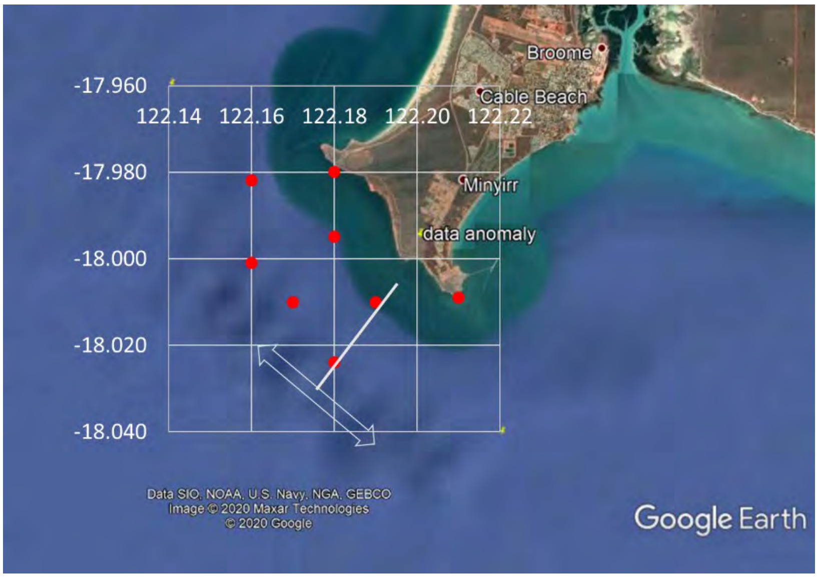

Figure 54: National Tidal Model high flow rate tidal stream data points

Environmental constraints

An environmental study has yet to be carried out. However, there are no marine parks or marine nature reserves in the immediate vicinity of Broome and all estimates given here are based on tidal stream energy extraction limits of less than twenty percent.

System Specification

The tidal turbine installation example used here is based on a plateau region with a tidal stream of 2 m/s to 2.5 m/s in depths of 45 m. the location is 18° 0.941' S 122° 12.426' E. This is 0.8 kilometres south of Entrance Point, 1.5 kilometres south of the Kimberley Port Authority and four kilometres south of Horizon Power. The tidal energy converter is a single free stream turbine with a rotor diameter of 26 metres. The two alternative routes for cables allow for supplying either the Kimberley Port Authority or Horizon Power.

Solar energy farm component

200	m^2	Solar farm
3.1	MW	Rated power
5.9	GWh	Generated electricity per annum
0.67	MW	Average power
22%	percent	Capacity Factor
0.20	MW	Dispatchable (continuous) tidal power
7.6	MWh	Battery for a minimum power of 0.20 MW for 38 hours

Tidal energy farm component

0.78	MW	1x TECs 26m 0.782MW
1.75	GWh	Generated electricity per annum
0.20	MW	Average power
25%	percent	Capacity Factor
0.20	MW	Dispatchable (continuous) tidal power
0.6	MWh	Battery for dispatchable (continuous) tidal power of 0.20 MW for 3 hours

Hybrid solar and tidal farm parameters

3.85	MW	Total Rated Power
0.87	MW	Total Average Power
0.20	MW	Dispatchable (continuous) tidal power

7.62	GWh	Generated electricity per annum
0.6	MWh	Battery for dispatchable (continuous) tidal power of 0.20 MW for 3 hours
23%	percent	Capacity factor
23%	percent	Percentage dispatchable electricity
$427,061	AUD	Annual value of generated electricity per year at $56/MWh

Capital Costs

AUD	Capital cost with tidal energy
$5,440,355	3.1 MW solar farm
$357,676	Battery (0.6 MWh, 0.2MW for 3hr)
$1,500,000	1.5 km subsea power cables
$3,759,479	0.78 MW tidal turbine farm
$11,057,510	**Total**

AUD	Capital cost without tidal energy
$7,065,397	4 MW solar farm
$4,530,569	Battery (7.6 MWh, 0.2MW for 38 hours)
$11,595,966	**Total**

Opportunities

A potential opportunity has been identified for using a tidal energy converter installed off Entrance Point to provide an emergency power capability to Horizon Power and the Kimberley Port Authority.

Challenges, gaps and uncertainties

Key issues include:

- A high-resolution assessment is needed of tidal velocities, depths and sea-bed conditions between Gantheaume Point and Entrance Point to confirm the project feasibility
- Community and stakeholder consultation are required including Kimberley Ports Authority and Horizon Power
- Detailed environmental and resource assessments are required
- Checks are needed to confirm if any proposed installation would interfere with navigation channels or other operations such as dredging maintenance.
- The project would require expansion of the grid infrastructure to accommodate the additional generation capacity
- The estimates for submerged infrastructure: capital equipment costs are indicative and based on GenCost and industry estimates for the tidal energy converter industry[73] they will need to be assessed in more detail. The operations costs remain to be determined as they are location specific.

Key findings and outcomes

Findings

- A key advantage in this application was the low intermittency of tidal power in a location that had a history of grid instability induced by high levels of household solar installations and extreme weather during the cyclone season.
- The distribution of high peak tidal velocity sites between Gantheaume Point and Entrance Point suggest that there may be potential for an emergency supply for additional key facilities in Broome.

Outcomes

- A tidal energy converter has been assessed as capable of supplying emergency dispatchable power to facilities such as the Kimberley Ports Authority or Horizon Power contingent on a higher resolution tidal stream assessment and a more detailed cost benefit analysis.

Recommendations/next steps

The following are required prior to making a presentation to key stakeholders interested in the project:

- A high-resolution chart of tidal velocities between Gantheaume Point and Entrance Point

[73] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

- A preliminary determination on whether a tidal energy converter can operate within the Port Broome navigation and environmental protection constraints
- Consultation with the community, the Port Broome Authority and Horizon Power
- Preliminary cost estimates should be confirmed and preliminary environmental and resource assessments are required as a first priority before further consideration of the project

Case Study: Clarence Strait – LNG liquefaction - waste carbon dioxide to methane conversion

Executive summary

This case study discusses the use of tidal energy converters (TECs) to provide power for the conversion of waste carbon dioxide to methane. The waste carbon dioxide would come from the Ichthys liquefied natural gas (LNG) plant at Wickham Point in Darwin and methane gas would be produced using hydrogen from a hybrid solar-tidal energy farm and electrolysis complex near Gunn Point. The tidal component of the plant has a central role in ensuring 20 percent dispatchable energy is continuously available. This is likely to be an essential requirement both for the methane production plant and for emergency power backup options. The plant would produce 3538 tonnes of methane a year and remove up to 9906 tonnes carbon dioxide.

Background

Projections for annual carbon dioxide (CO_2) emissions from Australia's nine largest LNG projects range from 49 to 89 million tonnes per annum[74]. A very significant proportion of this is due to the stripping of carbon dioxide from natural gas and releasing it to the atmosphere. Proposals are in place to sequester up to 4 million tonnes of this carbon dioxide in depleted oil and gas reservoirs, or deep, un-minable coal beds. An additional approach could be to convert the carbon dioxide to methane by reacting it with hydrogen using processes such as the Sabatier reaction. The power and the hydrogen for this reaction could be obtained using renewable energy.

The Ichthys LNG liquefaction plant at Wickham Point in Darwin taps two main gas fields: one at Brewster with 8 percent and another at Plover with 17 percent carbon dioxide content. The production of LNG releases about seven million tonnes a year of carbon dioxide. Over the 40-year life of the plant this will amount to 280 million tonnes of carbon dioxide. About a third of this will come from the concentrated waste carbon dioxide stripped from the LNG during its liquefaction. Provisions have been made in the liquefaction plant design for carbon capture and storage but these are not implemented yet.

Project Details

Overview

A significant tidal energy resource has been assessed in Howard Channel and South Channel near Gunn Point and 40 km from the Wickham Point LNG plant. A preliminary assessment estimates that it could supply 4.4 MW of dispatchable power[75] and this combined with an average 17 MW of power from a solar farm located between Gunn and Glyde Points could be used in a pilot plant to produce hydrogen and react it with carbon dioxide from the LNG liquefaction plant. The methane could be recycled into the liquefaction plant or Ichthys pipeline. In emergencies either the methane or the electricity generated by the hybrid solar tidal farm could be used as a backup supply to Channel Island Power Station or HMAS Coonawarra.

The largest renewable energy to gas conversion plant in the world is the Audi e-gas plant in Werlte, Germany (Figure 55). It consists of 4x 3.6 megawatt off-shore wind turbines driving an electrolyser for producing hydrogen and a Sabatier carbon dioxide to methane conversion (methanation) unit[76] [77]. The Werlte plant switches between mains grid electricity and wind energy dependent on the intermittency of the wind turbines. A hybrid solar-tidal power plant with 20 percent dispatchable electricity might be a better match to the load requirements of both the electrolysis and methanation stages of the plant operation.

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[74] Fogarty, D., (2011). Factbox: Projected CO2 emissions from top Australia LNG projects. Reuters https://www.reuters.com/article/us-australia-lng-carbon-fb/factbox-projected-CO2-emissions-from-top-australia-lng-projects-idUSTRE7491FU20110510

[75] Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C., (2020). Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished)

[76] Lambert, M., (2018). Power-to-Gas: Linking Electricity and Gas in a Decarbonising World? Oxford Energy Insight: 39, The Oxford Institute for Energy Studies, Accessed 12 Sept 2020, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/10/Power-to-Gas-Linking-Electricity-and-Gas-in-a-Decarbonising-World-Insight-39.pdf

[77] Gorre. J, Ortloff. F, van Leeuwen. C, (2019). Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage, Applied Energy Volume 253, 1 November 2019, 113594, Accessed 14 September 2020, <https://www.sciencedirect.com/science/article/pii/S0306261919312681>

Figure 55: The Audi e-gas plant in Werlte – converting carbon dioxide to methane

This case study suggests a two-phase project: first setting up a tidal plant in Howard Channel, Clarence Strait to provide power for a carbon dioxide to methane conversion plant near Gunn Point, and then scaling it up by a factor of five using a solar farm at Gunn Point. Dispatchable power would be supplied from 18 tidal turbines located in Howard Channel in Clarence Strait (fig 2) and a relatively small battery would ensure dispatchable power to maintain process flow in the continuously operating plant.

Location and the tidal and solar resource

Figure 56 shows the distribution of tidal energy across the Vernon Islands and Figure 57 gives the rated power, average power and corresponding electricity generation as well as the number and size of TECs required[78]. A 20 percent continuous dispatchable energy level has been set to accommodate the needs of a 24-hour chemical processing plant. This requires either a tidal energy component of 4.4 MW coupled with a three- hour, 13 MWh battery, or a 38-hour 166 MWh battery, if a solar farm is used without the tidal energy component. This allows the plant to manage solar power intermittency due to the diurnal solar radiation cycle and during the wet season in Darwin[79].

Environmental constraints

An environmental study has yet to be carried out. The Vernon Islands are a conservation reserve and there is a reef to the south of Vernon Island. However, Gunn Point is currently being considered for industrial development so that the presence of a hydrogen production plant and overland pipeline to the Liquefaction plant in Darwin may not be an issue. All estimates given here for energy extraction from tidal streams are subject to tidal stream energy extraction limits of less than twenty percent.

[78] Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C., (2020). Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished),

[79] Darwin Solar Exposure, Climate Data Online, Australian Government Bureau of Meteorology, Accessed 11 Sept 2020, http://www.bom.gov.au/climate/data/index.shtml?bookmark=203

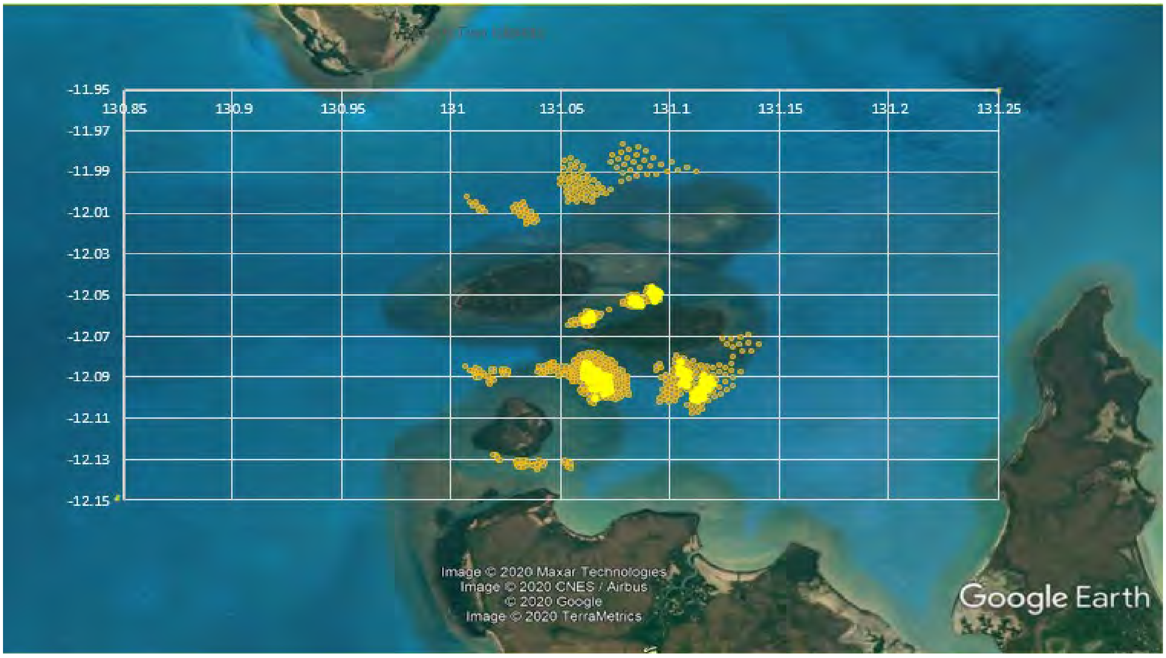
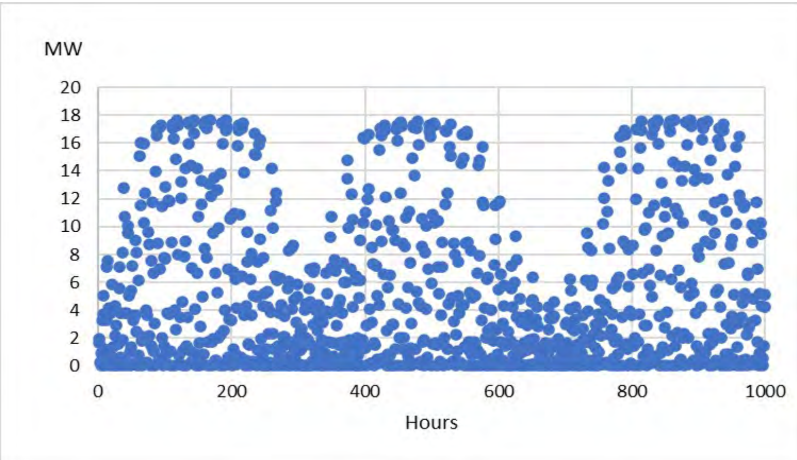


Figure 56: National Tidal Model high flow rate tidal stream data points



Power generation Howard Channel			
Rated		**Generated**	
154493 MWh		46831 MWh	
17.6 MW		5.3 MW	
Tidal Energy Converters			
Diameter	**No'**	**Rating**	**CF**
16 m	5	296 kW	25%
24 m	2	666 kW	29%
26 m	18	782 kW	31%

Figure 57: Tidal energy farm parameters

System Specification

Solar energy farm component

1000	metres squared	Solar farm
78	MW	Rated power
147	GWh	Generated electricity per annum
17	MW	Average power
22%	percent	Capacity Factor
4.36	MW	Dispatchable (continuous) tidal power
165.6	MWh	Battery for dispatchable (continuous) tidal power of 4.36 MW for 38 hours

Tidal energy farm component

14	MW	18x TECs 26m rated power 0.782 MW
38.2	GWh	Generated electricity per annum
4.36	MW	Average power

31%	percent	Capacity Factor
4.36	MW	Dispatchable (continuous) tidal power
13	MWh	Battery for dispatchable (continuous) tidal power of 4.36 MW for 3 hours

Hybrid solar and tidal farm parameters

92.02	MW	Total Rated Power
21	MW	Total Average Power
4.36	MW	Dispatchable (continuous) tidal power
13	MWh	Battery for dispatchable (continuous) tidal power of 4.36 MW for 3 hours
23	percent	Capacity factor
21	percent	Percentage dispatchable electricity
$10,375,344	AUD	Annual value of generated electricity per year at $56/MWh
185	GWh	Generated electricity per annum
3535	tonnes	Equivalent hydrogen based on 0.00001901 tonnes/kWh
3538	tonnes	methane output based on Audi Werte plant reports 167 tonnes/MW/yr.
9906	tonnes	CO_2 consumption based on Audi Werte plant reports 467 tonnes/MW/yr.
$1,096,756	AUD	Annual value of methane at $0.31 per kg
$520,074	tonnes	Annual value of CO_2 mitigation at $0.0525 per kg (non-recyclable reuse)
$1,040,149	tonnes	Annual value of CO_2 mitigation at $0.105 per kg (recyclable reuse)
$10,375,344	tonnes	Alternative annual value of generated electricity per year at $56/MWh
$7,070,463	tonnes	Alternative annual value of hydrogen produced at $2/kg

Capital Costs[80]

Capital cost with tidal energy

$139,358,824	78 MW solar farm
$7,787,910	3hr 13 MWh battery
$10,000,000	10 km subsea power cables
$66,133,760	14 MW tidal turbine farm
$223,280,494	Total

Capital cost without tidal energy

$175,756,697	Solar farm (rated power 95 MW, average power 21 MW)
$98,646,854	Battery (dispatchable power 4.4MW for 38 hours)
$274,403,551	Total

Opportunities

Two opportunities have been identified for using tidal energy from Clarence Strait: i) the conversion of carbon dioxide to methane or ii) the production of either electricity or hydrogen for general power and fuel usage.

In the first opportunity the production of 3538 tonnes of methane a year for re-injection into the Ichthys pipeline is associated with the removal of up to 9906 tonnes carbon dioxide emissions per year noting that the degree of mitigation will depend on whether or not the methane is subsequently used in a recyclable carbon dioxide power plant[81] . The value of the

[80] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

[81] Antenucci A, and Sansavini G., (2019). Extensive recycling in power systems via power-to-Gas and network storage, Renewable and Sustainable Energy Reviews, Vol 100, February 2019, Pp 33-43. Accessed 12 September 2020, <https://www.sciencedirect.com/science/article/pii/S136403211830724X>

combined emissions mitigation and methane production is estimated from $0.5M to $1M per annum[82] depending on the degree of carbon dioxide mitigation[83].

In the second opportunity the production either of hydrogen or electricity could be used as an emergency supply for the Channel Island Power Station or HMAS Coonawarra. The electricity would have a peak rated power of 92 MW with a capacity factor of 23 percent and a wholesale value per year of $10.4M. Alternatively 3535 tonnes year of liquid hydrogen could be produced with a value of $7M.

Challenges, gaps and uncertainties

Environmental impact

Detailed environmental and multi-use impact assessments need to be carried out, in particular:

- The installation might be susceptible to any dredging maintenance operations, so this aspect would need particular attention
- Checks are needed to confirm if any proposed installation would interfere with navigation channels.

Technological readiness

Power to gas chemical plants are both commercially available and adapted for use with renewable energy. The project has been proven technically feasible. It remains to determine the exact level of dispatchable power required for reliable operation of the electrochemical processing plant so that the ratio of tidal to solar energy and battery storage can be more accurately estimated.

Cost benefit

- The estimates for submerged infrastructure: capital equipment costs are indicative and based on GenCost estimates for the tidal energy converter industry[84] they will need to be assessed in more detail. The operations costs remain to be determined as they are location specific. The costs of methane and hydrogen production from renewable energy are not included as this technology is rapidly developing.
- There is also a need for long term consultation, evaluation and planning to adapt the tidal energy resource for the benefit of the Ichthys LNG plant and/or for the benefit of the Channel Island Power Station and HMAS Coonawarra.

Degree of carbon mitigation

The degree of carbon dioxide mitigation will depend on whether or not the methane is subsequently used in a recyclable carbon dioxide power plant. If it is combusted without recycling then the mitigation would be at least halved. Alternatively, if the methane is subsequently used for energy transfer i.e. continuously recycled then the mitigation could be complete[85].

Level of Dispatchability

Significantly greater than 20 percent dispatchable power may be achieved depending on the performance of a solar panel in low light conditions. The results given here are based on known reductions in solar irradiance by up to 75 percent during the wet season from November to March. The precise level of dispatchability that can be achieved will depend on the temperature and irradiance dependence of the solar panels used. The 20 percent value quoted here is conservative and depends only on the performance of the tidal energy converter.

Key findings and outcomes

Findings

A key advantage in adding a twenty percent tidal energy contribution is that it provides a level of dispatchable power that would be essential to run a chemical processing plant in a 100 percent renewables grid scenario. It was noted that the hybrid tidal solar plant provided dispatchability at a lower cost than a solar farm without a tidal dispatchable energy contribution. Likewise, the solar farm added cost effective capacity that would have been impossible in a tidal farm without a solar energy contribution.

Outcomes

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[82] Graham, Hayward, J. Foster, J. and Havas, L., (2019). GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

[83] Antenucci A, and Sansavini G., (2019). Extensive recycling in power systems via power-to-Gas and network storage, Renewable and Sustainable Energy Reviews, Vol 100, February 2019, Pp 33-43. Accessed 12 September 2020, <https://www.sciencedirect.com/science/article/pii/S136403211830724X>

[84] Hayward et al., GenCost 2019-20: preliminary results for stakeholder review

[85] Antenucci & Sansavini, Extensive recycling in power systems via power-to-Gas and network storage

- A technologically ready system has been outlined for a hybrid tidal-solar energy farm operating from Howard Channel in Clarence Strait and Gunn Point to power an electrochemical plant capable of removing 9906 tonnes carbon dioxide emissions per year by converting it to 3538 tonnes of methane a year at a combined annual value of up to $2.1M.
- Preliminary capex estimates for the hybrid tidal-solar plant have been made. Detailed capital and operations costs per year for TEC installation and maintenance and for the power to gas conversion plant are yet to be determined
- Phase 1 of the project is a pilot study tidal energy farm for generating dispatchable power for the carbon dioxide to methane conversion plant. Phase 2 is the expansion of the plant to five times capacity by incorporating a solar farm.
- The hybrid tidal-solar energy farm could be convertible at short notice to an emergency backup power supply for the Channel Island Power Station and/or HMAS Coonawarra.

Recommendations/next steps

The following are required prior to making a presentation to key stakeholders interested in the project:

- Consultation with the key stakeholders including Darwin City Council, Inpex (The owners of the IchThys LNG plant), Darwin Port Operations Pty Ltd, Department of Defence.
- Consultation with the managers of the Audi e-gas processing plant in Werlte, Germany on the feasibility of replicating and expanding such a plant in Australia and the cost benefit of tidal dispatchable power
- Confirmation of the preliminary cost estimates.
- Prepare a pilot plant proposal for consideration by the Blue Economy CRC

Case Study: Port Melville - Tidal energy - high security electricity supply

Executive summary

This project is to provide electricity from a tidal energy converter (TEC) to provide a secure electricity supply during disasters and emergencies for the NT Port and Marine's Melville Port facility. The ARENA National Tidal Model together with Port Melbourne tidal assessment suggests there are a number of fast tidal streams south of the port that may be suitable for tidal energy electricity generation or hydrogen production.

Background

Port Melville is operated by Northern Territory Port and Marine and is located on Melville Island, Appsley Strait, approximately 50 km NNW of Wurrumiyanga and 2.5 km from Garden Point Airport. It is a security regulated port approved by the Commonwealth Government of Australia and provides facilities for accommodation for 150 offshore workers, marine and land fuel supply from a 30 million litre 'fuel farm', and areas for berthage, laydown and storage.

Project Details

Overview

A renewable energy resource could provide energy security for essential services to the local community at Port Melbourne in the event that diesel supply is interrupted for long periods. Wind energy is precluded because of its intermittency and low intrinsic capacity factor in the region. Solar and tidal power could provide complementary services with a 100-metre square solar farm rated at about 170 kW but with some vulnerability due to its intermittency, exposure and high profile. Tidal energy is less exposed to fire and flying debris and able to provide cost effective dispatchable power when used with a relatively small battery.

Resource

During spring tides at Melville Port, the ebb begins an hour after high water, increases rapidly over two hours to speeds of 2 m/s to 2.5 m/s and then maintains its velocity for three hours after which it rapidly slows. The neap tide flow rate is about half the spring tide flow rate. The maximum velocity during the flooding tide from the north is 1.25 m/s. There is very little high-resolution data on tidal flow velocities south of Port Melville. Port Melville reports[86] [87] [88]suggests there are a number of fast tidal streams in its vicinity and a fairly strong tidal current to the south of Harris Island was identified from the ARENA AUSTEn National model at 11.43°S, 130.41°E with a peak flow of 1.5 m/s and a depth of 11 metres. A 45-metre deep 500-metre wide channel runs from Port Melville wharf to 2 km south of Harris Island. The strait narrows and becomes shallower at the southernmost point of the channel and this may create higher tidal ebb flow speeds and allow greater rotor diameters to be used but this needs to be verified in a high-resolution assessment of the tidal resource.

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[86] NT Port and Marine, 2018, Port Procedures and Information for Shipping. Northern Territory Port and Marine. November 2018, Accessed 13 September 2020
<https://www.ntportandmarine.com/wp-content/uploads/2018/11/Port-Melville-Port-Procedures-and-Information-for-Shipping.pdf>

[87] NT Port and Marine, 2017, Port Melville Information Booklet. Northern Territory Port and Marine. August 2017, Accessed 13 September 2020
https://amgmarine.com.au/assets/pdfs/port_melville_information_handbook.pdf

[88] NT Port and Marine, 2020, Mermaid Shoal Tide Predictions 2020, Accessed 13 September 2020, <https://www.ntportandmarine.com/wp-content/uploads/2020/01/MermaidShoal_hrly_TideTable.pdf>

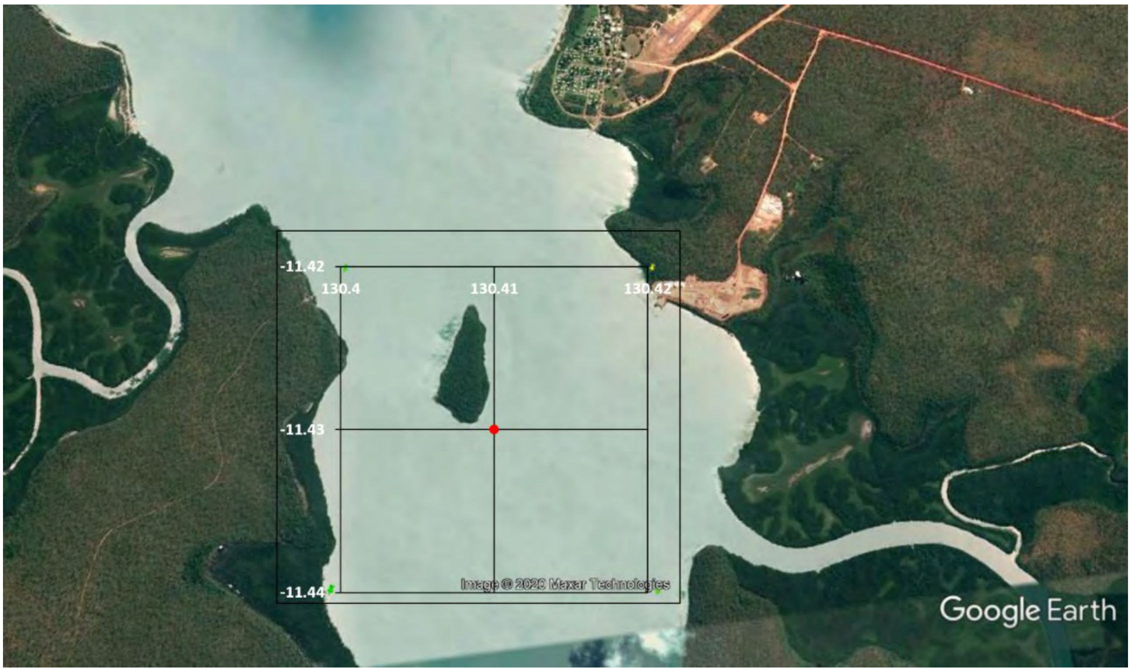

Figure 58: National Tidal Model high flow rate tidal stream data points

Figure 58 shows the location south east of Harris Island (130° 24.6'E, 11 ° 25.8'S) for a strong tidal stream (Figure 59) found using the ARENA National Tidal Model. A TEC with a 16-metre rotor diameter was assessed using data from the National Tidal Model and the ARENA AUSTEn project[89]. Its rated power was estimated as 296 kW with a power factor of 12 percent and producing 311 MWh electricity per annum. However, this location may not be optimal given that the National Tidal Model is low resolution. Nevertheless, the assessment suggests a TEC would produce enough electricity to power several households and a small office complex including lighting, computing and a satellite or short-wave radio communications or broadcast facility.

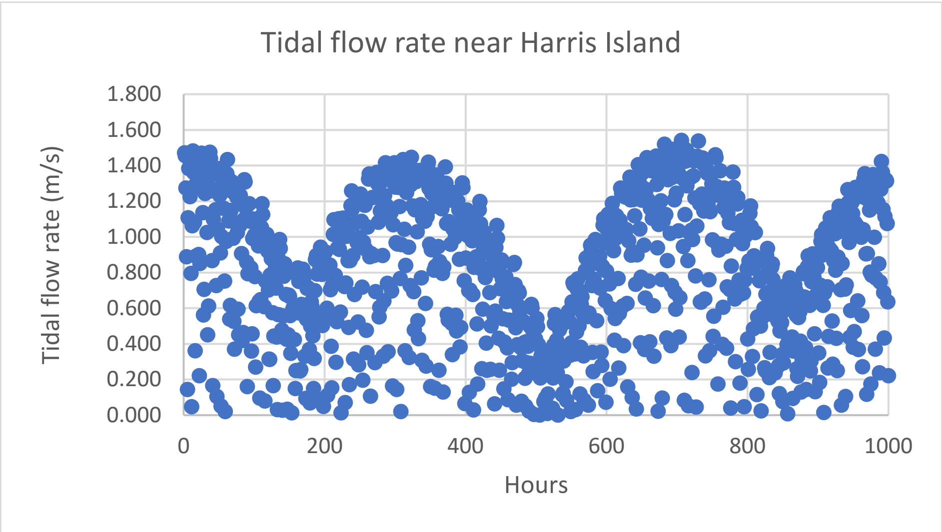

Figure 59: Tidal stream flow rate near Harris Island

An assessment was also carried out for prospective sites located at the southern end of the 5 km channel. A prospective site might be south of Herbert Point in the region centred on 11° 26.325'S, 130°24.930É. Electrical power could be generated and supplied via a cable traversing between 0.5 km to 1 km underwater and 1 km to 2 km overland ii) Hydrogen fuel might also be produced for storage in the Melville Port fuel farm based on an electrical cable between 0.5 km to 1 km underwater and an 8 inch 1 km to 2 km overland hydrogen gas pipeline.

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[89] Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C. 2020, Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished)

Environmental impact

The energy that could be extracted using a high-power tidal farm may need to be limited to avoid flooding up stream of the ebbing tide. A limit of up to four megawatts rated power has been applied assuming a tidal velocity of two metres per second available for up to five 10 metre or 26 metre rotor diameter TECs. If the ebbing tide flow velocity assumption is correct then this should extract approximately 10 percent to 20 percent of the tidal energy at mid tide and this accords with current guidelines for limiting the impact of TECs on the environment. However, this is subject to the need for full environmental and high-resolution tidal stream velocity assessments.

Specification and indicative capital costs

Three tidal energy converter configurations are given. The 10 metre and 26 metre rotor turbines are for deeper sites about 5 km south of Harris Island, and a tidal fence/reef is for shallower locations.
Table 27 shows performance data for the three tidal turbine options, based on finding a tidal stream resource with an average peak velocity of at least 2.5 m/s.

Table 27 and Table 28 shows indicative capital costs for the three options estimated from data provided by the ARENA AUSTEn tidal energy project and GenCost tables[90].

Table 27: Performance data for the turbine farm options

	4 m rotor	10 m rotor	26 m rotor
Number of TECs	16	4	1
Rated power per TEC (2m/s tidal flow)	18 kW	116 kW	782 kW
Tidal farm total rated power	288 kW	464 kW	782 kW
Capacity factor	0.1	0.1	0.1
Dispatchable (minimum continuous) power	28.8 kW	46.4 kW	78 kW
Annual electricity production	0.25 GWh	0.41 GWh	0.68 GWh

Table 28: TEC costs including turbines power cables and batteries for dispatchable power

Item	Cost
0.8MW (26m rotor) tidal turbine	$3.7M
5km power cable	$5M
Energy storage	$0.29M
Total	$9.0M
4x 116 kW (10m rotor) tidal turbines	$11.5M
5km power cable	$5M
Energy storage	$0.17M
Total	$16.7M
Tidal Reef 16x 18kW (4m rotor) tidal turbines	$10.5M
1.5km to 5km power cable	$1.5M to $5M
Energy storage	$0.11M
Total	$12.1M to $15.6M

[90] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

Opportunities

The proposed benefit is for a secure emergency power system. This could be implemented using portable TECs or in-situ TECs for a range of depths depending on the location of strong stable tidal streams that may be found in a high-resolution study.

Challenges, gaps and uncertainties

- The need for a high-resolution assessment of tidal velocities, depths and bed conditions. between Harris Island and Fletcher Point
- The installation might be susceptible to any dredging maintenance operations and will be subject to the navigational constraints expected for Port operations
- Any investment decision will require a much more detailed cost assessment.
- There is a need for long term consultation, evaluation and planning to adapt the tidal energy resource for the benefit of the maritime industry and defence communities. Port Melville and Department of Defence stakeholders who may be interested in this project

Key findings and outcomes

Findings

- Tidal power's key advantage in this secure emergency power application was the low-cost of converting tidal power to dispatchable (continuous) power that took full advantage of tidal energy predictability.

Outcomes

- Two opportunities have been identified to improve power security for essential services at Port Melville:
    - Use of portable and transportable TEC generators upstream of the ebbing tide in Appsley Strait South of Harris Island
    - A potential site to be further assessed for the installation of a tidal farm rated between 100 KW to 5 MWatt. This is located west of Herbert Point
- Three options for tidal energy converter installations have been shown to be capable of providing sufficient power to run a range of key essential services in the event of disruption to the electricity supply at Port Melville.
- A region upstream of the ebbing tide has been preliminarily assessed for a tidal farm with a rated power of between 100 kilowatts and 5 megawatts.

Recommendations/next steps

The following are required prior to making a presentation to key stakeholders interested in the project:

- A high-resolution chart of tidal velocities between Harris Island and Fletcher Point
- A preliminary determination on whether a tidal energy converter can operate within the Port Melville navigation and environmental protection constraints
- Preliminary cost estimates should be confirmed and community consultation and preliminary environmental and resource assessments are required as a first priority before further consideration of the project

Case Study: Yampi Sound, tidal energy for Cockatoo and Koolan Islands

Executive summary

The Cockatoo and Koolan Islands in Yampi Sound each hold large reserves of high-grade iron ore, and have significant potential for mining into the future. Mining at Cockatoo island is not being carried out at present and the mine has flooded following the shutdown of seepage pumps. Managing seepage of seawater into the mine would cost about $0.3M per month. A five-megawatt rated power tidal energy farm would ensure continuous running of the pumps at lower cost, whether or not the mine is shutdown. Additionally, on both islands tidal energy converters could supply a significant proportion of the site electricity and would provide useful infrastructure for the local community on completion of mining at the island.

Background

The ARENA National Tidal Model shows that the general region of King Sound and Yampi Sound has some of the strongest tidal currents and tidal energy resource in Australia. However, where the resource is most powerful and well defined it is also distant from communities and industrial enterprises so that power cabling costs limit the practical distance for most small installations to just a few kilometres. This is a significant factor affecting tidal power's ability to compete against solar and wind power except where land area is at a premium and where the security and stability of the power supply is paramount. Koolan Island and Cockatoo Island in Yampi Sound meet both these criteria and could benefit from tidal power.

At Cockatoo Island a sea wall isolates the main ore body pit from the sea. On two occasions pumps that manage seepage into the pit have been shut down, leading to flooding of the pit. The first flood event was in 2016. The pit was dewatered in 2017 an operation that took about eight months as it had to be done slowly to avoid overstressing the sea wall[91]. Maintaining the pit dry after dewatering is estimated to have cost from $0.5M to $1M per month[92] [93]. The dewatering pumps were subsequently shutdown and the mine refilled with water over a period of six weeks.

The Cockatoo Island mine is currently closed and some remediation work is being carried out on the sea wall to protect the local marine environment. A major concern is that a flooded pit will lead to sea wall failure[94], inundating local coral reefs with sediment and altering whale migration routes[95] [96]. Dewatering the mine could also cause months of delay if the mine is recommissioned, with a subsequent maintenance pumping cost of about $0.3M per month. A permanent electricity supply could be provided by a six-megawatt tidal energy farm for water pumps to counter ongoing seepage into the main ore body pit.

Koolan Island mine is fully operational and has accommodation for its work force so the associated electrical load could justify the use of tidal energy converters. A tidal energy resource to the south east of the island matches the electricity demand of the mine offices, workshops and employee accommodation. It may also be possible to find additional tidal stream resources.

Project Details

Overview

An approximately six megawatts power rated TEC, with 20 percent dispatchable electricity, could be used for supplying electricity to continuously pump seepage water from the Cockatoo island ore pits. For Koolan Island a one-megawatt power rated TEC could supply the electricity demand for offices, accommodation and workshops. Wind energy is unsuitable because of its intermittency and low intrinsic capacity factor in the region. Solar energy is precluded because insufficient land is available on the islands. Tidal power has the advantage that it is compact and remains relatively constant throughout the year.

Tidal energy resource

The ARENA National Tidal model provides a low-resolution map (Figure 60) of tidal stream flow velocities around Koolan Island and Cockatoo Island (Figure 61) to within one or two-kilometres resolution. But, while the model shows very strong tidal currents around most of King Sound and its neighbouring waters, but it does not show tidal velocity streams near Cockatoo or

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[91] Powell, CL and Hall, J., (2020). Cockatoo Island: pit dewatering and wall depressurisation behind critical seawall infrastructure, in PM Dight (ed.), Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering, Australian Centre for Geomechanics, Perth, pp. 1359-1372, Accessed 9 September https://doi.org/10.36487/ACG_repo/2025_93Russell

[92] Daly, J., (2018). Bryan Hughes Interview ABC Country Hour, 7 July 2018, Accessed 9 September https://www.abc.net.au/news/rural/2018-07-07/new-hope-for-wa-cockatoo-island-iron-ore-mine/9949968

[93] Amendment Notice 1 - 19 August 2019, Licence, Pluton Resources Limited, Cockatoo Island Iron Ore Mine and Processing Plan Accessed 9 September https://www.der.wa.gov.au/

[94] Powell and Hall, Cockatoo Island: pit dewatering and wall depressurisation behind critical seawall infrastructure

[95] Amendment Notice 1

[96] Dambimangari Aboriginal Corporation, (n.d.). Accessed 9 September https://www.dambimangari.com.au/

Koolan Islands that would efficiently power a TEC. However, local environmental assessments describe tidal ranges of 10 to 11 meters around the islands and the presence of strong tidal currents[97] [98]. This together with a study of a local site 'The Gutter' that recorded flow rates of up to 3 m/s[99], suggests that other tidal streams may be found that could power a TEC.

In Cockatoo island there are two zones that may have tidal flows capable of powering one or two TECs. One is located 1.5 kilometres north east of the mine site and about 200 metres off shore, a second is 1.5 kilometres south west of the mine site and 1.5 kilometres off shore. A power cable from the northern site may have to traverse quite hilly terrain but this would be mostly overland. A power cable for the southern site would be mainly subsea.

Koolan Island has an identified tidal resource at The Gutter to the south east of the island that is capable of powering a 16 turbine TEC with a rated power of 0.3-megawatt and a capacity factor of about 20 percent[100]. The turbines are arrayed in a 'fence' or 'reef' that traverses part of The Gutter channel. This is desirable because the channel is shallow and the tidal stream changes position from flood to ebb. There are also two zones close to the mine, and deep enough to be economically viable if tidal streams can be found. One is 0.5 kilometre north of Mullet Bay on the north side of the island and the second is the channel south west of the sea wall that has a nominal depth of 20 metres.

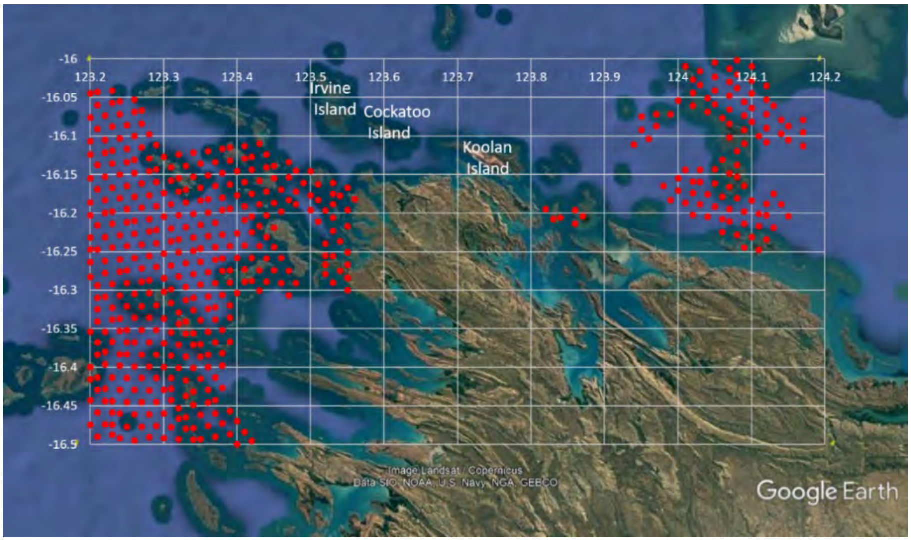

Figure 60: Tidal velocities in King Sound and Yampi Sound

[97] Kimberley Technology Solutions Pty Ltd, (2017). Cockatoo Island Multi-User Supply Base, Technical Study - Marine Flora and Fauna, June 2017, Accessed 9 September https://consultation.epa.wa.gov.au/
[98] Koolan Island Iron Ore Mine and Port Facility, (2005). Report and recommendations of the Environmental Protection Authority, Environmental Protection Authority, Perth, Western Australia, Bulletin 1203, [November, 2005] Aztec Resources Limited, Accessed 9 September
https://www.epa.wa.gov.au/sites/default/files/EPA_Report/2147_B1203.pdf
[99] Current Study at Koolan Island, (2009). DHI Water & Environment (S) Pte.
[100] O'Neil, L., (2016). The Tidal Turbine Reef ARENA Tidal Turbine Design Report <https://arena.gov.au/projects/tidal-turbine-reef-feasibility-study/>

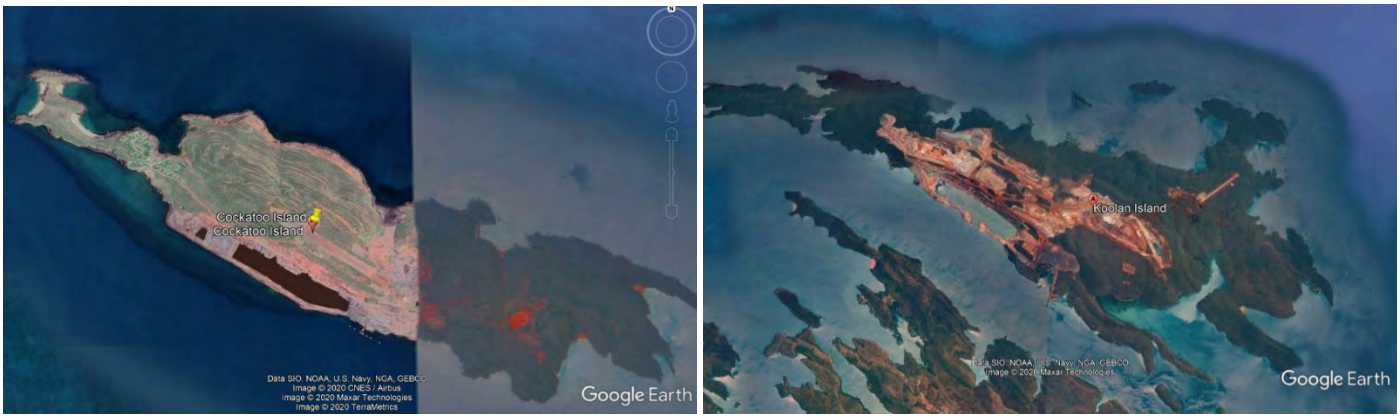

Figure 61: Cockatoo (left) and Koolan (right) Island Mine Sites

Environmental impact

Cockatoo and Koolan Islands are about 30 kilometres to the north west of the Horizontal Falls marine park and lie on a migration route for humpback whales that breed in the Lalang-Garram marine park 100 kilometres to the north east. Cockatoo Island has a number of listed marine and land based migratory and threatened species and most of the sea around Koolan island is assigned a high level (E2) of environmental protection. On the south side of Koolan Island, a zone adjacent to the seawall at Arbitration Cove is assigned a moderate level (E3) of protection and the mixing zone around the main pit dewatering discharge is an area of low level (E4) protection[101] [102]. A port security zone is defined adjacent to the Cockatoo Island mine on the south side of the island and there are areas inside and outside the zone marked as having unexploded ordnance on the sea floor.

Specification and indicative capital costs

Table 29 shows the performance data for the three tidal turbine options used for a range of potential locations and site depths, based on finding a resource with a tidal stream with an average peak velocity of at least 2.5 m/s.

Table 29: Performance data for the turbine farm options

	4 m rotor	**10 m rotor**	**26 m rotor**
Number of TECs	16	4	1
Rated power per TEC (2m/s tidal flow)	18 kW	116 kW	782 kW
Tidal farm total rated power	288 kW	464 kW	782 kW
Capacity factor	0.2	0.2	0.2
Dispatchable (minimum continuous) power	57.6 kW	92.8 kW	156.4 kW
Annual electricity production	0.50 GWh	0.81 GWh	1.37 GWh

Table 30 and Table 31 show indicative capital costs for four locations. Options 1,2 and 4 are based on the data provided by the ARENA AUSTEn tidal energy project and GenCost tables[103] [104]. Option 3 is based on an assessment by DHI Water and

[101] Koolan Island Iron Ore Mine and Port Facility Project, (2013). Marine Management Plan, Revision 2013, Accessed 9 September https://www.mtgibsoniron.com.au/wp-content/uploads/Koolan-Island-Marine-Management-Plan.pdf

[102] Perth's Coastal Waters, (2000). Environmental Values and Objectives, the position of the EPA - a working document, February 2000, Accessed 9 September https://www.epa.wa.gov.au/sites/default/files/Policies_and_Guidance/1982_PerthsCoastalWaters.pdf

[103] Dambimangari Aboriginal Corporation, (n.d.) Accessed 9 September https://www.dambimangari.com.au/

[104] Graham, P., Hayward, J. Foster, J and Havas, L., (2019), GenCost 2019-20: preliminary results for stakeholder review, accessed 5 September 2020, <https://www.aemo.com.au/>

Environment of the Gutter channel tidal stream to the east of Koolan Island[105], together with an assessment carried out for ARENA of a TEC Reef concept that could be well suited to Koolan Island[106]. The lowest cost option 1 reflects economies of scale in turbine size so that deeper sites will prove most economical. Option 3 uses much smaller rotors because it is located in relatively shallow water and must accommodate a tidal range of 9 m. The multiple rotors also take advantage of a shift in tidal stream direction between the ebbing and flowing tide. All turbines are anticipated to function with an approximately 20 percent capacity factor. The highest cost option 4 relates to the more power intensive task of dewatering a mine compared to the options 1 to 3 that relate to supplying office and accommodation power.

Table 30: Koolan and Cockatoo Island – Capex: Power for offices, workshops and accommodation

	Location	*Item*	*Cost*
1	Koolan Island north of Mullet Bay	0.8 MW (26 m rotor) tidal turbine	$3.7M
	Cockatoo Island north or south of mine	1.5 km to 5 km power cable	$1.5M to $5M*
		Energy storage	$0.19M
		Total	$5.4M to $8.9M
2	Koolan Island south of Arbitration Cove	3x 116 kW (10 m rotor) tidal turbines	$11.53M
		1.5 km to 5 km power cable	$1.5M to $5M*
		Energy storage	$0.11M
		Total	$13.1M to $16.6M
3	Koolan Island South East (The Gutter - adjacent to Round Island)	Tidal Reef 16x 18 kW (4 m rotor) Tidal turbines	$10.5M
		4 km power cable	$4M
		Energy storage	$0.07M
		Total	$14.6M

*Dependent on Location

Table 31: Cockatoo Island – Capex: Power for Dewatering

	Location	**Item**	**Cost**
4	Cockatoo Island north east of North Bay	1 MW (6x 26 m rotor) tidal turbine	$22M
		1.5 km to 5 km power cable	$1.5M to $5M*
		Energy storage	$1.14M
		Total	$24.6M to $28.1M

*Dependent on Location

Opportunities

- The maintenance of a dewatered mine at Cockatoo Island may remove a key barrier to the development of a mine capable of returning 2bn dollars over ten years
- The constant availability of power for pumping out water seepage should contribute to maintaining the sea wall integrity and further protect the local marine environment
- The constant availability of tidal power and water seepage management could reduce the time to recommission the Cockatoo mine by up to six months
- Substituting tidal power for diesel to supply electricity to the mine sites could reduce carbon emissions by up to 3000 tonnes of CO_2e per year
- The TECs could support community enterprises such as tourism or aquaculture that may be initiated following decommissioning of the mines

[105] Current Study at Koolan Island, (2009). DHI Water & Environment (S) Pte. Ltd
[106] O'Neil, L., (2016). The Tidal Turbine Reef ARENA Tidal Turbine Design Report <https://arena.gov.au/projects/tidal-turbine-reef-feasibility-study/>

Challenges, gaps and uncertainties

- Additional bathymetry and high-resolution modelling of tidal stream velocities is needed to confirm if TECs can be economically used for the Island's mines.
- Most of the sea around Koolan island is assigned a high level (E2) of environmental protection. An environmental impact study is required of the environmental impacts a tidal farm might have.
- The estimates for submerged infrastructure: capital equipment costs are indicative and based on GenCost estimates for the tidal energy converter industry[107] they will need to be assessed in more detail. The operations costs per year for remain to be determined as they are location specific.
- Assessment may be needed for unexploded ordnance on the sea floor south of the Cockatoo Island mine sea wall
- Power consumption estimates need to be confirmed with the mine operators.
- There is a need for long term consultation, evaluation and planning with mine managers and the local community, to optimally access and apply any potential tidal energy resource.

Key findings and outcomes

Findings

- In remote locations the regularity and reliability of the tidal power resource and its low-cost conversion to dispatchable power may have a significant advantage over other power sources for critical applications requiring continuity of supply such as managing seepage in a vulnerable structure such as a sub-sea mine sea wall.

Outcomes

- The tidal stream at the Gutter is capable of supplying a significant proportion of the mine's office, work shop and accommodation electricity demand and a high-resolution tidal energy survey may identify additional high velocity tidal streams
- A preliminary assessment using the methodology and modified turbines described in the ARENA AUSTEn tidal energy survey, suggests that it would be feasible to use TECs to remove seepage through the sea walls at the Cockatoo island mine site.

Recommendations /next steps

The following are required prior to making a presentation to key stakeholders who may be interested in the project including: traditional owners of the land, miners, environmentalists, tourism industries and government agencies:

- A high-resolution chart of tidal velocities within a two-kilometre band off shore on the northern and southern borders of the mine sites is needed to confirm the feasibility of each project and to allow more detailed cost estimates and environmental impact assessments
- Preliminary cost estimates should be confirmed and preliminary environmental and resource assessments are required as a first priority before further consideration of the project
- More information is needed on power usage and diesel costs for both Cockatoo and Koolan Island.

[107] Koolan Island Iron Ore Mine and Port Facility, (2005). Report and recommendations of the Environmental Protection Authority, Environmental Protection Authority, Perth, Western Australia, Bulletin 1203, [November, 2005] Aztec Resources Limited, Accessed 9 September
https://www.epa.wa.gov.au/sites/default/files/EPA_Report/2147_B1203.pdf

Case Study: Autonomous tidal powered off-shore surveillance

Executive summary

This case study outlines the system and component design for small tidal energy powered subsea surveillance networks. These would be widely distributed, acoustically networked, autonomous and small enough to be difficult to locate. Such units are technically feasible given the tidal surveys carried out to date and the current status of maritime surveillance technology.

Background

Mainland Australia has a coast line of approximately 36,000 kilometres, its exclusive economic zone extends 200 nautical miles and covers 8.2 million square kilometres of ocean off Australia and its remote offshore territories, and two million square kilometres off the Australian Antarctic Territory[108].

Surveillance of marine territories is of key importance for defence, policing, security of commercial operations and protection of the environment. Currently Australia's surveillance systems use aircraft, maritime radar and surveillance satellite services. Arguably this does not adequately address subsea threats. During the last twenty years floats, buoys and autonomous underwater vehicles have been increasingly equipped with sensing and telemetry equipment and used for subsea surveillance. There may also be a need to reintroduce permanent surveillance systems on the sea floor[109].

Project Details

Functional definition for a tidal energy powered surveillance device

- Tidal energy powered devices should be well suited for operation offshore near estuaries, river mouths and harbours that needed protection.
- Tidal energy powered surveillance devices should be capable of autonomous operation, not requiring cable links to shore or nearby vessels and not requiring batteries to be replaced or radio-isotopic power.
- The availability of relatively high-powered tidal energy devices should allow significant areas of ocean to be monitored using spread spectrum acoustic communication for covert networking between devices[110] [111].

Location and the tidal resource

The power requirements for a tidal energy powered subsea surveillance device typically range from 1 to 50 watts[112]. However, devices in a network designed to surveil hundreds of square kilometres could operate from as low as one watt up to a kilowatt of power to maintain acoustic communication links within the network. Given these power requirements if highly geared turbines were used for electricity generation as described in the ARENA AUSTEn Tidal Project, it should be possible to power TECs from relatively slow tidal currents without having to use overly large TEC rotor diameters.

Specification and technical feasibility

There do not appear to be any technical barriers to implementation given the following very preliminary specification:

- A preliminary estimate of the practical range for acoustic telemetry range in Australian waters is about 5 km, but this could be extended by using: i) buoy technology (e.g. the OPT Hybrid Power Buoy[113]) for greater range, and/or ii) other TEC surveillance devices in a subsea network
- The device may be equipped with acoustic pattern recognition and possibly vessel AIS via a buoy

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108 Australian Government Dep't of Home Affairs - Future Maritime Surveillance Capability, Accessed 13 September 2020, <https://www.homeaffairs.gov.au/how-to-engage-us-subsite/Pages/maritime-surveillance-capability-project.aspx>

109 Stashwick, S., (2016). US Navy Upgrading Undersea Sub-Detecting Sensor Network. The Diplomat, Accessed 13 September 2020, <https://thediplomat.com/2016/11/us-navy-upgrading-undersea-sub-detecting-sensor-network/>

110 Stojanovic M, Proarkis J. G, Rice J. A. and. Green M. D, (1998). Spread spectrum underwater acoustic telemetry, IEEE Oceanic Engineering Society. OCEANS'98. Conference Proceedings (Cat. No.98CH36259), Nice, France, 1998, pp. 650-654 vol.2, doi: 10.1109/OCEANS.1998.724319. Accessed 13 September 2020, <https://ieeexplore.ieee.org/abstract/document/724319>

111 Zia, M.Y.I., Poncela, J. and Otero, P., (2020). State-of-the-Art Underwater Acoustic Communication Modems: Classifications, Analyses and Design Challenges. Wireless Pers Commun (2020). Accessed 13 September 2020, <https://doi.org/10.1007/s11277-020-07431-x>

112 Marsh, P. Penesis, I. Nader, J. Cossu, J.R. Auguste, C. Osman P. and Couzi C., (2020. Assessment of tidal current resources in Banks Strait, Australia including Turbine Extraction Effects (Unpublished),

113 Ocean Power Technologies, (2020). Hybrid POWERBUOY, Accessed 13 September 2020, <https://oceanpowertechnologies.com/hybrid-powerbuoy/>

- A passive sonar range of up to 10km that could be extended up to 40 km if it is possible to take advantage of the SOFAR Sound fixing and ranging channel
- Underwater acoustic telemetry at a rate of up to 9 kBits per second, over a range of five km and with a power consumption of 25 W
- Subsea communication networking capability
- Optional subsea glider capability
- Power requirements of one watt to one kilowatt depending on the application

Environmental constraints
There should be no lasting environmental impact from the use of low power TEC powered surveillance devices.

- The tidal power surveillance devices could be made small with shrouded rotors of less than two metres diameter.
- Spread spectrum techniques for acoustic communication would operate well below the ambient noise level so the network communications should not impact on sea life.
- The devices can be designed to be retrievable
- The devices are autonomous neither producing waste or consuming resources except for a very small amount of tidal energy

Opportunities

The absence of permanent surveillance systems on the sea floor of Australia's territories could open an opportunity for small TEC powered subsea surveillance networks that are widely distributed, acoustically networked, autonomous and small enough to be difficult to locate. Such units are technically quite feasible given the tidal surveys carried out to date and the current status of maritime surveillance technology. The technology could find application in defence, customs, security of offshore infrastructure such as oil and gas wells and environmental monitoring.

Challenges, gaps and uncertainties

The estimates for a networked TEC powered surveillance system will require a much more detailed technical and cost assessment. The engineering approach is well understood. However, the devices are conceptual and will require consultation, design and evaluation if they are to meet the needs of the maritime industry and defence communities.

Key findings and outcomes

Overview
The AUSTEn National Tidal Energy Model and the High-Resolution Model provide the baseline information required to design and locate tidal powered surveillance networks. The surveys have highlighted the need for TECS to be designed for Australian conditions in particular the need to match the rated power of the TEC to the tidal velocity by appropriate gearing and turbine blade sizing. In general turbines for Australian conditions are likely to need higher gear ratios and larger rotor blade diameters for any given turbine power rating. These design conditions should not pose any great difficulty for the design of low power surveillance devices.

Findings
A preliminary assessment shows that tidal energy converters could be used to set up networks of sea bed mounted tidal powered surveillance devices in Australian waters.

The relatively low tidal velocities found in Australian waters should not be a barrier to setting up tidal powered surveillance because of their intrinsically low energy requirements.

Tidal power ensures autonomous operation of the surveillance device. The absence of device to shore cabling for power provides additional security. The absence of batteries allows operation without the need for relatively frequent replacement operations and the absence of radio-isotopic power sources avoids contamination risks to the environment.

Recommendations /next steps

The following are required prior to making a presentation to key stakeholders interested in the project:

- Consultation with Department of Defence and Maritime Industry stakeholders to better determine the design parameters
- Design and demonstration of prototype TEC powered surveillance devices in a small surveillance network as proof of principle

7. AUSTEn Workshop

The AUSTEn workshop was held directly succeeding the Australian Ocean Renewable Energy Symposium (AORES2018) in Perth, Australia on the 23rd of November 2018. Stakeholders present at the meeting included governmental bodies, regulatory bodies, grid and network expert as well as wave and tidal turbine engineering firms, developers and academia. The workshop was facilitated by Gareth Davies, Managing Director of Aquatera. The workshop was organised around three major parts:

- Presentation on the overview of the AUSTEn project to start and several outcomes of the project components of work followed.
- Expert panel on "Perspectives on the future development of commercial-scale tidal energy projects in Australia";
- Participant discussion on "Steps to Commercialisation: Site feasibility, design, planning, operation and maintenance".

The Expert Panel was comprised of representatives of key organisation related to the development of tidal energy in Australia listed in Table 32

Table 32: AUSTEn workshop expert panel

Panel Member	Position	Organisation
Stephanie Thornton	Honorary Secretary/Manager	Australian Ocean Energy Group (Prev. AMET)
Paul Hodgson	General Manager Innovation and Stakeholder Engagement	NERA
Daniel Coles	Project Resource Analyst	SIMEC Atlantis Energy
Vicky Coy	Project Manager	ORE Catapult
Tim Sawyer	Director	Evolutive
Shervin Fani	Principal Engineer	Western Power
Matt Lewis	Research Fellow	Bangor University, UK

Their feedback and their input on the project and in the workshop discussion were extremely valuable. The key factors discussed towards site commercialisation are presented below. Feedback from the attendees was very positive and encouraging. The workshop outcomes were also highly valuable in ensuring alignment of the technically and economically feasible deployment scenarios from Component 3 and the Multi-Criteria Evaluation (MCE) method in selecting the best location for the site B field campaign- Clarence Strait, Northern Territory.

An outline of the workshop is included in Figure 62.

AUSTEn
AUSTRALIAN TIDAL ENERGY

Tidal Energy Workshop

Tidal Energy in Australia - Assessing Resource and Feasibility to Australia's Future Energy Mix

November 23, 2018 | The Indian Ocean Marine Research Centre,
The University of Western Australia, 64 Fairway, Crawley WA 6009

8.30 – 9.00	Arrival and morning tea
9.00 – 9.10	**Welcome, introductions and outline of workshop**
	Associate Professor Irene Penesis, AUSTEn Project Lead
	Facilitator, *Gareth Davies, Managing Director, Aquatera, UK*
9.10 – 10.10	Presentations followed by Q & A session
	AUSTEn Project: Overview of the project objectives and outcomes, progress on components of work, preliminary findings and next steps
	AUSTEn Team
	Global tidal energy outlook
	Gareth Davies, Aquatera
10.10 – 10.40	Morning Tea and networking
10.40 – 12.10	Presentations by expert panel followed by Q & A session
	Perspectives on the future development of commercial-scale tidal energy projects in Australia
	Stakeholder & Expert Panel
12.10 – 1.00	Lunch and networking
1.00 – 3.00	Participant Discussion
	Steps to Commercialisation: Site feasibility, design, planning, operation and maintenance
3.00 – 3.15	**Discussion on next steps for AUSTEn and close of workshop**
	Irene Penesis and Gareth Davies

UNIVERSITY of TASMANIA | AMC Australian Maritime College | THE UNIVERSITY OF QUEENSLAND AUSTRALIA | CSIRO | ARENA Australian Government Australian Renewable Energy Agency
MAKO TIDAL TURBINES | ATLANTIS RESOURCES | ARCADIA UNIVERSITY | PRIFYSGOL BANGOR UNIVERSITY

Figure 62: Workshop programme for event held in Perth, 2018.

Spatial Planning for Tidal Energy Developments: the key factors

Successful planning and executing of a tidal energy development needs careful, broad-based and informed decision making. This decision making needs to take into account factors relating to (in no particular order):

- Tidal resources
- Energy markets
- Engineering design
- Environmental factors
    - Physical
    - Ecological
    - Social
    - Economic
- Existing energy/electricity supply context, and
- Supporting facilities and infrastructure.

Many of these factors have a specific relationship with space and place. In other words the scale, character and importance of these factors will differ subtly or dynamically from place to place, from site to site and from berth to berth within a site. Additionally from this spatial variation, some factors may also change over time either cyclically such as from season to season or due to a longer-term trend of change or cyclic variability. It follows therefore that any site-oriented evaluation of potential development or delivery of a project will need to consider the spatial and temporal characteristics associated with key determining factors.

The AUSTEn workshop aimed to identify these key factors that needs to be used by tidal project developers and site evaluation processes. The workshop provided an opportunity for the different stakeholders to discuss, confirm and validate the key issues and to begin to explore how best these issues should be investigated at each stage in the development process.

Three particularly important issues arose during the discussions.

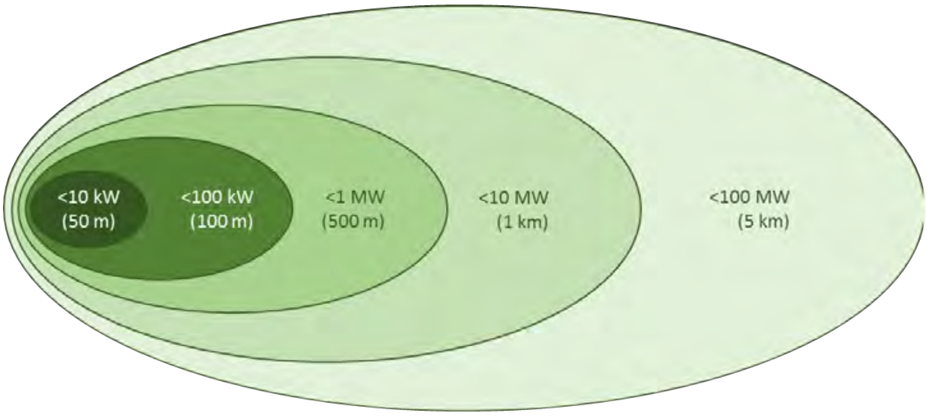
Firstly, the importance of taking into account market needs and opportunities early in the project development process was emphasised. Too often in the past the available energy markets for a particular resource area or technology type have not been considered early enough, leading to a misalignment of understanding between early energy expectations and actual energy market delivery.

Secondly was the role of resource modelling vs resource measurement and the nature of measurements undertaken. Clearly, there are useful and important insights that can come from modelling of tidal currents. Good observational data requires an insignificant level of investment. A model-based understanding of the potential available resource (and other competing or complementary resources) for a potential market identified at step 1 is a necessary first step to justify the observational investment. It is therefore important to ensure that appropriate measurements are obtained at suitable timeframes within the development cycle.

Thirdly, the issue of how to best characterise the economic performance of tidal projects, technologies and indeed the sector was discussed. It became clear that at the present time there is an insufficient data base of real cost metrics upon which to draw from. There are a great diversity in tidal sites, technology specific cost factors, major balance of plant cost factors and finally many different market economics factors that all need to be considered. It was concluded therefore that cross sector single point estimates of economic performance are actually meaningless, and if such figure were produced they should be presented as ranges covering the possible development conditions which need to be applied to particular market applications. At this stage in the sector development pathway, it was considered appropriate to establish, as far as practical, a common finance model structure into which any particular project metrics could be populated. This process would start to create a suitable basis for gaining greater understanding of comparative economic performance, but without being labelled or encumbered with a benchmark target that was inaccurate or inappropriate.

Detailed consideration of key decision factors

Direct impacts



Wider influences

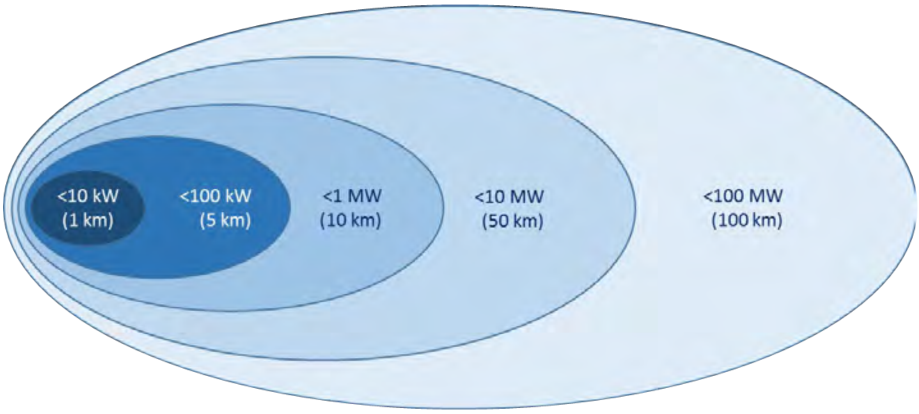


Figure 63. Schematic diagram representing a) the direct impact and b) the wider area of influence of a tidal farm as a function of the farm power extraction capacity

In addition to these three major issues, there were a number of other points raised which have been incorporated below along with observations made on the basis of Aquatera's own experience of tidal project and technology development around the world.

In considering what factors should be taken into account, how this can and should be done, and any guidance as to what might be appropriate, the following table has been compiled dealing systematically with each topic area.

Spatial modelling

There is a commitment within the AUSTEn project to develop a spatial suitability mapping approach to tidal project development. There are a number of possible approaches that could be taken to achieving such an analysis. The AUSTEn team are also undertaking a similar approach. Discussions on what criteria may be most appropriate to consider in such a scheme and also how they could be best taken into account were also included.

Range of impact and influence

Any tidal project development will have a limit to the range over which it will have direct influence. Generally smaller scale projects will have a more restricted range of influence and larger projects a wider range of influence. Whilst there may be specific locations, technologies and aspects of the influence factors to be taken into account, the following scheme outlines an assumed base case zone of effect which can be applied from a direct physical impact to a wider area of influence (cf. Figure 63).

Assessment of key factors

Tidal resource

The characterisation of tidal resources at a prospective tidal generation site is evidently a key priority. There are several factors that need to be taken into account to fully determine the nature of a tidal resource and are outline in Table 33.

Table 33: Key factors for tidal resource characterisation.

Factor	Considerations	Importance
Tidal pattern	Determine the number of high and low tides daily and whether each tidal event is similar or asymmetric to the last.	The overall tidal pattern will determine whether flows come in 2 or 4 periods over 24 hours, whether each flow period is similar to the last and how long/how many slack tide periods there are.
Velocity	This is firstly characterised by an estimate of the max average spring tidal flow, and by the corresponding average neap tidal flow. Modelling may also be used to give an indication of tidal stream velocities – but this is often done in 2D depth-averaged velocities only. Unfortunately, spring and neap tides can be somewhat meaningless in various parts of the country/world where we have meteorological-driven currents. Hence, we need to establish other metrics, and flow percentiles is probably the most suitable. Boat based Acoustic Doppler Current Profiler (ADCP) measurements or radars may be used to characterise the tide across a study area and finally seabed-based ADCP measurements may be used to more definitively characterise the tidal patterns at a particular location.	The appropriate characterisation of flows across the whole extent of a development site will be critical to the overall viability and economics of a site. To date site development plans have often been developed without enough information about resource conditions.
Water levels	Water level monitoring using boat-based or seabed-based measurements to establish time stamped water levels around a particular stream location.	The relationship between water levels and tidal flows in a given area can be complex. Where a stream exists between two basins with out of phase water levels or where a stream is created in a narrowing estuary or embayment, the occurrence of high and low water may not correlate with slack water.
Directional alignment	Existing tidal atlases and modelling results may indicate alignment issues. Actual ADCP measurements are needed to fully understand this issue. Patterns at difference depths need to be addressed as well.	During the power production phase of stream flow, a 180-degree reverse alignment of flood and ebb flows will be easiest to exploit. Where there is a degree of misalignment, then a choice may need to be made to align with either the flood or ebb flows or use yawing turbines. In some areas the direction of the tide may alter towards slack water meaning that marine operations activities need to be aligned differently to the main axis of device operation. This can lead to extra cost, safety issues and technical difficulties
Wave motion effects	This is one of the most challenging factors to measure since the occurrence of storm waves and strong tides may be rather sporadic but could be technically critical. Main consideration is that the wave characteristics of the site are well understood. Long-term wave measurement using buoys, ADCPs or radars are examples of	Wave induced surges in currents may affect resource exploitation and structural integrity.

Factor	Considerations	Importance
	what technologies can be used to determine this effect.	
Extent of resource area	Can be indicated by modelling by boat-based ADCP survey and other technologies – e.g., radar, are superior for this purpose.	The flood and ebb flows in many streams may build in different locations with relatively small area of overlap. The cost-effective development of an area for a given technology will need to be carefully established based on actual flood and ebb flows rather than average energy flows.
Micro resource characteristics	Direct skilled eye appraisal, video monitoring, aerial photographs, boat-based ADCP measurements and radar systems.	The micro layout issues associated with the structures of eddies/current boundaries, patterns of currents and turbulence can all have significant influences upon marine operations and power generation conditions.
Turbulence	Direct observation, aerial photographs, ADCP measurements.	Turbulent flows may affect the productivity of tidal turbines leading to lower outputs than would otherwise be expected. It may also impact on the structural integrity and fatigue of the device.
Water depth	Charted depths 3D bathymetric surveys.	Whilst charts are available for most of the oceans there are many areas, but in high-flow prospective tidal energy sites, existing bathymetry is almost unavailable, and the areas unsurveyed.
Timing of neap tides	The link between the tides and the sun and moon means that the best neap tides for installation periods can be forecasted precisely. These neap tides often occur once a month. Unfortunately, spring and neap tides can be somewhat meaningless in various parts of the country/world where we have meteorological-driven currents. Hence, we need to establish other metrics, and flow percentiles is probably the most suitable.	If this timing correlates with periods of darkness this can be problematic from an operational planning standpoint. As previously stated, we need to establish other metrics for example duration when a workable threshold is not exceeded.

Market conditions

The critical nature of market issues is becoming ever more apparent within the tidal energy sector. There is a growing realisation that there is not just one market for tidal energy, and that any development process needs a forensic analysis of what energy markets are being targeted and how they are structured in relation to both site and scale of development. Technologies can be both too big or too small depending upon what market is being serviced. The level of power balancing required in a project development plan will also be influenced by market needs. The price points that need to be reached can also vary greatly between different markets and different functions within markets. All of these factors need to be considered against the background of any alternative energy solutions that may be available. The following table, Table 34, identifies key market areas.

Table 34: Key market areas for the tidal energy sector.

Factor	Considerations	Importance
Location of demand	The specific location of energy demand/use and/or grid connection point and its proximity to generation locations.	The costs of making any connection between generation and demand are distance sensitive. There may also be excessive losses over low voltage long connections.

Factor	Considerations	Importance
Scale of demand	The size of the demand centre or customer base measured in MW or MWh. Within an interconnected grid matrix, this may be difficult to define but tidal resource areas will be often associated with grid spurs rather than strong continuous output.	Determines the size of generation scheme that may be appropriate. Need to factor in capacity factors and possible storage buffers.
Physical access routes to market	Grid or pipeline connections, road/rail/boat transport for relevant energy products. The distance to connection and demand centres is important.	Cost effective connectivity to a suitable market is a key success factor for project development. Connectivity costs can be a critical cost factor.
Fiscal access to market (any licenses required)	Any market access restrictions in terms of price or timescales for a suitable license or access mechanism.	Some energy markets, particularly grid electricity markets are protected by stringent licensing requirements which must be met before a new supplier can operate.
Price for energy	Level of energy prices associated with the existing and future energy markets in an area, including spot and advance prices as well as average prices.	The prices available for energy of different types and patterns may greatly influence overall project viability, technology choices, energy delivery mediums and the need for storage buffer systems.
Availability required	The level of availability or reliability needed to underpin the specific energy service delivered.	Tidal energy is very predictable but also almost always variable. This pattern of energy generation may or may not match the demands of the energy services nearby. Storage or energy conversion steps may help reduce variability or bring it more in line with demand. There are some demand scenarios where variability may be less critical. Variability needs to be considered on a second by second, minute by minute …. hourly, daily, monthly and seasonal basis.
Potential for new markets	Listing of present and future markets for energy including markets driven by a rapidly changing decarbonisation agenda.	Although there are well established energy markets in many places there are also numerous new and emerging markets that could be served by tidal energy.
Back-up needs	How will any planned or accidental interruption to energy supply be dealt with, including maintenance outages and storm outages.	The incorporation of necessary back-up systems will be important to the overall viability of tidal energy and these considerations need to be built into cost models. Where existing diesel capacity is available this may offer very effective back-up options.
Character of competitive alternatives	Consider the key character of present and future alternatives to tidal energy. These may include renewables or conventional energy sources.	These options will provide the competitive context to tidal energy. Tidal will need to show overall economic, industrial, social, environmental advantages to support its adoption.

Engineering planning

There are many project planning activities that are directly related to local conditions and circumstances. These factors need to be taken into account on a site by site, project by project basis to ensure that a suitable and appropriate approach is adopted. The key factors are outlined in Table 35.

Table 35: Key engineering planning factors.

Factor	Considerations	Importance
Survey prospective sites and routes	Need to consider the appropriate study area which should relate to the area of influence from the tidal array. Typically, direct ecological influences may be restricted to within a few km of a site, similar to direct community effects making a 5 km study area buffer often suitable. For indirect hydrodynamic and economic effects, a wider study area may be applicable, particularly for large scale arrays. Strategic research programmes should establish wider ecological and socio-economic conditions.	The extent of the survey has a profound effect upon costs, the results of the survey will affect the viability of certain technological solution and may indicate the need for certain engineering support measures to be taken such as additional cable protection, levelling of the seabed etc.
Prepare site and routes	Works may be needed to prepare device deployment sites or to prepare cable corridors and onshore/coastal infrastructure sites.	These works may have cost and timescale issues associated with them as well as particular impacts relevant to the local conditions and works needed.
Install connecting cables/ pipelines	The suitability of any site or route for cable laying will be dependent upon a range of factors.	The route identified and approach needed will lead to specific cost and schedule issues.
Install foundations/ moorings	The suitability of the seabed in the area and associated sea conditions with regards to anchor emplacement.	Type of foundation will have significant cost and engineering implications.
Install devices	The techniques available to install devices will arise from a combination of the size of the device, the deployment method, the availability of device handling vessels, the distance from device assembly to device deployment locations etc.	Direct installation costs and the cost risks associated with the reliability or the method and the availability of suitable weather windows can all be important factors. Also, the accuracy of device installation can have a major baring on energy production performance and array layout.
Install any offshore connectors/ substations	The ability to install connectors will be a function of device separation, device orientation, numbers of devices, seabed and bottom current conditions, connection types and support vessels/craft/ people available to support such operations.	The availability of a suitable means of connection could be a key limiting factor. Connection costs may also be important.
Commission devices	This is a relatively small part of the overall operations but it will be critical to have suitable contingency plans and equipment available if a fault is found. It follows that any pre-installation commissioning that can be done will be helpful. In addition deployment systems that provide easy access for commissioning and maintenance, especially in remote areas may provide a distinct advantage.	Validating operational readiness will be critical when moving from construction/installation into operational mode. This will be important in terms of service supply to customers as well as contractually.
Operate	This is the critical phase in terms of energy generation and revenue creation. Different technologies and size classes of devices may have	Given that operations will extend typically over a 20 years timeframe, it is critical that an optimal technology configuration is achieved. Also the

Factor	Considerations	Importance
	quite different energy outputs in any particular location. Specific models of devices may therefore be optimal in different sites and even in different berth locations at a site. The complexity, reliability as well as the cost of different technologies will also be important. The integration of generation technologies with storage and balancing mechanisms will also be important depending upon both site characteristics and market requirements. Development plans will need to optimise the technology operations strategy based upon local circumstances.	efficiencies in construction and operation that can be achieved with a uniform design device across different markets.
Monitor conditions and equipment	Both before, during and after operations it may be required or beneficial to monitor installed devices and wider development scheme performance.	The cost associated with monitoring and the type of data gathered will determine how much performance optimisation can take place.
Inspect and maintain at sea	There will be benefits from and needs to carryout regular inspections of devices and other in-sea equipment.	These will have some costs – typically AUS$15k per inspection.
Recover and maintain ashore	There are costs and timescales associated with maintenance cycles. For larger devices, a 1-year cycle is assumed, for smaller devices, a quicker change round may be possible, the minimum planning window for maintenance is likely to be 2 months. The distance to any support/maintenance base will also be important.	This will affect costs and number of in-fill devices required.
Replacement devices	It is assumed that any device will need major overall every 5 years – hence any project capacity figure will need to consider an installed capacity along with costs for back-up devices.	Assuming a 1 to 5-year maintenance period including installation and recovery windows could add 20% to the required build of devices. Spare cable lengths and connectors are also needed to minimise disruption in the event of failure or damage.

Engineering design and operations constraints

As well as key project planning factors there are also key design and operational factors that need to be considered. These factors may give rise to specific requirements and/or constraints during design, fabrication, construction and operational activities. To some extent some of these can be addressed through good planning, but a number will still need to be addressed during design and subsequent operations. The topics in Table 36 are considered to be particularly important.

Table 36: Key engineering design and operations factors and constraints.

Factor	Considerations	Importance
Sea conditions	There are a wide range of sea conditions factors that will influence a tidal energy development. These can include the following factors: • Water depth • Tidal range (water levels) • Seabed currents (Ultimate Max)	These factors will influence the scale of device that can be deployed and will also likely influence the type of technology that may be most suitable and how it needs to be constructed (structural standards), handled and deployed, sited and operated.

Factor	Considerations	Importance
	• Current profile • Wave exposure • Wave and tidal flow interactions (areas of standing waves/overfalls etc) • Residual oceanic flows • Salinity/temperature • Dissolved oxygen • Water borne debris • Type of biofouling communities	
Seabed character & geotechnical capacity	The following factors will need to be considered on a site by site, as well as specific device location basis: • Rock type and stratification • Sediment type and depth • Seabed slope • Seabed roughness • Scour/depositional tendencies • Seabed strength • Integrity (cavities, faults etc) • Hardness • Seabed friction	These factors will influence the scale of device that can be deployed and will also likely influence the type of technology that may be most suitable and how it needs to be constructed (structural standards), handled and deployed, sited and operated.
Weather conditions	These will tend to be more site wide considerations but may also be important along supply routes: • Wind patterns • Air temperature • Visibility • Precipitation • Daylight periods	These factors will influence the types of support vessels needed and the techniques that need to be applied to installation, operations and maintenance activities.
Extreme events	There are a number of extreme or unplanned events that may influence a tidal development. These may include: • Storm events • Lightning • Seismicity • Tsunamis • Storm surges • Wildfires • Dust storms • Sabotage • Vandalism • Cybersecurity • Theft • Collision (ship/carcass) • Anchor dragging • Fishing gear entanglement	These events affect the structural integrity of devices or connections, they may create excessive forces.

Electricity supply context

There are several aspects to the existing and future electricity supply situation that can influence the viability of a tidal energy development. These are outlined in Table 37.

Table 37: Key electricity supply aspects.

Factor	Considerations	Importance
Existing generation sources	Any existing electricity supply will be provided from either grid connected of off-grid resources. These may be conventional or renewables. Each source will have distinctive issues associated with it.	The nature of the existing supply mechanisms will influence the character of the current supply and its future suitability and acceptability. Key factors may be fuel availability or cost, capacity of existing resources, difficulties in balancing supply and demand cycles.
Any retirement dates for existing generation	Dates around or by which existing energy supplies may need to be replaced, upgraded or changed out, due to cost, decarbonisation or technical lifecycle issues.	Since energy systems are going to need to decarbonise over the coming decades and established energy generation systems may be nearing the end of their technical lifetimes, there may be clear dates by which existing energy systems need to change. This may make the need for new systems more essential- in particular timescales.
Capacity factors for existing plant	No energy systems work at 100% capacity factors. Even conventional gas, coal, oil and even nuclear plants have downtime related to maintenance, breakdown and repair and even accidents. Some remote generators may not work for 24 hrs a day, providing electricity only at peak periods of generation or demand.	Tidal energy generation is generally likely to have a capacity factor of between 30 and 40% over a year. This will mean that a greater installed capacity (approx. 3 times more) is needed to deliver a specific amount of electricity over a year. However, in order to deliver a constant supply intermittency needs to be addressed.
Overall capacity of network and current/future levels of use	The capacity of energy systems varies in both space and time. Market trends, customer trends, climate trends may all influence. Being able to foresee and predict future energy scenarios at a local level will be important to identifying opportunities for tidal energy.	The capacity of established and future energy networks is a matter of potential uncertainty and variation, but tidal energy should remain part of the future renewable energy mix. Levels of demand for electricity may vary over time depending upon the number of customers, type of customers and the types/levels of energy use by customers. Any customer/industry adjacent to a tidal resource would benefit from an available, predicable energy supply.
Intermittency issues and balancing systems	Tidal energy is an infinitely variable renewable resource that is also extremely predictable and cyclical. The availability or potential for any additional balancing capacity will need to be considered. This will include: • Type of storage • Location • Capacity • Existing service cycle • Cost of establishment or use	The viability of a tidal development may need to take into account any balancing capacity required in order to make the energy proposition viable for energy customers.
Location of grid and substations at different voltages	Key issues to be considered include: • Substation connection points, • Existing and future capacity • Any expansion plans.	The cost of any new substation type infrastructure may be a significant part of the overall project costs. Any local capacity can therefore help a project to be viable, and any existing substations where there is renewable energy generation from solar, wind and waves.

Support facilities and infrastructure

There are various supporting facilities and infrastructure that need to be considered. Some of the key factors are outlined in Table 38.

Table 38: Key support facilities and infrastructure factors.

Factor	Considerations	Importance
Cable pipeline route	Metocean conditions, seabed character, weather conditions, vessel access and manoeuvring potential.	The availability of suitable cable or pipeline route from the site to the shore or to a suitable offshore energy processing facility can be as important as the availability of the resource itself. The route deemed suitable and the ease of laying a cable/pipeline along that route also needs to be considered. Where the landfall is being considered new technologies such as directional drilling needs to be assessed alongside the usual beach cut and fill approach.
Onshore substation /conversion centre	Ground conditions, ground character, geotechnical capacity, weather conditions, accessibility, supporting services.	The location of existing grid and substations at different voltage levels will be an important factor in determining where connections should be made. It is possible to build new substations but these are costly. Existing substations may be present but may also lie some distance away from the development site.
Marine support & deployment/ maintenance base	Sea/ground conditions, seabed/ground character, geotechnical capacity, weather conditions, accessibility, supporting services Technical expertise.	The marine support and maintenance base will also need to be carefully considered in terms of the ground conditions, coastal water conditions and also in terms of its disaster resilience. The distance from any marine support facility to the operational site will also be a key factor.
People	Numbers of prospective workers available and their skill levels. If imported labour needed how will this be achieved.	In terms of people there are a wide variety of expertise and experience that will be needed to be in the team for a successful project. Some of these skills can be acquired through experience on the job but it is most likely that established technical expertise will be necessary to start the project. It must be recognised that tidal streams present some highly operating risks and an inexperienced team will lead to safety hazards and failure modes which are in the end going to be detrimental to any project.
Vessels	• Access to vessels and port infrastructure. • Price variability for vessels	Another key resource that will be required is vessels. These vessels need to be appropriate for the work to be completed in a tidal stream and they need to be cost-effective for the economic basis of that particular project. Again, normal vessels that are used for general marine work may not be suitable for the more specialised requirements and conditions associated with tidal streams. Typically, if vessels need to work overnight instead of being able to do day work, this will significantly increase the cost of marine support activities and it may be hard for tidal energy to show a viable return under such operating conditions.
Service logistics	Length of supply lines	As well as the site facilities there is a need to deliver materials and people to the site and therefore the logistics of people and goods will be of critical importance.
Data connectivity	Capacity available and location	It will also be important to be able to monitor the performance of the site through appropriate data connectivity. This may or may not be possible to include in the cable connection and in certain geographies may create particular problems. There is also a need to store and manage large volumes of data about local sea conditions and about the performance of the devices and the associated infrastructure.

Factor	Considerations	Importance
Digital communications	Coverage, capacity and speed of connections	there will likely be a need for an ongoing communications links to allow data to be transferred to the appropriate storage location.

Key distance factors

There are several key decision criteria that specifically relate to distance between the development area or specific device locations and the relevant factor. Examples of some key distance related factors are outlined in Table 39.

Table 39: Key distance factors.

Factor	Considerations	Importance
Distance to users	Examining the distance to possible customers taking into account possible connectivity technologies.	The distance to end users will affect the cost of any connection, the energy losses associated with the connection and the consequent generation level in terms of voltage/temperature etc. needed to get usable energy at the end point.
Distance to infrastructure	Examining the distance to possible (grid, ports, manufacturing, roads…).	The distance to supporting infrastructure will influence operating costs and the type of technology that can be feasibly deployed.
Cable laying routes	Establishing distances for possible cable laying corridors taking into account seabed conditions, landfalls and onward overland routing options.	The length of cable or pipeline routes will affect cost as well as energy losses.
Operations and maintenance	Establishing the possible distances and travel times to marine and onshore support bases.	The time spent moving between base location and operational locations will have an influence on overall profitability as well as the reliability of routine and interventions.
Health and safety / emergency response times	Establishing possible response times from existing or any project specific response services.	The time for emergency response resources to reach the site or places along the route to the site will be critical to risk management.
Search and rescue facilities	Establishing possible response times from existing or any project specific response services.	The mobilisation time for any SAR resources to be deployed, especially for maritime accidents in colder water conditions will be critical to risk management.
Distance to other users. Third party interactions	Establishing the response times for any drifting equipment to reach other sensitive sites and vice versa the time any mishap elsewhere may take to affect the tidal development.	The time for any such objects or materials to drift from place to place dictates the response time needed to mitigate any drift related risks. Typically, a response should be achievable in 50% of the travel time, allowing some time for the response to be undertaken. If the response time is less than 1 hr then built in mitigation is probably necessary to avoid or manage any consequent impacts.
Clustering of similar development activities	The distances between the development site and other sites with similar needs.	Clustered sites may be able to share key resources.
Potential for co-located resources	The capacity for new/additional projects with similar requirements to be co-located near to the proposed development.	Clustered sites may be able to share key resources and development costs.

Environmental issues – ecological and physical

These include a variety of topics associated with the physical and ecological environment and the relationships between them. The issues, presented in Table 40, are often linked to the topics in any EIA process which will often be required to gain an operating license.

Table 40: Key ecological and physical environmental issues.

Factor	Considerations	Importance
Local habitats	Maps of different water column, seabed, freshwater rand terrestrial habitats.	Different habitats have a number of associated species and consequently different types and levels of sensitivity to direct physical disturbance and to any changes in water circulation. Understanding the distribution of sensitive habitats can help a project avoid unnecessary conflicts and impacts.
Local species	Maps of the distribution of key mobile species, not represented by particular habitat types.	There are certain species, often larger and mobile ones whose habits and ranges transcend a number of habitat types. Examples could include some birds, fish and sea mammals. Understanding the distribution of such species, especially where they may have a particular sensitivity to tidal developments will be important. Site and technology selection processes can then be informed by such information.
Migrating species/routes	Maps showing typical routes and behaviours exhibited by migrating species.	Migration routes hold a particular importance since by definition the species involved will be passing through and not necessarily familiar with a particular development activity. Species might be considered more vulnerable to disturbance during migration. Finally, disruption of migration may have a knock on importance to even more sensitive feeding or breeding activities that take place either side of a given migration. Any activity that could interfere with or act as some kind of barrier to migration will be of particular interest. As well as the location, the timing of migrating activity may be important.
Specialised feeding and foraging areas	Maps showing locations and areas known to be preferentially used for feeding and foraging activities.	The ability of species to forage and feed productively over a limited period of time may be a trait that is associated with some tidal stream areas and their environments. Being aware of any such areas and considering whether any proposed activity would disturb such behaviour will be a key issue to consider. As well as the location, the timing of any feeding activity may be important.
Protected habitats and species	Maps showing the areas designated to protect certain habitats and species.	In addition to the general good practise measures outlined above to consider any particularly sensitive habitats or species there may be designated or protected habitats and species under conservation guidelines. These may have additional levels of protection from disturbance and impact applied to them and different levels of justification needed in order to obtain any necessary licenses.
Breeding sites/areas	Maps showing locations and areas known to be preferentially used for breeding activities.	Many discrete and location specific breeding sites are often already designated, but where they are not they may require special consideration within any site finding and optimising process. As well as the location, the timing of breeding activity may be important.
Biofouling communities	Zones within which different types of biofouling might be expected.	Biofouling communities may affect the performance of a device or key equipment, it may inhibit maintenance and handling of equipment and it may affect the structural

Factor	Considerations	Importance
		integrity of equipment. Understanding the spatial, depth and timing aspects of biofouling colonisation and species succession may be important.
Ambient noise levels	Any existing sources of natural or manmade noise identified. Spot measurements made over time at particular locations of interest – either near a sensitive receptor or near a particular noise source.	Underwater noise disturbance is becoming an increasing focus for impact evaluation. Although tidal devices are generally very quiet when working properly there are concerns about different frequencies of machine and support vessel noise disturbing species in areas previously free of anthropogenic noise.
Seabed stability	Based upon the bathymetry and habitat types any indications of seabed instability should be noted and mapped. This would most likely be manifest by dynamic sand wave features.	Features such as sand waves may create issues regarding the longer-term stability of gravity base type foundations and may also affect cable/pipeline routes.
Shoreline stability and coastal dynamics	Mapping any features which indicate stability or instability along the coast will be important.	Whilst is it very unlikely that tidal generation will itself disturb coastal processes, the associated infrastructure such as cables may need to intersect sensitive and dynamic shorelines.
Water circulation	Maps showing the pattern of tidal flows and of wider oceanic/coastal circulation patterns. These may be hr by hr for tides or more seasonal for wider circulations.	The patterns of water circulation may help identify downstream and upstream areas and habitats influenced by any tidal flows and reservoirs. It is noteworthy that generally swift tidal flows have relatively little consequence upon wider coastal and ocean circulation patterns. However, NW Australia has some complex and linked tidal flow regimes, however, they currently lie away from likely energy markets.
Water exchange rates	Calculations of water exchange rates, especially for enclosed or semi enclosed basins may be a useful metric.	Any change in the flux of tidal in-flows and out-flows may alter nutrient balances etc. in affected areas leading to associated changes in productivity and species succession cycles.
Locations of frontal mixing zones	Mapping the locations of any frontal type mixing zones between mixed and stratified waters.	Frontal mixing zones can be defined by tidal flows and tidally mixed waters hitting up against a more stratified and stable water mass. These frontal areas often have enhanced productivity and associated food chain activity. The location and intensity of such areas for foraging species such as seabirds may be important in terms of energy balances.
Distance to coastline	Establishing the distance from different part of the site to adjacent coastlines, viewpoints etc.	This may affect the visual acceptability and suitability in the landscape of development activities.
Cumulative stressors on environment	Temporal trends of species interactions associated with other sectors can be relevant.	

Social issues

There are many social and societal issues that tidal energy can influence. Over the last few years the best and most universal framework for addressing these is through the United Nations Sustainable Development Goals (UN SDGs). There are 17 overall Sustainable Development Goals, including two ecological focussing goals, that have been addressed earlier under environmental issues. The possible relationship of these SDGs to tidal energy is outlined in Table 41.

Table 41: Key sustainable development goals.

Factor	Considerations	Importance
Goal 1: End poverty in all its forms everywhere	Are there any areas affected by poverty in the vicinity of the development? This poverty may be urban, rural or cultural in nature. Any such vulnerability needs to be characterised and understood in terms of scale and distribution.	Tidal energy may provide an additional source of jobs, it may also replace more expensive diesel-based generation in remote locations. In less remote locations it may be more expensive that traditional forms of generation. Careful consideration should be made into any influences a project may have on energy poverty (proportion of disposable income spent on energy for heating; cooling; mobility etc.)
Goal 2: End Hunger, achieve food security and improved nutrition and promote sustainable agriculture	Locations of any food gathering or production activities within the range of influence of the project.	Are there any existing of new food production or food hunting/gathering activities that are going to be influenced by the development? If so where do they take place, can any interactions be optimised by co-location of renewables and aquaculture production?
Goal 3: Ensure healthy lives and promote well-being for all at all ages	Any activity or link to well-being.	There may be little interaction between tidal energy and this SDG, but any link should be considered on a specific project basis.
Goal 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Any activity or link to education and lifelong learning.	Tidal energy may provide new opportunities for engineering, energy, environmental and marine skills to be used in underdeveloped and remote locations.
Goal 5: Achieve gender equality and empower all women and girls	Direct employment, indirect employment and energy facilitated activities and employment.	Opportunities for women to participate directly in the sector and to benefit from availability of additional energy sources.
Goal 6: Ensure availability and sustainable management of water and sanitation for all	Can tidal energy be used to produce additional freshwater where required?	Provision of water may be a better economic prospect for tidal energy than electricity production in certain circumstances.
Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all	Does the potential for tidal energy add new capacity to local energy systems or replace existing carbon intense energy sources?	The need for carbon free energy sources will increase rapidly over coming years as the challenges associated with climate change increase.
Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Tidal energy can help secure or broaden the productive activity in an area.	Tidal energy offers a transition from other declining offshore sectors. The link between appropriate industrial activity or islands with reliance on diesel generation, and tidal energy production, may be critical to the adoption of tidal energy.
Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	Tidal energy can be a conduit for industrialisation and innovation and can also be incorporated into bridge and causeway type infrastructure.	Tidal energy developments can help develop rural industrialisation. Linking tidal production to infrastructure may help tidal energy achieve economic viability.
Goal 10: Reduce inequality within and among countries	Using early adoption of tidal energy to help prove new technologies for wider application.	Tidal energy technology can be shared across the globe and early adoption of tidal energy will help prove the technology for wider application.
Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable	Establish the contribution tidal energy can make to sustainable energy outcomes.	Tidal energy can help decarbonise energy supplies.
Goal 12: Ensure sustainable consumption and production patterns	Establish the contribution tidal energy can make to sustainable energy outcomes.	Tidal energy can help decarbonise energy supplies.

Factor	Considerations	Importance
Goal 13: Take urgent action to combat climate change and its impacts*	Establish the contribution tidal energy can make to sustainable energy outcomes.	Tidal energy can help decarbonise energy supplies. Lifecycle emissions from offshore energy technologies is one of lowest of all available technologies (~5 times less than solar).
Goal 14: Conserve and sustainably use the oceans, seas and marine resources	See environmental section above.	See environmental section above.
Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems	The largest stressor to ecosystems is climate change, and despite some potential negative impacts from tidal energy on ecosystems, it must be viewed as potential contributor to decarbonisation of societal energy needs.	The question is whether tidal energy can contribute sufficiently to justify any environmental cost.
Goal 16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	Will tidal energy help to redistribute wealth and commercial activity to new communities.	Past and existing energy solutions have been very centralised and have centralised associated economic opportunities. Tidal energy can help disperse such opportunities .
Goal 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development	Using early adoption of tidal energy to help prove new technologies for wider application.	The successful deployment of tidal energy can be used to help spread sustainability across South east Asia and the Pacific islands.

Economic issues – other sea and coastal users

Table 42 presents the key issues associated with other sea users.

Table 42: Key economic issues related to other sea and coastal users.

Factor	Considerations	Importance
Fisheries activities	Are there fishing activities taking place in the vicinity of the generation site and associated infrastructure?	Marine spatial planning and stakeholder consultation can be utilised as a tool to ensure the construction of a tidal development facilities and operation of tidal generators have a minimal impact on such activities.
Shipping activities	Are there any local or ocean shipping routes associated with the tidal development area?	
Recreational activities	Are there any recreational activities associated with the tidal development area?	
Existing and future cables	Are there any cables associated with the tidal development area?	Stakeholder consultation can avoid any impact on undersea cables, pipelines and nearby outfalls.
Pipelines	Are there any pipelines associated with the tidal development area?	
Outfalls	Are there any outfalls associated with the tidal development area?	
Oil and gas development areas	Are there any oil and gas activities associated with the tidal development area?	Marine spatial planning and stakeholder consultation can be utilised as a tool to ensure the construction of a tidal development facilities has minimal impact on such nearby activities and provides carbon offsetting or an available energy resource where co-location is advantageous.
Aquaculture development areas	Are there any aquaculture areas associated with the tidal development area?	
Coastal mining areas	Are there any coastal mining areas associated with the tidal development area?	

Factor	Considerations	Importance
Tourism sites	Are there any tourism sites/ areas associated with the tidal development area?	Stakeholder consultation can avoid any impact on tourism activities and/or open up new tourism opportunities showcasing renewable energy developments.
Military and defence area closures	Are there any military/ defence areas associated with the tidal development area?	Consultation with defence would be undertaken where commercial tidal farms are proposed and normally via marine spatial planning can avoid restricted areas for naval training.
Restricted zones	Are they any restricted areas such as national park, marine park, indigenous rights on land and water or other restricted areas?	Specific permits might be needed. More in depth environment assessment might be required part of this permit. Marine spatial planning allows for restricted zones/areas to be avoided for tidal energy site selection.

The following Table 43 outlines the attendees at the AUSTEn workshop.

Table 43: AUSTEn workshop attendees

Organisation	Contact	Position
	AUSTEn Team	
AMC - UTAS	Irene Penesis	Project lead
AMC - UTAS	Jean-Roch Nader	CI
UQ	Remo Cossu	CI
CSIRO	Mark Hemer	CI
CSIRO	Jenny Hayward	CI
CSIRO	Saad Sayeef	CI
AMC-UTAS	Philip Marsh	Post Doc
AMC-UTAS	Camille Couzi	Field Engineer
AMC-UTAS	Constantin Scherelis	PhD Student
AMC-UTAS	Christelle Auguste	PhD Student
UQ	Larissa Perez	PhD Student
UNSW	Wei Shen	PhD Student
	Partners	
Bangor University, UK	Matt Lewis	Research Fellow
SIMEC Atlantis Energy	Daniel Coles	Project Resource Analyst
MAKO Tidal Turbines	Jarrod Sinclair	Engineer
	Workshop Facilitator	
Aquatera	Gareth Davies	Managing Director
	Panel Members	

Organisation	Contact	Position
Australian Ocean Energy Group (Prev. AMET)	Stephanie Thornton	Honorary Secretary/Manager
NERA	Paul Hodgson	General Manager Innovation and Stakeholder Engagement
SIMEC Atlantis Energy	Daniel Coles	Project Resource Analyst
ORE Catapult	Vicky Coy	Project Manager
Evolutive	Tim Sawyer	Director
WesternPower	Shervin Fani	Principal Engineer
Bangor University, UK	Matt Lewis	Research Fellow
	Attendees	
AMC-UTAS	Jessica Walker	Senior Lecturer
AMC-UTAS	Nazanin Ansarifard	PhD student
AMC-UTAS	Eric Gubesch	PhD student
AMC-UTAS	Alan Fleming	Lecturer
Australia Ship Simulation Centre	Anna Jenkins	Environmental Scientist
BMT	Peter Ross	Mechanical Engineer
BMT - WBM	Chris Shearer	Senior Mechanical Engineer
Capacitus	Luke Murray	Managing Director
CENTRO	John Plummer	Senior Consultant
City of Mandurah	Karin Wittwer	Energy Efficiency Project Officer
Dalhousie University	Alex Hay	Professor
Dutch Marine Energy Centre	Peter Scheijgrond	Ocean Energy Expert
Echoview	Haley Viehman	Fisheries Acoustician
Geoscience Australia	Andrew Carroll	Assistant Director
Pacific Marine Energy Centre at Oregon State University (OSU)	Bryson Robertson	Director
SABELLA SAS	Jean-Christophe ALLO	Commercial Director
University of Edinburgh/ OES	Henry F Jeffrey	Research Fellow
UNSW	Francois Flocard	Principal Engineer, Water Research Laboratory
UWA	Ian Milne	Research Fellow
UWA	Christophe Gaudin	Head, Oceans Graduate School Director, Wave Energy Research Centre

Organisation	Contact	Position
Verdant Power	Trey Taylor	Co-Founder & Director
Zen Energy Systems	Mark Sinclair	General Manager

Photo 1: Irene Penesis and Gareth Davies Welcome Speech

8. Project Summary and Recommendations

For tidal energy converters to be useful in Australia they need to be cost competitive with solar and wind energy resources and should be well adapted to Australian conditions. This includes managing relatively low velocity tidal currents covering large areas of sea and with the best tidal resources located typically 50 to 200 kilometres from the larger communities and industries that might use the resource. The following suggestions for future research and development address the need to reduce TEC costs and to place them in developments where they can add commercial value using the power security and availability that is intrinsic to tidal energy.

Recommendation 1: Technical improvements to tidal energy converter (TEC) design to increase capacity factors that are then competitive in relation to the Australian available tidal resource. This will require a design that uses rotors from 20 to 26 metre diameter with generators that are appropriately geared and rated for peak 2 m/s currents. Low tidal flow velocities will require lower rated power generators and the associated lower stresses and ratings for support infrastructure and power management should allow cost savings to be made in the design. A more than fifty percent cost reduction to less than 1200 $/kW is the target for this development.

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The AUSTEn study provides a preliminary data base on tidal energy that identifies the applications where it can be most useful. The data makes it clear that tidal energy is too valuable to be used on the national grid and in any case would not compete with solar and wind energy in that environment.

Recommendation 2: Tidal energy should primarily be reserved for applications where intermittency can't be tolerated, for example high security / backup power in remote regions, or chemical processing for renewable fuels where tidal energy can save millions of dollars of capital expenditure, or for operating in environments on- or off- grid where tidal energy is the best resource to supply dispatchable power cost effectively. The case studies described are a few examples of the reliability that can be achieved and the millions of dollars that can be saved when tidal energy is incorporated into a renewable energy network.

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Five potential sites should be assessed in further detail (Warrumiyanga, Yimpinari, Wadeye and Tharramurr, Ardyaloon and Derby and Banks Strait) due to having the strongest tidal resources in Australia together with communities that have ownership and ready access to regional areas associated with the sites, as well as a track record of industrial and commercial development. It is unlikely that TECs at any of these sites will be able to compete with wind energy and solar PV cost effectively as suppliers of electricity.

Recommendation 3: The communities associated with the sites listed have a track record of industrial and commercial development. If they were interested in the opportunity to use tidal energy, they may also be able to provide cost-effective on-site services. This could be explored further by early engagement with the communities and organisations such as the Indigenous Land and Sea Corporation, subject to the caution that the cost effectiveness of the technologies is unproven and would need to be developed and investigated much further before any significant investment is considered.

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Recommendation 4: The modelling has revealed that the north eastern corner of Tasmania, the T1 REZ where Banks Strait is located, is also a region with significant renewable energy resources including tidal energy. It also has a low demand for electricity along with a constrained network and this is one of the reasons why tidal is not economic in this region. There may be an opportunity for an industry to locate there that requires significant quantities of electricity e.g. green steel production and it could develop all renewable resources in that region to supply its energy needs, without impacting the rest of the grid. This would clearly support the 200% Tasmanian energy pledge.

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Recommendation 5: Carry out a detailed cost benefit analysis of hybrid solar/tidal and wind/tidal energy farms aimed at providing up to 30 percent dispatchable (continuously available) electricity for wind/tidal and 50 percent dispatchable electricity for solar/tidal energy farms. It should include a heat map of benefits vs. location; quantify the impact of intermittency in solar radiance and wind as well as extreme weather events; and estimate the demand for dispatchable

power in locations not connected to the National Grid. The analysis would focus on defence, emergency services, fuel production and manufacturing that may require continuous power.

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Recommendation 6: Detailed feasibility studies to be carried out of the potential for scale-able demonstration hybrid renewable energy farms. These would be based on the AUSTEn data and case studies, for the Banks Strait tidal/wind power station and the Clarence Strait tidal/solar power stations.

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The national AUSTEn tidal model has significantly enhanced understanding of Australia's national tidal stream and range energy resources. The development of a high resolution national scale tidal with accurate representation of tidal elevations and currents is a further step towards development of a national unstructured baroclinic model, to supply the accurate, detailed knowledge and predictions of ocean state that Australia's defence, industry and government need, as outlined in the Australian National Marine Science Plan (NMSP, 2018). This impact is already being seen, with the AUSTEn model having attracted interest from several other Australian Government bodies, including Defence and the Bureau of Meteorology via the BlueLINK initiative, AMSA and Geoscience Australia.

Recommendation 7: Development of a national Australian oceanographic modelling system will have wide-reaching impacts. The offshore renewable energy industry is one of several blue economy industry sectors which will see further benefit from continuing development of an integrated system capable of meeting Australia's industry and governmental needs. For the offshore tidal energy sector, this will provide benefits of integrated knowledge of wave influence, and contribution of non-tidal flows (wind and density driven circulations) at prospective sites.

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Modelling Australia's marine domain at high resolution requires trade-offs. The AUSTEn model has been able to focus resolution in areas of higher tidal stream energy interest. This has enabled a maximum spatial resolution of approximately 400 m to be achieved in focus areas. This has enabled exceptional performance of the national model when compared to available in-situ observations of Australia's tidal elevations and currents. However, in areas of highest tidal stream energy, we find the tidal streams represented in the higher resolution regional models to better capture the high resolution, high energy flows. This result being a consequence of higher model resolution and better refinement (purpose collected) of bathymetry for areas of interest. However, this results also highlights the limited spatial extent of commercial scale tidal stream energy resources, with few very constrained locations having tidal streams of magnitude currently considered commercially viable. The national resource layers likely remain an underestimate of Australia's tidal stream resources. There will be areas not identified by the national model where tidal currents are sufficiently large to provide power to meet end-user needs. This will however be typically small-scale flows, where total integrated available energy is limited.

Recommendation 8: The available resource at small-scale high flow sites not identified by the national model requires targeted efforts to determine the resource viability. The scale of energy delivery achievable from these sites will be small, best suited to focused (off-grid) applications.

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The national AUSTEn tidal model provides a representation of Australia's national tidal currents with unprecedented accuracy. However, the model still has biases that need to be resolved through further development. In particular, it should be noted the Lunisolar diurnal tide (K1) presents a low bias nationally, likely a product of the forcing global tidal model.

Recommendation 9: The ability of hydrodynamic models to accurately resolve high flow currents is highly dependent on the quality of the bathymetry available. Ongoing collection of bathymetry for Australia's marine domain provides broad benefits to many sectors, of which offshore renewable energy is an emerging participant.

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The AUSTEn national model was validated by a large body of opportune in-situ tidal elevation and current observations, and bathymetry funded via various historical Government, Academic and Private sector initiatives. Substantial more data are available through other ocean-based sectors, which were unaccessible. Each dataset presented differences in quality and workflow required to contribute to the study. Collection and coordination of data via IMOS and the Australian Ocean Data Network were integral to a large component of the data used in this study.

Recommendation 10: As outlined as a core area for action in the UN Global Compact Sustainable Ocean Principles (UNGC, 2020), increased, ongoing mutual collection, sharing and standardised management of data from ocean based industries alongside Government, defence, academic and non-governmental communities will enable development of best future decision making tools for emerging and current ocean industries.

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The national tidal energy resources presented via Australia's renewable energy mapping infrastructure present only the theoretical resource.

Recommendation 11: Considerations of alternative uses of the marine domain must be addressed – this potentially limiting the accessible resource.

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The AUSTEn high-resolution numerical models of the Banks and Clarence Straits were successfully developed, calibrated and validated, with assessments of the tidal energy resource to international standards completed. Promising locations for TEC deployments were found at both sites in water depths suitable for TEC diameters ranging from under 5 to above 25m. For both the Banks and Clarence Strait sites, the potential area for tidal turbine deployment was found to increase substantially when viewing sites with maximum flow speeds of 1.5 m/s or less, opening up new areas for potential deployments. These sites open huge possibilities for TEC deployments once turbines rated to operate in these flow conditions are developed.

Recommendation 12: Research and development should be considered for the development of a TEC for Australian conditions that is optimised to work in average tidal velocities of about one metre per second. These low tidal flow velocity TEC's will require lower rated power generators with associated lower stresses and ratings for support infrastructure and power management which should allow cost savings to be made in the design, reducing LCOE.

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The Influence of tidal turbines on their hydrodynamic environment was performed using high-resolution 2D bottom friction models to simulate four TEC arrays at two promising sites in Australia. The energy extraction by these TEC arrays was found to have minimal influence on surface elevation and current speed distribution in both the near and far-field regions. However, the calibration and validation of these models is severely limited by the lack of field measurements for installed full-scale TEC / TEC arrays using high resolution survey techniques.

Recommendation 13: Performed full-scale ADCP flow measurements of the flow field surrounding an operating TEC / TEC array, include near and far-field regions, , to enable calibration and validation of numerical turbine models and to understand the impact of turbulence on the TEC device loads and performance. To be of maximum benefit, this information should be freely available and include all oceanographic and turbine parameters.

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Recommendations 14: Development of new numerical models that link the non-hydrostatic ocean models as used in this study with hydrostatic computational fluid dynamics turbine models that resolve the boundary layer flow over the turbine blades, allowing for the simulation of the entire flow field at all scales. This would allow for the development of TEC simulation at all scales as well as 'digital twin' models to aid TEC design, operations and maintenance.

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The AUSTEn workshop clearly identified numerous factors that will influence the location of TEC farms, ranging from hydrodynamic to environmental site conditions, many of which are not accounted for in either resource assessments or economic feasibility studies.

Recommendation 15: Perform a Multicriteria Assessment using the AUSTEn national resource model and factors identified during AUSTEn workshop to identify and further rank promising sites nationally.

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High spatial and temporal bathymetry surveys are fundamental to the quality of site characterization procedures. The better the resolution, the safer the hydrographic survey (identifying locations of moorings) and the more accuracy of numerical studies.

Recommendation 16: The benefits of having high-resolution bathymetry available at different stages of site characterization is crucial, for instance model boundaries often lie outside of the bathymetry survey and rely on artificial or synthetic data.

Ongoing collection of bathymetry and generating a data base that is available for the marine industry and blue economy will advance and improve model results but also fast forward marine survey campaigns.

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The Banks Strait has extended periods of time where the sea state would not be conducive for safe surface operations and increase the costs associated in operating in this environment.

Recommendation 17: Installation and maintenance operations are not part of the initial resource characterization but such environmental factors can impact on the device design and economic viability of a project. Information about severe conditions – especially if prevalent for extended periods of time – should be made available to tidal turbine developers early on to be considered for assessment of suitability of a site.

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High frequency velocity data throughout the water column data were collected in Banks Strait and Clarence Strait over several months, making this a unique data set for wave-current interaction and turbulence. The results provide new insights into description of turbulence characteristics over longer periods at tidal energy sites.

Recommendation 18: Existing technical guidelines (e.g. IEC) for site characterisation should be extended to include accurate procedures for turbulence measurements and parametrization in tidal energy sites and to provide turbine developers real world data to design in-stream systems.

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Environmental monitoring undertaken at both candidate sites gave new insights into instrument performance for use in environmental impact assessment studies. The current ADCP technology is suited for a first order approximation of fish abundance and distribution but does not replace conventional echosounders.

Recommendation 19: Instruments for site characterisation should be chosen such that they can accurately provide simultaneous measurements of currents, waves and turbulence (and other environmental parameters) over the required period. Data of this form can provide valuable information for a more targeted environmental impact assessment study and can minimize uncertainties surrounding in-stream tidal turbines.