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The Australian Wave Energy Atlas Project Overview and Final Report

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CSIRO Oceans and Atmosphere Business Unit

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Executive summary and highlights

The Australian Wave Energy Atlas (AWavEA) project aimed to support continued growth of Australia's emerging wave energy sector. Key outcomes from the project include:

An improved assessment of the Australian wave resource

The revised wave energy resource information generated in the project provides an independent and verified dataset that spans a greater spatial extent with higher resolution and quality than has previously been available. Assessment of these data indicated the magnitude of resource is not a constraint for its future uptake, and confirmed the majority of the accessible Australian wave resource is in the south-east and south-western regions. An assessment of wave energy variability contributed new understanding of the resource, where favourable conditions (low variability) were identified in the southern regions. Until now, credible independent information about the resource had been a key limitation for the growth of Australia's wave energy industry.

The Australian Wave Energy Atlas

The revised Australian wave resource data is made openly available to all users via the Australian Wave Energy Atlas. The Atlas also delivers high quality spatial planning information that is crucial for wave energy developers and marine planners to identify prospective regions for wave energy developments. The Atlas is easy to use, has processing capability and many other features to support future developments in Australia.

The Atlas is already averaging one hundred processing enquiries per month, with the total visits to the site likely to be an order of magnitude higher.

The Australian Wave Energy Atlas is hosted by the Australian Renewable Energy Mapping Infrastructure (AREMI) <http://nationalmap.gov.au/renewables/#share=s-gGd5ztFcxe2ysy9f)>.

One of the first field studies of the physical effects of wave energy extraction on the surrounding wave field

The project included a field case-study on the effect of deployed wave energy converters (WECs) on the surrounding wave field in the natural environment. The observations indicated a small but statistically significant wave energy loss at discreet frequencies attributable to the presence of a single WEC. These field measurements were used to test and validate a numerical model (SNL-SWAN) which is being increasingly used to assess potential physical effects by the international community.

Guidelines for assessing physical impact of wave energy converters

The guidelines use evidence-based methodology, using outcomes from the Garden Island case-field and numerical model study. The guidelines are proposed to provide initial empirical estimates of the potential spatial extent of hydrodynamic effects surrounding a planned array of WECs. Look-up tables/graphs show potential effects of wave attenuation by the presence of the WECs. The intention is to inform proponents and policy makers of the potential spatial extent over which any effects should be more rigorously investigated.

Ocean Renewable Energy Stakeholder engagement

Stakeholder engagement was integral to the project. Regular meetings were held with an Advisory Committee made up of key stakeholders. Committee meetings provided valuable feedback on project activities as well as an avenue for industry round-table discussions. Two highly successful stakeholder workshops were also held:

- The first workshop, held in December 2014, engaged with stakeholders to communicate the project's goals and elicit stakeholders' input into the early project design.
- The second workshop took the form of the first Australian Ocean Renewable Energy Symposium (AORES) in October 2016. The symposium was jointly organised by CSIRO, Swinburne University of Technology and the University of Tasmania. Funding for the symposium was leveraged from allocated project stakeholder workshop funds with additional supporting funds from CSIRO's cutting edge science symposia scheme. This support enabled attendance of invited international guests, and a wide range of sector stakeholders.

AORES has contributed to a stronger Australian ORE community, evidenced by:

- the formation of an industry consortium - the Australian Marine Energy Taskforce (MET) - which aims to unify the fledgling Australian ocean energy industry, and
- strong interactions amongst the ORE research community (Universities and publicly funded research agencies (PFRA)), with key consortia proposals in preparation.

A range of communications including a White Paper presenting key priorities for the Australian ocean renewable energy industry to move forward

A White Paper presenting future priorities for the Australian ORE sector is a significant output from the project. The Paper is based on the outcomes of the AORES 'way forward' full-day workshop and is intended to represent the shared view of a wide range of sector representatives and invited international guests.

Along with the Australian Wave Energy Atlas (AWavEA) and the physical impact guidelines, other communication activities included: 6 journal articles published, or under review, in peer-reviewed international research journals; 17 conference presentations/ papers at national and international conferences; 5 published reports; 8 electronic articles; and 2 magazine articles. In addition to conference presentations, the Atlas was discussed in four other national and international networking meetings. The project team were involved in several media interviews. One project-related PhD is near completion, and the Atlas is being used to support many PhD and early-career research projects in the Australian research community.

Furthermore, another ongoing communication vehicle is the project data which is all publically available and easily accessible by the community.

1 Project Background

The Australian Wave Energy (AWavEA) project was a three-year project led by CSIRO with funding support from the ARENA Emerging Renewables Program, and in collaboration with the Bureau of Meteorology (BoM), Australian Maritime College/ University of Tasmania (AMC/ UTas), Carnegie Clean Energy Ltd, Biopower Systems and Swinburne University of Technology.

The AWavEA project was established with an aim to address three key knowledge gaps that were impeding development of the Australian wave energy industry:

a. Limited (scientifically credible and industry independent) knowledge of the resource, including its temporal and spatial variability and its spectral characteristics
b. Difficulty accessing spatial information identifying multiple designated marine management regimes of Australian marine territories
c. Limited evidence-base and methodology for assessing impacts of wave energy extraction on the marine and coastal environment.

These needs were identified through dialogue with industry representatives prior to the start of the project, and with ongoing stakeholder engagement throughout the project. By seeking to fill these knowledge gaps and share the knowledge gained with all stakeholders, the project ultimately aimed to provide benefit for continued growth of Australia's wave energy industry and to make a contribution towards improved competitiveness and supply of renewable energy technology and progress towards a sustainable energy economy for Australia.

In order to address these three needs, two principle outcomes were planned and implemented:

- the Australian Wave Energy Atlas, providing a revised wave energy resource assessment, and
- Guidelines for Physical Impact Assessment, based on field study and a numerical modelling study.

These were delivered through four streams of project activity: A. Stakeholder Input; B. Wave Atlas portal development, resource assessment, and data management; C. Field program and numerical modelling study; and D. provision of the Atlas and data for long-term management.

2 Project outputs

2.1 Assessment of the Australian wave energy resource

The assessment of the Australian wave energy resource undertaken in the project (Hemer, Zieger et al. 2017) provides a revised estimate of the wave energy resource magnitude and distribution in Australian waters. The assessment shows Australia has arguably the largest wave resource of any country in the world. However owing to the distribution of the Australian electricity grid, only a fraction of the resource is accessible (within 50km of Australian grid). Despite these limitations, provided technological challenges to reduce costs can be overcome, wave energy has the potential to deliver a significant proportion of Australia's future low-emission energy demand.

2.2 The Australian Wave Energy Atlas

The Australian Wave Energy Atlas is the signature output from this project.

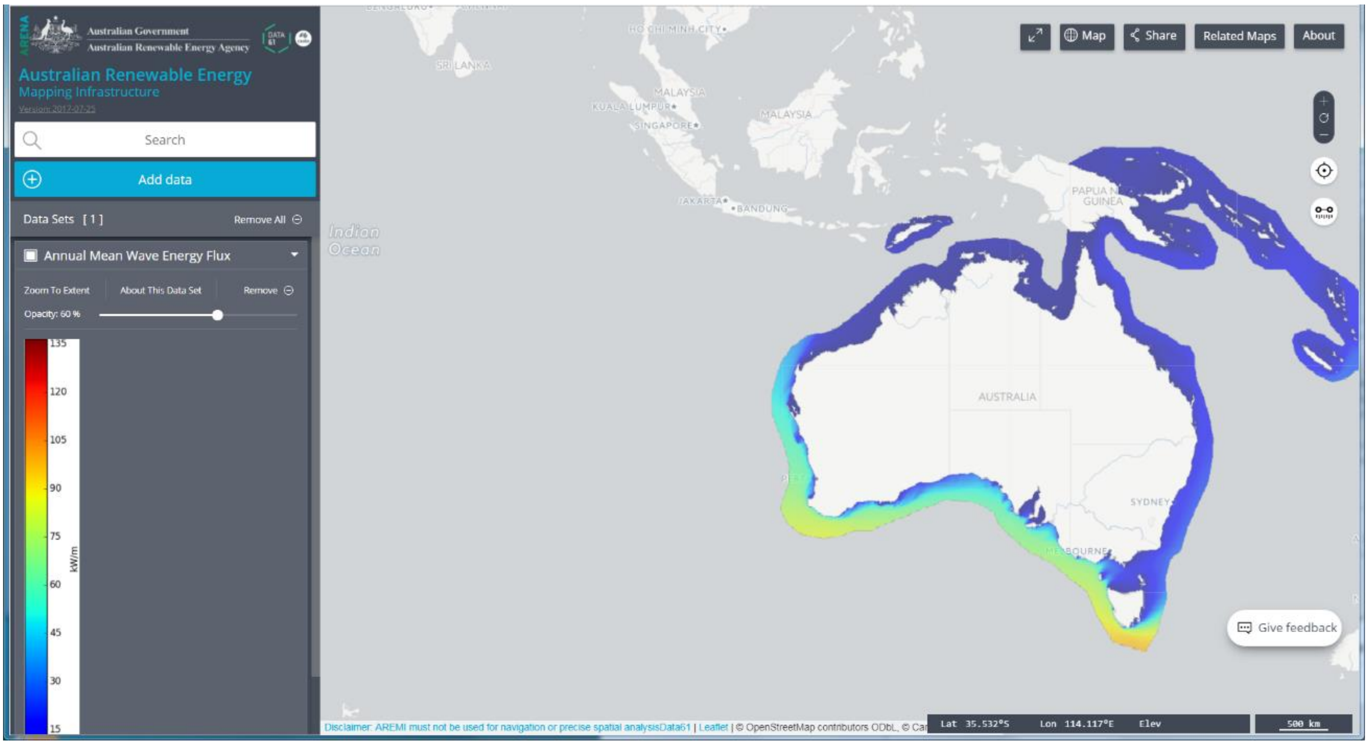


Figure 1. A screenshot of the Australian Wave Energy Atlas (AWavEA), displaying the Annual Mean Wave Energy Flux (in kW/m) and key, as incorporated into the Australian Renewable Energy Mapping Infrastructure (AREMI).

Features of the Atlas

- easily accessible – integrated within the publically available web-based Australian Renewable Energy Mapping Infrastructure (AREMI) tool
- easy-to-use format
- dynamic processing capability enabling users to undertake analysis and processing of the data in different ways according to the information they require

- fast processing times despite technical challenges
- compatibility with other datasets and portals by strict adherence to Open Geospatial Consortium (OGC) standards
- delivers resource information (e.g., Figure 1) alongside complementary spatial information, including marine spatial constraints (e.g., complementing and competing marine uses), supporting marine infrastructure (e.g., ports and facilities) and supporting electricity infrastructure (e.g., electricity network)
- novel portal design that addresses the challenge of managing data from multiple sources, and ensures the Atlas is presenting data that is the most up-to-date, and
- a detailed technical report about the resource assessment process underpinning the information provided by the Atlas.

Stakeholder input into the portal design

Along with feedback from the two stakeholder workshops, targeted stakeholder feedback was sought via an on-line survey in March 2016 after the release of the demonstration portal. Fifteen responses were received. The spatial resource information was positively received, with comments commending the availability of information. It was clear however that further guidance was required for users to make full use of the query-driven point-process functionality of the Atlas. The project team responded to the feedback received, and where possible, the Atlas was updated to respond to feedback. In the few instances where the comments pointed to ideas that were out of scope for the project, the stakeholder was informed.

The portal link

The Atlas is delivered through Australia's Renewable Energy Mapping Infrastructure (AREMI). A link to the wave atlas component of AREMI is:

<http://nationalmap.gov.au/renewables/#share=s-gGd5ztFcxe2ysy9f >.

Note that in transition to AREMI, a functionality developed by the AWavEA team (point query values extracted from data layers) has not been implemented by the AREMI team. The AWavEA team will continue to work with the AREMI team to identify an alternate approach to provide this functionality. This issue is considered very minor, although many requests (>10) for this functionality (noting its absence) have been received to date.

Uptake of the Atlas

The Atlas is averaging one hundred processing enquiries per month, and has a total of 668 requests in the first 12 months of operation (Figure 2). This statistic assesses only the use of processing or analysis tool requests – the total visits to the site, making use of the spatial resource and marine domain use information, is likely to be an order of magnitude higher.

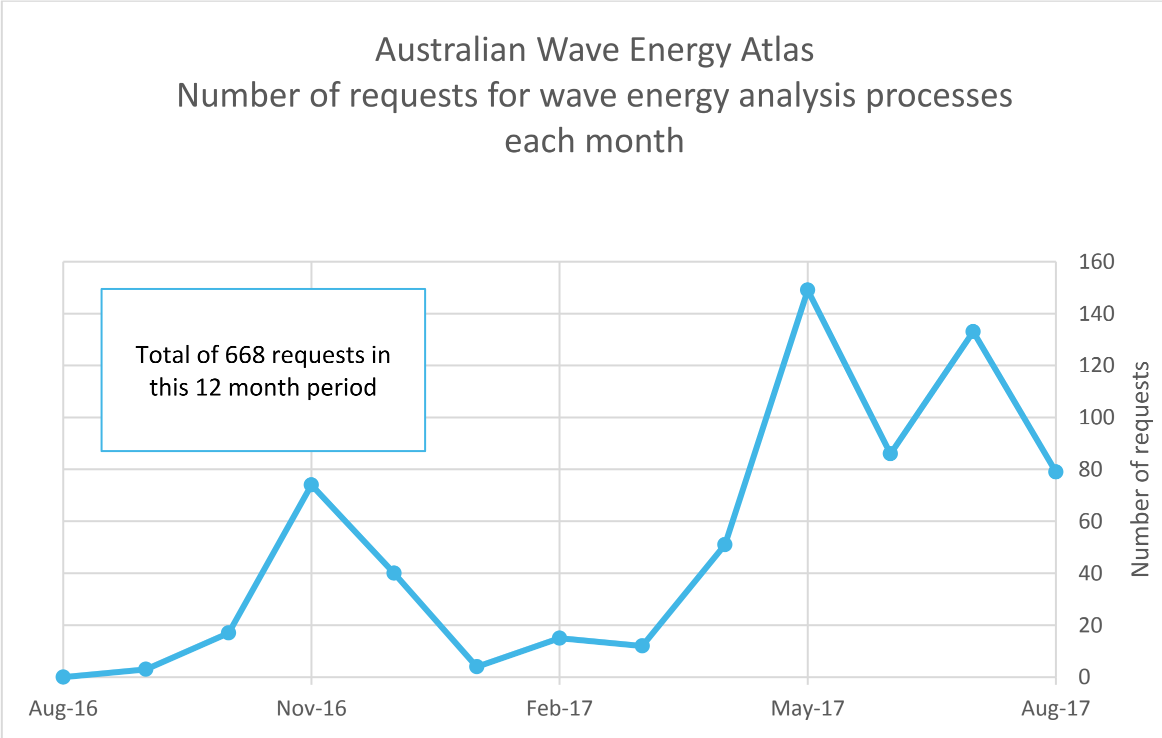


Figure 2 Plot of processing requests made on the AWavEA website in the first year

2.3 Field case study on the effects of wave energy extraction

A field study was undertaken with the support of Carnegie Clean Energy Ltd at their Garden Island wave energy test site. Observations of the wave field surrounding their deployed CETO-5 array indicated a small but statistically significant wave energy loss at discreet frequencies attributable to the presence of a single operating WEC. The results and conclusions have been submitted for publication to the international peer-reviewed journal 'Coastal Engineering', and the manuscript is currently under review. These observations provide some of the first published measurements of the effects of WEC installation on the wave field, in an operational 'in-sea' environment.

Numerical model simulation of the case study experiment was undertaken to test and validate the SNL-SWAN wave model – a phase-averaged spectral wave model being widely used by the international research community to simulate the effects of WECs on the surrounding wave field. The project identified SNL-SWAN was able to capture the bulk wave attenuation associated with the presence of a WEC with high skill, however discrepancies in the spectral discretisation of energy was highly dependent on the power matrix associated with the in-situ WEC. Modification of the input power matrix provided by the technology developer was required to reproduce observed changes in the wave spectrum.

Figure 3 CSIRO RV Linnaeus monitoring the Carnegie CETO device at Garden Island.

2.4 Guidelines for assessment of physical impact of wave energy extraction

Having measured effects of wave energy extraction on the surrounding wave field, and establishing confidence in the phase-averaged model to simulate mid-field effects, a set of guidelines (McInnes et al., 2018) have been proposed. These guidelines aim to inform future project proponents and policy makers on the potential spatial extent of increased investigation required to ensure the absence of negative effects due to WEC array deployment. In this way, the guidelines help ensure minimal environmental effects of WEC deployments and may contribute to a social license for wave energy developments and operation.

Using the validated SNL-SWAN model, a large number of idealised numerical simulations were completed, accounting for different wave climates, sites (steep and gentle sloping bathymetry) and array configurations (size and design). These simulations were used to establish a set of semi-empirical equations to estimate the spatial extent over which potential effects of wave attenuation by the presence of the wave energy converters may be felt. Owing to the limitations of the SNL-SWAN model, the focus of the guidelines is on mid-field effects with some discussion about far-field impacts. Near-field impacts (within immediate proximity of the array) are dependent on processes poorly captured by the phase-averaged model.

Ongoing study is required to deepen the understanding of potential environmental (physical and ecological) effects of WEC deployment in the near-, mid-, and far- fields. Here, the intention is to inform policy makers and proponents of the potential spatial extent over which effects should be more rigorously considered.

2.5 Stakeholder engagement

Throughout the project there was regular interactions with key audiences for the sector.

1. **Two stakeholder workshops**: the first workshop affirmed the project goals and methods, and the second workshop was the nucleus for the first Australian Ocean Renewable Energy Symposium (AORES), held in October 2016. AORES was noted as a highly successful event for the sector which would not have occurred without the support of the AWavEA project. The success of AORES is evidenced by advance planning for future AORES, including a second AORES planned for Perth in October-November 2018, and a third AORES to align with the Asian Wave and Tidal Energy Conference (AWTEC) to be hosted in Australia (by UTAS and CSIRO) for the first time in Hobart in 2020.

2. The project has gained audience and interest from a number of stakeholders with interest in project outcomes. Figure 4 below illustrates the range of attendees at the second stakeholder workshop (aligned with AORES) demonstrates the breadth of this engagement.
   AORES had 93 registrants over the three days, including:
   - Australian wave and tidal energy technology and project developers (16 registrants),
   - four international invited speakers,
   - the Australian research sector (31 university registrants, 15 registrants from publicly-funded research agencies (PFRA),
   - State and Federal Government representatives (13 registrants), and
   - 14 others spanning the banking sector, electricity grid operators, engineering and power consultants, and the Clean Energy Council.

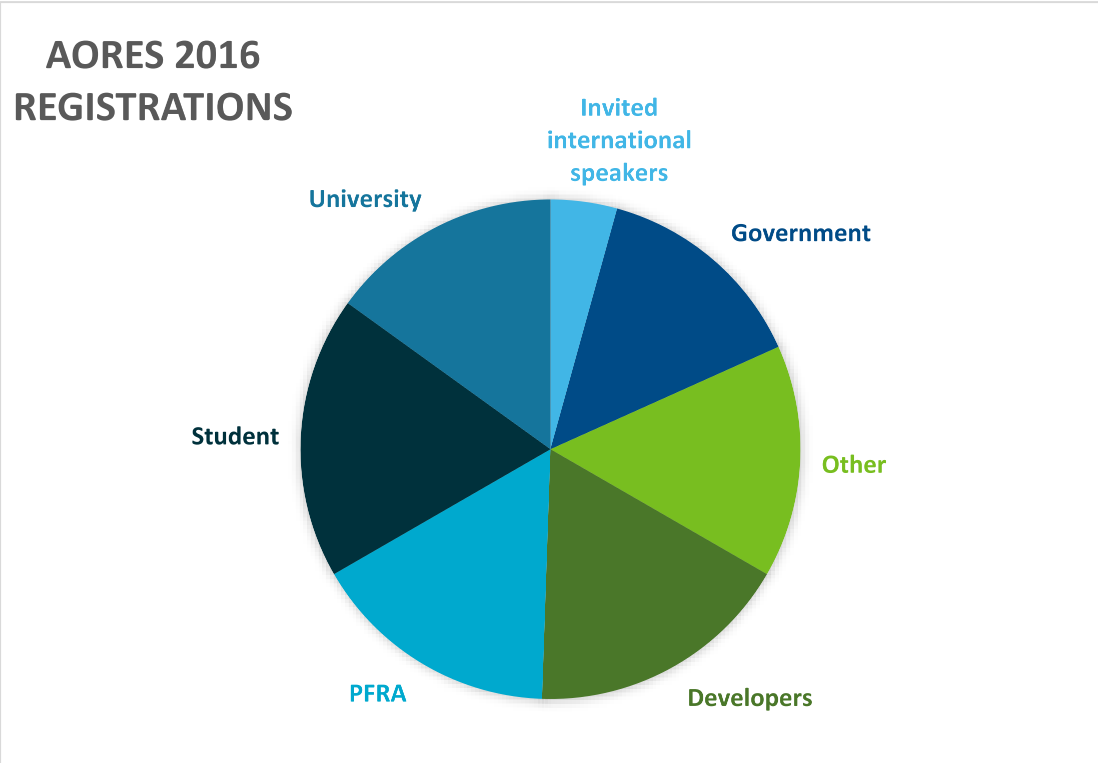


Figure 4 Registrations at AORES 2016 by sector

3. Stakeholder input received during the AORES workshop informed the writing of a **White Paper titled 'Perspectives on a Way Forward for Ocean Energy in Australia'**. This paper, submitted to the international peer reviewed journal 'Renewable Energy' (Hemer et al. currently under review), is a significant outcome from the project, and presents key priorities for Australia's marine energy sector to move forward.

4. The project provided networking opportunities sorely needed by the fledgling Australian ocean energy sector, and two stakeholder workshops were instrumental in the **formation of a new Australian ocean energy industry body** (the Australian Marine Energy Taskforce was publically announced in August 2017).
5. An Advisory Committee provided oversight throughout the project. Ten meetings were held over the life of the project; three of these were face-to-face. Apart from providing valuable feedback to the project team, these meetings provided an avenue for **regular industry 'round-table sharing'.**

6. Following the preliminary release of the Portal, stakeholders were invited to respond to a **survey seeking feedback on the beta version of the Australian wave energy atlas**. Feedback received was invaluable for ensuring the atlas met user needs.

2.6 Publications and communications

Key publications include:

The Australian Wave Energy Atlas - Technical Report – a CSIRO publication

> Authored by Hemer, Zieger et al.
> This report provides details about the methodology used to develop the wave resource information provided by the atlas, and is openly available via the CSIRO publications repository with a unique digital object identifier (https://doi.org/10.4225/08/5a85cab02e91d).

Perspectives on a Way Forward for Ocean Renewable Energy in Australia (submitted to *Renewable Energy)* authored by Hemer, Manesseh et al.

> This paper was prepared by the AORES organising committee in response to the outcomes and feedback from the third day of AORES, which was a full day workshop focused on 'the way forward' for the Australian ORE sector. The workshop participants included a wide range of sector representatives, as well as having the benefit of the expertise and insights from the international invited speakers.

A full listing of publications and communications is in Attachment A. The list includes 6 journal articles, 17 conference presentations/ papers, 5 published reports, 8 electronic articles, and 2 magazine articles. Apart from the numerous conferences, the Atlas was also covered in four other international networking meetings and has one PhD near completion.

These communications cover a wide range of audiences including national and international scientific community, national and international wave energy industry community and the Australian public, including students.

The release of the Atlas at AORES in October 2016 was a pivotal moment for the project. An accompanying '*The Conversation*' article (Hemer et al., 2016) attracted considerable media for the project and the industry, with the following communications statistics:

- **Mainstream media:** 7 separate clips, reaching an audience of **18,574**
- **Twitter reach:** We put out 12 different Tweets, which were all retweeted. Others also tweeted about the conversation article, the Atlas and the AORES event.
  Total reach: **183,000**
- **CSIRO Blog** (repost of the Conversation article): viewed **921 times**, with average reading time of 5m 16s (CSIRO blog average is 3m 18s)
- **Conversation article:** 13000 reads, 186 comments
- **Facebook reach: 48,343**
- **Web page: 215** visits over the AORES symposium week

2.7 Project data contribution and availability

Project data has been made openly available: Atlas data is available on a geonetwork catalogue <http://waveatlas.marine.csiro.au/geonetwork/>. Other data are published publically via the CSIRO data access portal (DAP) <http://data.csiro.au> with a unique digital object identifier (DOI). This includes data collected from the Garden Island case study field study <http://doi.org/10.4225/08/5993b202070c2>, and numerical simulation data from the case study <http://doi.org/10.4225/08/59a4a54eae290>.

3 New knowledge gained during the project

The AWavEA project was inherently one of knowledge gathering and dissemination, and many of the planned outputs are learnings. As knowledge was gained throughout the project, any lessons learnt were documented and shared.

3.1 Improved understanding of wave resource and wave variability

A comprehensive revised estimate of Australian wave energy resource was completed (Hemer et al. 2017). Australia's long southern-facing coastline gives rise to arguably the largest wave energy resource of any country in the world, and this study improved the understanding of that resource, with the following findings:

- The wave energy resource assessment (Hemer et al. 2017) revised prior estimates of resource (Hughes and Heap, 2010; Hemer and Griffin, 2010), which did not adequately capture the spatial distribution of Australia's resource.
- The total wave-energy flux across the depths of 25, 50 and 200 m is estimated to be 1796, 2652 and 2730 TW h/year, respectively.
- Australia's total available wave energy resource is an order of magnitude larger than the 248 TW h electricity generated in Australia in 2013–2014 (Department of Industry and Science, 2015), and indicates that the magnitude of the wave resource is not a constraint to its future uptake.
- The vast majority of this resource is available to the southern coastal region with 1455 TW h/year estimated at the 25-m depth contour (the depth around which many wave devices are presently being tested), from 29°S on the Western Australian coast to 148°E on the southern tip of Tasmania including western Victoria.
- In contrast, the wave-energy resource over northern Western Australia (north of 23.5°S) and Northern Territory at the 25-m contour is 61 TW h/year.
- Wave variability is also an important consideration for wave-energy extraction. An assessment of wave variability at the 25-m isobath indicates that much of the southern, mid-latitude coastal region is also favourable because it displays relatively low variability in wave energy with respect to the total available wave energy. In other words, large waves are generally not much greater than the wave height at which most energy is received, and episodes of minimum wave heights and energy (significant wave height, Hs, of <1 m) are relatively short-lived, typically exhibiting durations of less than a day and are relatively uncommon with typically >100 days between events.
- Conversely, in the tropical north, the lower available wave resource is also characterised by a larger ratio of large waves to mean wave height. This is due to the occurrence of tropical cyclones. This region also experiences periods of minimal wave energy that are more frequent and of longer duration (Hemer et al., 2017).

3.2 Technical lessons learned

A novel portal design was adopted by AWavEA to provide speed and dynamicity, while meeting the challenges of:

- a large wave resource spatial dataset (>20 TB),
- large amounts of associated metadata, as is commonly the case for scientific data,
- the need for fast analysis operations in order to provide practical query time-frames, despite the large dataset,
- a path of release through the NationalMap portal (www.nationalmap.gov.au/renewables), which publishes data with no single controlling authority.

The AWavEA portal development team created a new way of publishing and integrating data services, that is, by using a metadata catalogue to fully describe both the data and the analysis operations that AWavEA provides. All information required to access these services is taken from the catalogue at request time and therefore will always reflect the most up-to-date data available. Also, associated provenance information with and about the services is provided.

The AWavEA approach to portal design and data management is highly efficient (repetition is minimised), for example user-initiated point queries to provide values and statistics calculated against the very large dataset in real-time can be provided in less than 10 seconds. The analysis processes required optimisation of very large data holdings (> 20TB) that facilitates the fast time-frames required for processing. The design also adheres strictly to Open Geospatial Consortium (OGC) standards protocols, ensuring compatibility with other datasets and allows incorporation into third party managed portals.

The AWavEA portal methodology was presented at AORES and at eResearch Australasia 2016. Since the transfer of AWavEA to AREMI in October 2016, there have been several enquiries about this method, with organisations such as the BoM, Geosciences Australia and Australian Bureau of Statistics seeking support for implementing the approach.

Modelling the impact of power generating devices

In this study an observation-based power matrix was created and used for the simulations, as simulations using this power matrix were found to more closely match the wave spectrum observations than did simulations using the industry-supplied power matrix, at least in the wind-sea band. Further study is required to verify this finding for the swell band. The industry-supplied power matrix is based on bulk statistics and is well-suited for operations. However, Contardo, Hoeke et al. (submitted) recommend that: "*given the high dependence of wave shoaling processes on discrete wave frequencies, implementing such power matrices in spectral wave models may result in a misrepresentation of WECs' mid- to far-field impacts on the coast wave field.*"

Wave modelling

Whilst SNL-SWAN was found to represent mid- and far-field effects reasonably well (Figure 5), it is not likely the best model for assessing impacts of WECs in the near-field. An important next step will be to test the use of phase-resolving models in the near-field. However, significant challenges

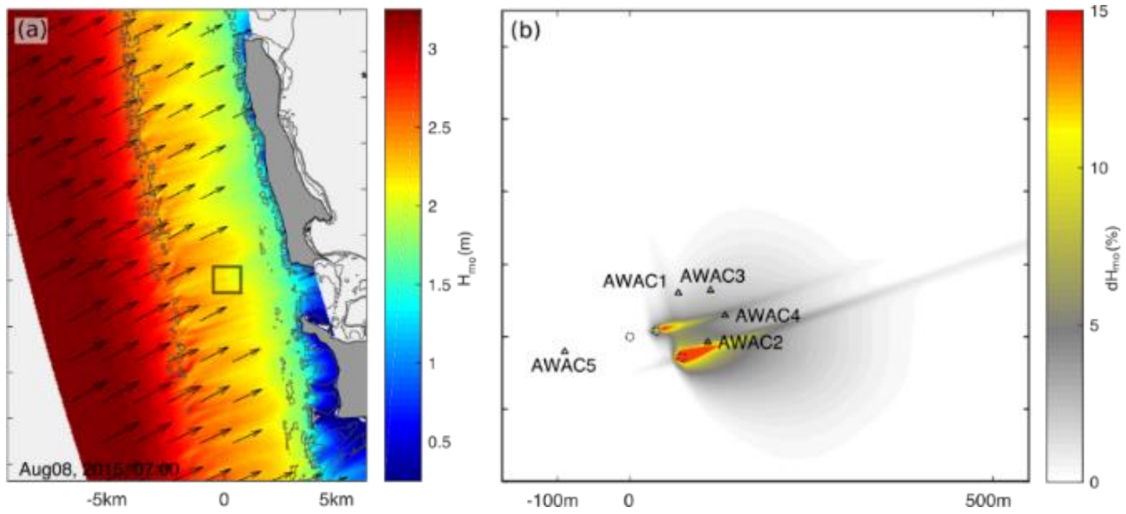
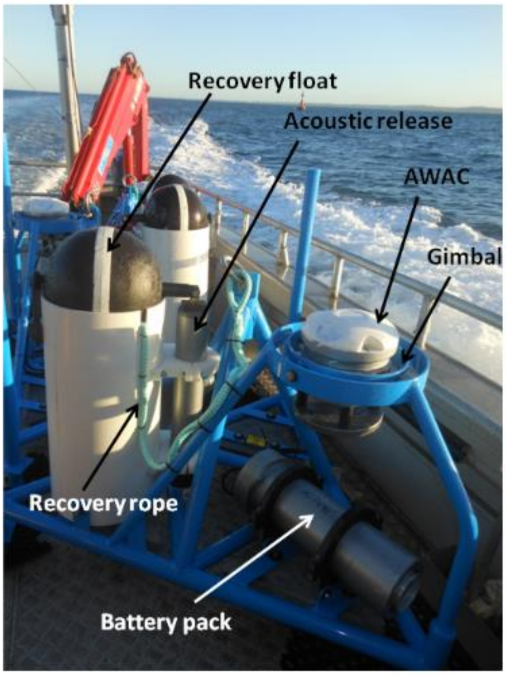


Figure 5. SNL-SWAN Simulated attenuation of significant wave height in the lee of the array of CETO WECs (represented by circles) at the Garden Island site. Triangles represent measurement sites in the field program.

remain, including how alternate WEC designs can be parameterised generally (without device specific characteristics having to be independently coded) within a phase-resolving model.

3.3 Lessons relating to field program

1. An extra field deployment was undertaken in order to better understand the natural variability across the site, and to distinguish this variability from the effect of the WECs. This deployment was not in the original plan and so was done after the WECs were recovered and in a different season.
2. Future experimental design will ideally include two additional control deployments in the presence of WECs: one to measure natural variability with WECs operating; and one with WECs not operating.
3. Having a mix of RDI ADCPs and Nortek AWAC ADCPs added some variability due to the different processing methods for each instrument type. To address this problem, the array of five CSIRO Nortek AWACs were re-arranged to cover all strategic locations with an aim to minimise the uncertainty introduced by variations in instrumentation.
4. Early deployments showed a consistently larger wave height on the north side of the array compared to the south side. To check for instrumental bias, instrument positions were swapped around between deployments. The results showed no instrumental bias, indicating these differences were attributable to natural variability of the wave field across the site.
5. The AWACs were mounted on gimbals on their frames (Figure 6), to allow them to remain vertical, even if the frame was not flat on the bottom. It became clear after the first recovery that the gimbals caused the instrument to tilt continuously following the current causing the directional spectra to be erroneous. This was corrected in later deployments by cable-tying the gimbals. In any future construction of frames for AWACs for data collection, we recommend avoiding the use of gimbals.



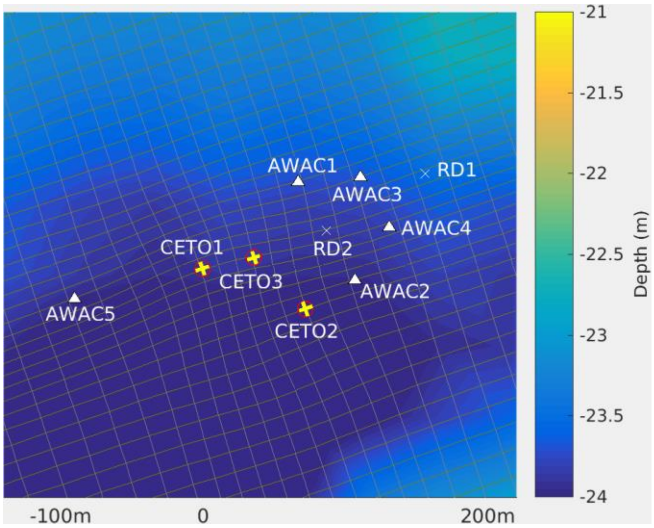


Figure 5. An example of the AWAC moorings (left) deployed adjacent to the array of CETO WECs (right).

3.4 Australian membership of the International Energy Agency – Ocean Energy Systems (IEA-OES)

Project advisory meetings allowed for community discussion of the issue of the lapsed Australian membership of the International Energy Agency – Ocean Energy Systems (IEA-OES) working group, which brings together countries to advance research, development and demonstration of conversion technologies to harness energy from all forms of ocean renewable resources. A clear message from international participants at AORES was Australia has much to contribute and learn through international engagement via avenues such as the IEA-OES, and IEC TC114 standards development. Engagement within international activities was noted as a priority for the Australian Ocean Renewable Energy community at AORES (as reported in the submitted White Paper), with recognition that engagement would minimise wasted investment in the Australian sector. The project highlighted the problem and possible solutions were explored, albeit without a satisfactory resolution of the issue. An internal CSIRO report was commissioned, and completed by CleanReach Ltd, outlining industry perspectives on benefits of OES membership.

4 Recommendations and next steps

4.1 Resource Assessment

- The project has developed a national scale assessment of the resource. The large spatial extent of this assessment has limited the spatial resolution of the information provided, and resolution of near-shore processes (e.g., depth-induced breaking, near-coast diffraction effects) are limited. This limits applicability for near-shore WEC installations. The project/Atlas provides multi-year spectral wave data on the inner-shelf which can be used to support down-scaled assessment of resource for any proposed near-shore activities. **RECOMMENDATION: downscaled resource assessments (to resolution in the order of 10's of metres) be completed for priority development sites to minimise constraints on developers and support accelerated development of wave energy projects. This capability could be incorporated into the Atlas processing capability, noting requirement for high quality site/bathymetry data to support assessment. Any downscaled assessment should adhere to international standards (e.g., IEC TC114).**
- The resource assessment has been validated with as much observational data as available. The network of in-situ observations surrounding the Australian continent is relatively sparse, with some regions poorly represented by observations. As example, the southern margin of the Australian continent is identified as having an internationally attractive wave energy resource. However no observations of wave direction are available for much of this region (between Esperance, WA and Eden, NSW). This dictates complete reliance on model output to characterise directional characteristics of the wave resource in this region, which can have important implications for directionally dependent wave energy converters. **RECOMMENDATION: in-situ observations in the southern margin of the Australian continent be upgraded to provide directional information to support prospective developers in this region.**
- The emphasis of the resource assessment carried out in the project has been on the theoretical wave energy resource. If wave energy is to be developed further, it must be demonstrated that a viable technical and economic resource also exists. **RECOMMENDATION: preliminary assessments of the technical resource have been carried out in the project, which suggest a 5-10% contribution of wave energy to Australia's electricity demand may be a realistic contribution. However we recommend more attention be given to assessing the technical and economic resource, with consideration of proximity to demand (both on- and off-grid markets), grid restraints, marine spatial constraints (e.g., marine protected areas (MPAs), shipping lanes, etc), and technological performance (identify best performing devices). With improved estimates of capital, operations and maintenance costs, the future economics of wave energy should be considered. Such an assessment should identify what costs are required for wave energy to be competitive (and where gains can be made); what capacity of wave energy needs to be developed to reach that level of maturity; and what are the costs required to develop that capacity.**

- The wave energy resource has been considered in isolation within the project. If wave energy is to develop it will be part of an energy mix to provide secure, reliable energy in a future low-carbon economy. **RECOMMENDATION: an integrated assessment of variable renewable resources be undertaken which captures both 'traditional' renewables, and offshore renewables. This assessment should consider the temporal and spatial variability of these resources, to identify an optimal mix/distribution of generation technologies to deliver reliable and secure energy to meet Australia's demand. An integrated assessment of theoretical, technical and economic resource will enable potential opportunities for offshore energy in Australia to be identified.**
- Wave energy is just one of several ocean renewable energy technologies under development. Wave energy is the only ORE resource currently captured within the Australian Renewable Energy Mapping Infrastructure (AREMI). ARENA has supported a project to add assessment of Australia's tidal energy resources to AREMI. **RECOMMENDATION: assessment of Australia's offshore wind resources, as the leading offshore energy technology, should be included within AREMI's assessments.**

4.2 Marine Spatial Data

- The Atlas has been developed to include spatial information for a number of criteria which act as either positive or negative constraints on location of wave energy developments. For example, the Atlas includes information on location of electricity grid infrastructure, supporting marine infrastructure (major and minor ports), and competing marine uses (e.g., MPAs, shipping routes, fishing and aquaculture zones, and Indigenous sites). Early stage demonstration of technology is being located at sites with cooperative coastal land holders over which grid connection points occur (e.g., Perth Garden Island Project; BPS aquaculture facility). This information is not currently captured by the Atlas. **RECOMMENDATION: future development of the Australian Wave Energy Atlas to capture coastal land to support grid connection facilities.**
- The marine spatial information captured within the Atlas is currently focussed on utility scale uptake of offshore ocean renewable energy. However, future wave energy development may mature through demonstrated application to alternative markets, such as off-grid electricity demand (e.g., island communities), complementary industry demands (e.g., offshore aquaculture facilities), or integrated demands (e.g., combined coastal protection and energy production technologies). **RECOMMENDATION: future development of the Australian Wave Energy Atlas to incorporate spatial information on opportunities associated with alternative markets, as the ocean renewable energy industry would likely benefit from access to this information.**

4.3 Portal Development

- Developing the delivery of services into an externally managed and supported infrastructure required collaboration and cross-pollination of the standard-based approach to implement the necessary infrastructure with the NationalMap development team. Some basic features – such as ‘point value query extraction from data layers’ - have not been considered by the NationalMap development team and detract from the full capability of the Wave Atlas. **RECOMMENDATION: that** ‘point value query extraction from data layers’ **features are implemented back into the Australian Wave Energy Atlas in due course.**

- The development of the wave atlas portal within the NationalMap infrastructure led to development of unique processing capability for analysis of resource. **RECOMMENDATION: developed processing capability be utilised for analysis of other resources within AREMI, and potentially extended to determine power output, and LCOE for all technologies given resource and other spatial constraints.**

4.4 Physical effects monitoring

- The project produced the first set of measurements of the attenuation of the wave field behind an array of WECs deployed at sea. These measurements are associated with a single device type (Carnegie Clean Energy’s CETO-5 wave energy converter), which is no longer in development (the CCE CETO WEC has undergone further development). **RECOMMENDATION: monitoring the physical and environmental effects associated with a larger range of devices (and upgraded devices as developed) should be undertaken routinely as devices mature and are deployed at sea. This would enable environmental effects associated with a device to be considered within the decision process (in addition to optimising power generation) to identify leading devices.**
- Monitoring the change in the wave field surrounding the array of WECs was carried out using a number of in-situ moorings, containing wave-enabled Acoustic Doppler Current Profilers (Nortek AWACs and RDI Sentinel). This necessitated a sparse network of devices which can only capture the change in wave characteristics at discrete points. Remotely sensed measurements spanning the array may offer the ability to obtain a more continuous representation of the wave field across the site. X-band radar is one technology which may achieve this. The Perth Wave Energy Project deployment site was 5km offshore, and a shore-mounted platform was deemed too far away to get reliable measurements. **RECOMMENDATION: should a WEC array deployment be nearer to shore, a shore-based X-band radar platform may be a suitable instrument for measuring spatial variability of the wave field across the deployment site. Experimentation with other technologies (e.g., ship-mounted radar; Aerial Lidar) are also potential solutions.**

4.5 Physical effects modelling

- The project used a phase-averaged wave model (SNL-SWAN) to simulate the effects of a WEC array deployment on the surrounding wave field. The SNL-SWAN model uses a WEC power-matrix to characterise the energy absorbed by the WEC at the position of deployment. This power-matrix is typically characterised by the energy provided to the electricity grid. In order to match observed changes in wave field, we modified the power matrix in the model from that provided from CCE for their WEC, and attribute these changes to the differences between an apparent ‘power-matrix’ representative of the energy removed at the location of the device, and the real power-matrix representative of the power generated by the device at shore. These differences can be attributed to transmission losses between the WEC and generated power. **RECOMMENDATION: test the assumption that differences in apparent 'power-matrix' and the actual power generated are due to transmission losses. This would require close collaboration with a developer to ensure commercial confidence.**

- The application of phase-averaged models to assessing environmental effects of WEC deployment has advantages of being numerically efficient and generalizable with regards to the specificity of the device technology. Phase-resolving wave models are now sufficiently mature that investigations are underway to parameterise the effects of WECs and assess changes to the wave field associated with the WEC presence. These models have advantages of being able to parameterise the effects of diffraction and radiation which cannot be resolved by the phase-averaged models. **RECOMMENDATION: rigorous inter-comparison of phase-averaged and phase-resolving models in both idealised and 'at-sea' conditions should be completed relative to observations. Continued development of phase-resolving models to parameterise WEC effects, independent of specificities of the WEC, should be undertaken.**

4.6 Engagement

1. A key objective of the project was stronger coordination across the Australian ocean renewable energy network. This objective was achieved in part through the stewardship role the project team played in creating and organising the inaugural Australian Ocean Renewable Energy Symposium (AORES). The success of AORES is demonstrated by the strong and unanimous community agreement for a second and third AORES to be held. The AORES committee prepared a comprehensive handover package to assist preparations for the second AORES, to be held in Perth in October/November 2018. **RECOMMENDATION: the AORES workshop developed recommendations to support growth of Australia's ORE industry, including: a supported and expanded Australian ORE network; appointment of an Australian ORE officer to lead communication domestically (within community, and upwards to Ministers) and internationally (contact point for international working group memberships); consideration of an ORE test facility as a means to support collaboration between industry, academia and Government, develop ORE technologies, build skills to support the emerging industry, grow public awareness and establish a social license to operate; carry out an economic value assessment for ORE in Australia; and encourage broad policy support for renewable energy in Australia. These recommendations are outlined more fully in the submitted manuscript: Hemer et al., "Perspectives on a way forward for ocean renewable energy in Australia".**

2. The Australian community is currently one of few developing nations not engaged with leading international ocean energy development groups, having withdrawn membership in recent years. As a country with some of the world-leading technology developers, and arguably the world's largest wave energy resource, Australia has potentially much to gain from the development of a global wave energy industry. **RECOMMENDATION: Australia should engage in primary international activities seeking to establish a global ocean energy industry (e.g., the International Energy Agency Ocean Energy Working Group – IEA-OES), to maximise the potential returns on investment already placed on wave energy in Australia.**

5 References cited in this report

Australian Government Department of Industry and Science (2015). Australian Energy Update, 2015. Office of the Chief Economist. Available at: https://industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2015-australian-energy-statistics.pdf

Contardo, S., R. Hoeke, M. Hemer, G. Symonds, K. McInnes and J. O'Grady (submitted). In situ observations and simulations of coastal wave field transformation by wave energy converters. Submitted to Coastal Engineering.

Hemer, M.A., and D.A. Griffin (2010) The wave energy resource along Australia's southern margin. J. Renew. Sustain. Energy **2**. DOI: 10.1063/1.3464753

Hemer, M., S. Zieger, T. Durrant, J. O'Grady, R.K. Hoeke, K.L. McInnes and U. Rosebrock (2017). "A revised assessment of Australia's national wave energy resource." Renewable Energy **114**(Special Issue on Wave and Tidal Resource Characterisation): 85-107. DOI: 10.1016/j.renene.2016.08.039

Hemer, M., R. Manasseh, K. McInnes, I. Penesis and T. Pitman (2016) Catching the waves: it's time for Australia to embrace ocean renewable energy. The Conversation, Available at: https://theconversation.com/catching-the-waves-its-time-for-australia-to-embrace-ocean-renewable-energy-66048

Hemer, M., R. Manasseh, K.L. McInnes, I. Penesis and T. Pitman (Under review). "Perspectives on a way forward for ocean renewable energy in Australia." Submitted to Renewable Energy.

Hughes, M.G., and A.D. Heap (2010) National scale wave energy resources assessment for Australia. Renewable Energy **35**: 1783-1791. DOI: 10.1016/j.renene.2009.11.001

McInnes, K., M. Hemer, J. O'Grady, R. Hoeke and S. Contardo (2018). Wave Energy Deployments - Physical Impact Guidelines. CSIRO Technical Report. DOI:10.4225/08/5a85cab472c5d. Available at: https://publications.csiro.au/rpr/download?pid=csiro:EP181064&dsid=DS3

Attachment A - AWavEA project publications and communications list

Web Pages (2)

AREMI and CSIRO (2017 to present). "Australian Wave Energy Atlas (AWavEA)." <https://nationalmap.gov.au/renewables/#share=s-gGd5ztFcxe2ysy9f>.

A tool that provides wave energy developers with crucial high quality information about the wave energy resource in Australia in an easily accessible and easy to use format. Until now, credible independent information about the resource had been a key limitation for the Australian wave energy industry.

CSIRO (2016 to present). "AORES." <https://events.csiro.au/Events/2015/December/18/Australian-Ocean-Renewable-Energy-Symposium>.

The AORES webpage provided regular updates in the lead-up to AORES, as well as being a repository for documents and information for stakeholders since the symposium. It will also provide a link to information about the second symposium in Perth, currently in early stages of planning.

Journal Articles (6)

Contardo, S., et al. (submitted). "In situ observations and simulations of coastal wave field transformation by wave energy converters." Coastal Engineering.

Hemer, M., et al. (Submitted). "Perspectives on a way forward for ocean renewable energy in Australia." Renewable Energy.

Winship, B., et al. (Submitted). “Preliminary investigation on the use of tank wall reflections to model WEC array effects.” Ocean Engineering.

Hemer, M., et al. (2017). "A revised assessment of Australia's national wave energy resource." Renewable Energy **114**(Special Issue on Wave and Tidal Resource Characterisation): 85-107.

Manasseh, R., et al. (2017). "Pioneering Developments of marine renewable energy in Australia." International Journal of Ocean and Climate Systems **8**(1): 50–67.

Manasseh, R., et al. (2017). "Integration of wave energy and other marine renewable energy sources with the needs of coastal societies." International Journal of Ocean and Climate Systems **8**(1): 1-18.

Reports (5)

AWavEA Project Team (2016). Report for Mid-Project Evaluation of the Australian Wave Energy Atlas Project, 31st March

Comprised of three components: the revised resource assessment, the first stakeholder workshop, and the Garden Island Case Study.

Folley, M. (2016). Review of the Report for Mid-Project Evaluation of the Australian Wave Energy Atlas Project, 24 May

Comprised of three components: a review of the revised resource assessment, a review of the first stakeholder workshop, and a review of the Garden Island Case Study.

Hemer, M. (2016). Responses to the Review of the Report for Mid-Project Evaluation of the Australian Wave Energy Atlas Project, July

Hemer, M., et al. (2018). The Australian Wave Energy Atlas - Technical Report, CSIRO Technical Report. https://doi.org/10.4225/08/5a85cab02e91d

McInnes, K., et al. (2018). Wave Energy Deployments - Physical Impact Guidelines. CSIRO Technical Report. https://doi.org/10.4225/08/5a85cab472c5d

Conference Papers (18)

Hemer, M., K. McInnes, J. O'Grady, R. Hoeke and S. Contardo (2018) Proposed guidelines for preliminary assessments of the physical impacts of wave energy deployments. Submitted to the 4th Asian Wave and Tidal Energy Conference (AWTEC), Taipei.

Flocard, F. and R. Hoeke (2017). Coastal protection through wave farms: feasibility assessment using numerical wave modelling and parametric study. Coasts & Ports 2017 Conference Cairns, Qld, Australia.

Presents the results of numerical experiments assessing the impacts of arrays of WECs on the surrounding wave field at the BPS Port Fairy pilot wave energy site

Hemer, M. (2017). Australia's Technical Wave Energy Resource. European Wave and Tidal Energy Conference (EWTEC), Cork.

Hemer, M. (2017). The Australian Wave Energy Atlas. Australian Meteorological and Oceanographic Society (AMOS), Canberra.

Rosebrock, U. and S. Pigot (2017). Making Terra-Bytes of data accessible in 'web-time'! eResearch Australia, Brisbane.

With increasing amount of data available and the cross-disciplinary use, it is no longer feasible to simply copy or query large data holdings remotely. Query processes are necessary in front of data. A simple measure will be presented which allows improved access and make incorporation in spatial portals feasible.

Hemer, M. (2016). The Australian Wave Energy Atlas. Asian Wave and Tidal Energy Conference, Singapore.

Hemer attended and presented in Technical Session 2.3 Resource Assessment S1. AWTEC is a biannual event, and this was the 3rd, where there were 14 keynotes speeches, 30 invited talks and more than 150 technical papers.

Hemer, M. (2016). The Australian Wave Energy Atlas. NSW Coastal Conference.

Hemer, M., et al. (2016). Building a pre-competitive knowledge base to support Australia's wave energy industry. Australian Meteorological and Oceanographic Society (AMOS), Melbourne.

This paper was presented by Ron Hoeke.

Hemer, M., et al. (2016). Building a pre-competitive knowledge base to support Australia's wave energy industry. American Geophysical Union (AGU) Ocean Sciences, New Orleans.

This was an invited poster presented by Ron Hoeke.

Hemer, M., et al. (2016). Building a pre-competitive knowledge base to support Australia's wave energy industry. Indo-Australian Marine Renewable Energy Workshop Chennai, India.

Hemer was part of the organising committee for the workshop, and McInnes attended the workshop presenting the wave energy atlas. The workshop provided opportunity to explore collaboration opportunities with the marine renewable sector in India, which is growing, as evidenced by their joining of the IEA-OES working group in 2016. The project team have contributed to workshop outcome reports which have been circulated to both the Indian and Australian Governments, and two academic publications (review articles) are in preparation (in collaboration with Swinburne University colleagues, and Indian researchers).

Hemer, M., et al. (2016). The Australian Wave Energy Atlas. Australian Coastal Ocean Modelling workshop, Canberra, IMOS.

Hoeke, R., et al. (2016). Impacts of wave energy conversion devices on local wave climate: the AWavEA project. Australian Meteorological and Oceanographic Society (AMOS), Melbourne.

McInnes, K., et al. (2016). The Australian Wave Energy Atlas. AWATEA (Aotearoa Wave and Tidal Energy Association), Wellington, NZ, 19 May.

McInnes, K., et al. (2016). The Australian Wave Energy Atlas. Indian-Australian Ocean Energy Meeting, Chennai, India, 4 April.

McInnes, K. L., et al. (2016). Nearshore coastal models for coastal hazards, adaptation and renewable energy applications. CSIRO Computational and Simulation Sciences and eResearch conference.

Rosebrock, U. and S. Pigot (2016). The Australian Wave Energy Atlas (AWavEA) – a novel approach for the delivery of scientific data into the next generation of Web-portals. (Accepted). eResearch Australasia, Melbourne.

Hemer, M. (2015). The Wave Energy Atlas Project. All Energy Australia.

Hemer, M. (2014). Projections of future wave climate for the ocean energy industry. International Conference of Ocean Energy, Halifax.

Presented as a poster. A number of valuable discussions were held, notably with the Chair of the IEA-Oceans Energy working group, Jose Luis Villate, and leader of the IEA-OE Annex IV on environmental impacts, Andrea Copping of the US Pacific Northwest National Laboratory. From these discussions, it is apparent that there is a strong desire from the community for field measurements as being carried out in the AWavEA project, and the opportunity for these to be an important contribution to the international community. Hemer also met with several researchers who have led development of their own national marine energy resource assessments, and established connections for ongoing discussions.

Other meetings where the AWavEA project was promoted (4)

Hemer, M. (2017). Forum for Operational Oceanography (FOO). Fremantle, Australia.25 - 27 July <http://www.foo.org.au/events/foo-2017/>

FOO brings together the four pillars of operational oceanography in Australia (Marine Industries, R&D Providers, Service Providers and Government Agencies). The marine renewable energy industry are seen as a key future marine industry within the FOO community.

Hemer, M. (2015). The Australian Wave Energy Atlas. Japan Exchange visit. Port and Airport Research Institute (PARI) in Yokohama, Japan

Hemer presented details of the project during discussions with Port and Airport Research Institute (PARI) in Yokohama, Japan. PARI have excellent facilities with interest in expanding to Ocean Energy research.

Hemer, M. (2015). The Australian Wave Energy Atlas Project. Forum for Operational Oceanography (FOO). Perth, Australia.21 - 23 July <http://www.foo.org.au/events/foo-2015/>

Hemer, M. (2014). European visit, University of Exeter and University of Plymouth, The UK Met Office and Deltares, The Netherlands.

Each group were interested in our project and glad to see Australia progressing ocean energy research. Of most benefit was interaction with the University of Exeter (UoE) group from which ongoing collaborations are expected implementing UoE wave model developments which have parameterised energy dissipation by wave energy converters, which is in need of field and lab tank experiments for validation.

Electronic Articles (8)

Grant, R. (2017) The quest for the perfect wave for renewable energy is being solved by Australian Science. ABC News

BoM (2016) Visualise Australia's renewable energy infrastructure. eXchange newsletter

CEC (2016) Wave energy atlas makes a splash on renewable energy map. Clean Energy Council (CEC) Newsletter

Chunn, J. (2016) Australia's wave energy inventors look for a break. ecogeneration

Hemer, M. (2016) Australia maps wave energy potential. Tidal Energy Today

Hemer, M., et al. (2016) Catching the waves: it's time for Australia to embrace ocean renewable energy. The Conversation, https://theconversation.com/catching-the-waves-its-time-for-australia-to-embrace-ocean-renewable-energy-66048

Young, A. (2016) Wave atlas helps map the way ahead for ocean energy. ECOS

Hemer, M. (2015) The Atlas – mapping Oz's wave potential. **86**, 17

Newspaper Article (1)

Mounster, B. (2016). Australian Maritime College electricity study rides wave of success. Mercury. Hobart, 28 March. (<http://www.themercury.com.au/news/tasmania/australian-maritime-college-electricity-study-rides-wave-of-success/news-story/dc33cf9c3b2d2c526de761597de95f9d)

Mark Hemer, from CSIRO Oceans and Atmosphere, said a few more hurdles needed to be overcome before wave power, which had been lagging wind power by about two decades, could take off commercially.

Magazine Articles (2)

Gannon, G. (2017). Leading the charge. <u>Australian Women's Weekly</u>.

Highlighting women in Australia's renewable energy sector, including Kathy McInnes. The Australian Womens' Weekly is one of the most read (top 3) magazines in Australia.

Thomsen, E. (2017). Catching the Power Wave. <u>Double Helix</u>. Australia, CSIRO.

Interview (1 of several)

Hemer, M. (2017). Wave energy research demonstration at the Australian Maritime College. ABC News. R. Grant.March 16 <http://www.abc.net.au/news/rural/2016-03-16/wave-energy-research-demonstration-at-the-australian-maritime-c/7251304

Press Release (3)

Hemer, M. (2016). Release of Australia's Wave Energy Atlas

Received good coverage across television (ABC, SCTV and Win News), Radio (ABC Rural) and Press (News Limited)

ARENA (2014). Atlas to map Australia's wave energy.

Together with a CSIRO media release, this resulted in high media uptake, across printed, on-line and radio media.

CSIRO (2014). Atlas to map Australia Ocean Energy

CSIRO News blog and twitter posts (24-July-2014) on project commencement, pointing to ARENA media release. These together resulted in high media uptake, across printed, on-line and radio media.

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