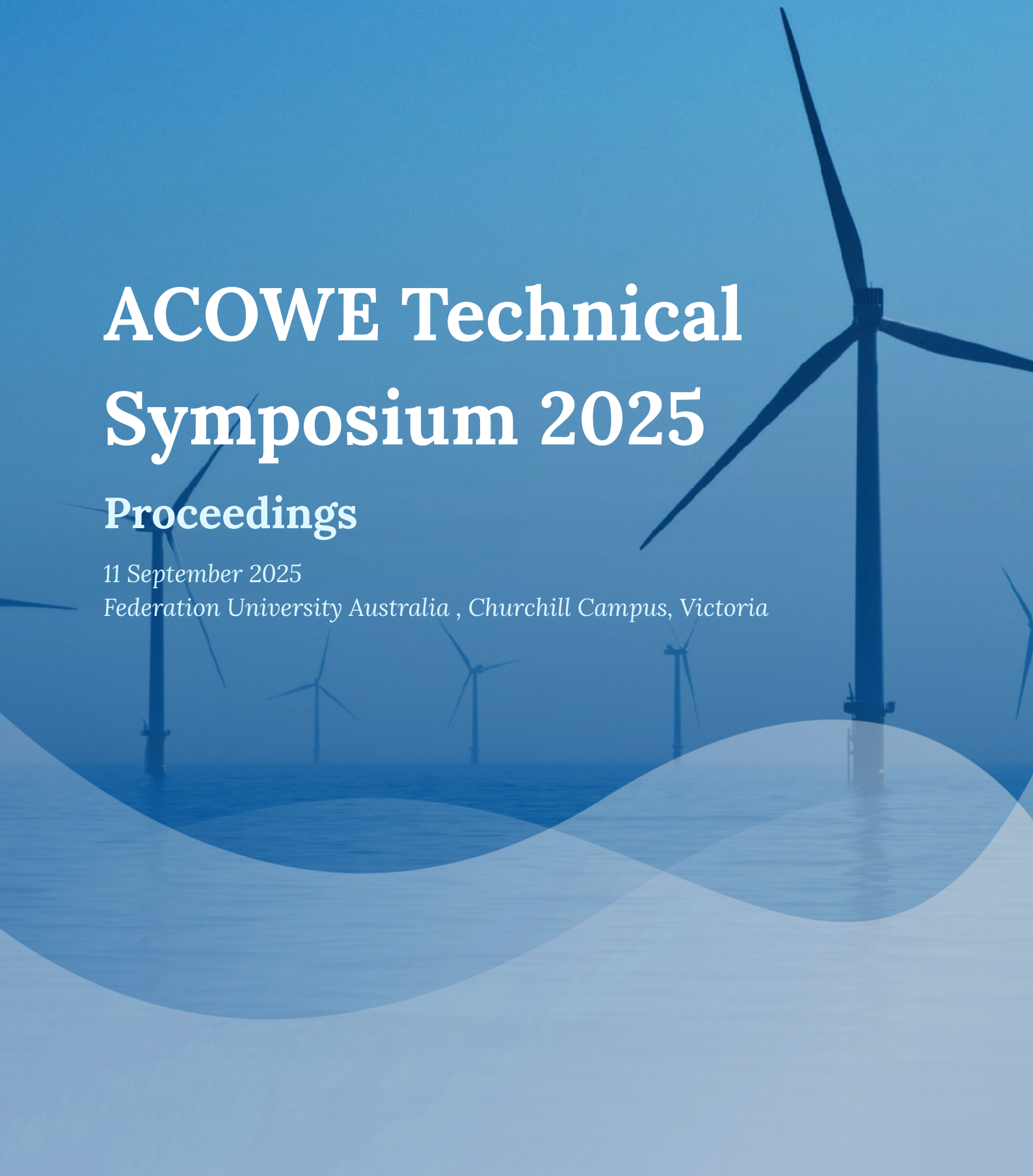
ACOWE
Australian Centre for Offshore Wind Energy



ACOWE Technical Symposium 2025

Proceedings

11 September 2025
Federation University Australia , Churchill Campus, Victoria

Preface

Offshore wind is a critical component of Australia's net-zero transition. The development of offshore wind energy in Australia is presenting challenges, but also exciting opportunities to address our unique cultural heritage, biodiversity, metocean and seabed, supply chain and workforce needs.

The Australian Centre for Offshore Wind Energy (ACOWE) is responding to these opportunities through a nationally coordinated, interdisciplinary research and training partnership.

Our Mission:

ACOWE will deliver evidence-based solutions and a new, skilled workforce to enable sustainable offshore wind development for the benefit of Australia.

Our Vision:

ACOWE will be the foremost research and training pathway for offshore wind energy and contribute positively to the decarbonisation of Australia.

Our Values:

ACOWE will ensure that Australian offshore wind development is pursued in an equitable, inclusive, socially, culturally and environmentally responsible manner.

With Gippsland as the first declared offshore wind zone in Australia, the 2025 ACOWE Technical Symposium: Enabling Offshore Wind in Australia aims to pave the way for the technical community to share their latest research on Australia's unique offshore wind challenges and opportunities.

The inaugural ACOWE Technical Symposium, held as a face-to-face event on 11 September 2025 at Federation University, Churchill Campus, Victoria, Australia was organised in collaboration with the Gippsland New Energy Conference 2025 (GNEC25). This symposium was designed to facilitate cross-sector dialogue and innovation to support offshore wind initiatives across Australia's declared zones.

The Symposium commenced with a welcome reception at the Morwell Innovation Centre on the evening of 10 September, providing an opportunity for informal networking ahead of the formal program. The technical program featured five keynote addresses and sixteen presentations, organised around four central themes: marine environment, logistics, offshore engineering, and metocean and hydrodynamics. The Symposium concluded with a panel discussion bringing together representatives from industry, government, and the research sector to discuss key research and development priorities to enable offshore wind in Australia.

Community Engagement and Cultural Heritage remains a key research theme for ACOWE and is essential to the successful and responsible implementation of offshore wind energy in Australia. While a dedicated session on Community Engagement was not included in the 2025 ACOWE Technical Symposium, the topic was addressed through facilitated workshops and presentations on community engagement featured in GNEC25, enabling broader outreach and engagement.

We thank all contributors, presenters, and participants whose insights and engagement made the inaugural ACOWE Technical Symposium a success. As offshore wind development progresses, ACOWE will continue to serve as a trusted platform for advancing research and fostering innovation to enable sustainable offshore wind development in Australia.

Acknowledgements

The ACOWE Steering Committee thanks the Gippsland Climate Change Network (GCCN) for their invitation to participate in the Gippsland New Energy Conference (GNEC) through the delivery of the ACOWE Technical Symposium 2025.

We are grateful for the support provided by the GNEC Organising Committee and the opportunity to provide a platform for researchers and key stakeholders to share knowledge.

We acknowledge ACOWE university partner, Federation University, who hosted both the Welcome Event at the Morwell Innovation Centre, and Symposium at the Churchill campus, in addition to providing event management expertise.

ACOWE Technical Symposium Committee

A/Professor Shiaohuey Chow, The University of Melbourne (Chair)
A/Professor George Kouretzis, The University of Newcastle
Professor Andrew O'Loughlin, Federation University
Dr Jana Orszaghova, The University of Western Australia
Professor Matthew Pepper, The University of Wollongong
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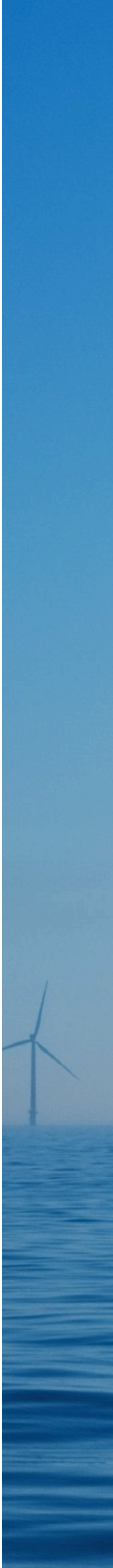

About the Keynotes

Professor David Kennedy

School of Geography , The University of Melbourne

With more than 20 years of expertise in coastal geomorphology, Professor David M. Kennedy is a leading authority in the field and recipient of the 2020 Eureka Prize for his work with the Victorian Coast Monitoring Program. A Professor of Physical Geography in the School of Geography, Earth and Atmospheric Sciences at the University of Melbourne, David has led numerous projects along the Gippsland coast, including a recent geomorphology study of the 30,170-hectare Nooramunga Marine and Coastal Park, which stretches from Port Welshpool to Seaspray. Not content with training citizen-scientists' skills to protect their coastlines, David is also the author of The Science & Culture of Surfing, published by Springer, as well as delivering Australian Surfing, a subject that examines surfing's Polynesian roots in the First Nations cultures and the science that shapes the perfect wave.

Dr Andrew Gill

Senior Research Scientist, Australian Institute of Marine Science

Andrew was recently appointed as Senior Research Scientist in Renewable Energy at the Australian Institute of Marine Science (AIMS), joining AIMS from a similar role he held for 6 years as the Strategic Lead for Offshore Renewable Energy (ORE) at Cefas, the UK Government agency for marine and freshwater science evidence and advice. His new role leads the strategic development of renewable energy activities, further developing AIMS-wide initiatives into the decarbonisation agenda that contribute to the sustainability and protection of Australia's natural resources.

A/Professor Peggy Chen

Centre for Maritime & Logistics Management, Australian Maritime College

As Director of Centre for Maritime and Logistics Management at the Australian Maritime College (AMC), University of Tasmania (UTAS, Peggy's research focus and publications are in the field of maritime logistics management including port governance, port management and strategy, climate change impacts and port adaptation strategy, and risk management. She is also the co-lead of Logistics and Supply Chain work package within the Blue Economy CRC funded project 'Pre- conditions for the Development of Offshore Wind Energy in Australia'.

Avi Shonberg

Chief Geotechnical Engineer, Ørsted

Avi has focused on offshore foundation design since joining Ørsted in 2014, with a particular focus on suction bucket design, pile design, pile load testing, soil-structure interaction, cyclic effects on soils and 3D finite element modelling. With experience across the full life cycle of offshore wind farm development, Avi has had responsibility for the detailed geotechnical design of numerous offshore wind farms in northern Europe and Taiwan.

Dr Jana Orszaghova

School of Earth & Oceans, University of Western Australia

With research focused on ocean renewable energy - applying analytical, numerical and experimental techniques to solve challenging problems in the field of hydrodynamics, Jana's work advances fundamental understanding of wave-structure interactions, and contributes towards safer, more reliable and more economical offshore wind and wave energy systems.

A/Professor Alan Jordan

NESP Marine and Coastal Hub, University of Tasmania

Alan Jordan is currently the southern node leader of the Marine and Coastal Hub funding through the Australian Government's National Environmental Science Program (NESP). This program involves over 30 Australian research institutional partners and collaborators. He has over 30 years experience in the university and government sectors focused on seabed mapping, biodiversity surveys and environmental risk assessment. He is coordinating the offshore wind environmental research component within the Marine and Coastal Hub, and working with Australian government partners to improve data supply chains to inform environmental assessments.

Programme

WEDNESDAY, 10 SEPTEMBER 2025 | MORWELL INNOVATION CENTRE	
5:30 - 7:30 PM	**Welcome Reception**
THURSDAY, 11 SEPTEMBER 2025 | FEDERATION UNIVERSITY, CHURCHILL	
8:00 - 8:30 AM	**Registration**
8:00 - 8:30 AM	**Welcome to Symposium** | *Professor Andrew O'Loughlin, Federation University*
	Welcome to Country | *Gunaikurnai Land & Waters Aboriginal Corporation*
	Welcome | *Professor Duncan Bentley, Vice-Chancellor, Federation University*
	Opening | *Professor Mark Cassidy, Deputy Vice-Chancellor (Research), The University of Melbourne*
9:00 - 9:30 AM	**Opening Keynote** | **Speaker** | *Professor David M. Kennedy, School of Geography, Earth and Atmospheric Sciences, The University of Melbourne*
	Opening Keynote Session Chair | *Professor Daniel Ierodiaconou, School of Life & Environmental Science, Deakin University*
9:30 - 10:55 AM	**Session 1 | Marine Environment** **Session Chair** | *A/Professor Craig Sherman, School of Life & Environmental Science, Deakin University*
9:30 - 9:55 AM	**Keynote | Understanding the Effects of Energy Emissions from Offshore Wind Development on the Marine Environment** **Speaker** | *Dr Andrew Gill, Senior Research Scientist, Australian Institute of Marine Science*
9:55 - 10:05 AM	**Predicting Far-Field Underwater Noise Exposure from Large- Diameter Pile Driving in Calcarenite Seabeds Offshore Victoria** **Speaker** | *Claire Lazarides, Senior Maritime Engineer, AMOG Consulting*
10:05 - 10:15 AM	**Understanding the impact of offshore wind on seabirds and seals** **Speaker** | *Professor John Arnould, School of Life & Environmental Sciences, Deakin University*
10:15 - 10:25 AM	**Assessing cumulative impacts on priority species from new and existing maritime activities in Bass Strait** **Speaker** | *Dr Keith Hayes, Senior Research Scientist, CSIRO*
10:25 - 10:35 AM	**Safeguarding marine mammals in Australia's offshore wind future: building robust impact assessments and mitigation strategies** **Speaker** | *Tamara Al-Hashimi, Director – Marine Science, RPS*
10:35 - 10:45 AM	**Windfarms and fisheries in Australia: Learning from the United Kingdom to plan for the future** **Speaker** | *Dr Bryce Stewart, Senior Research Fellow, Marine Biological Association, UK*
10:45 - 10:55 AM	**RERI 14 & 33 Updates: Bass Strait Mapping & Benthic Characterisation Best Practice** **Speaker** | *Aero Leplastrier, Offshore Renewables Best Practice Lead, Geosciences Australia*
10:55 - 11:25 AM	**Morning Tea**
11:25 AM - 12:30 PM	**Session 2 | Logistics** **Session Chair** | *Ty Christopher, Director, Energy Futures Network University of Wollongong*
11:25 - 11:50 AM	**Keynote | Navigating supply chain challenges: Port strategies for Australia's offshore wind industry** **Speaker** | *A/Professor Peggy Chen, Centre for Maritime & Logistics*
11:50 AM - 12:00 PM	**Strategic Multi-Use Port Infrastructure: Enhancing Australia's Offshore Wind and Maritime Capabilities for a Sustainable Future** **Speaker** | Dr *David Wilson, Department of Infrastructure Engineering, The University of Melbourne*
12:00 - 12.10 PM	**Early project-life treatment of export and inter-array cable risks** **Speaker** | *Jack Jorgensen, Subsea Engineer, Aurora Offshore Engineering*
12:10 - 12:20 PM	**The Critical Role of Local Supply Chain Integration in Offshore Wind Planning: Tailoring the Sector to the Australian Context** **Speaker** | *Melira Lister, National Business Development Manager, Boom Logistics*
12:20 - 12:30 PM	**Establishing a Trusted Environmental Data and Information Supply Chain to support impact modelling of offshore renewable energy infrastructure.** **Speaker** | *A/Professor Rachel Przeslawski, Marine Ecologist, Institute for Marine & Antarctic Studies and Peter Walsh, Manager, Data & Information, Institute for Marine & Antarctic Studies*
12:30 - 1:30 PM	**Lunch**
1:30 - 2:25 PM	**Session 3 | Offshore Engineering** **Session Chair** | *A/Professor George Kouretzis, School of Engineering (Civil Engineering), University of Newcastle*
1:30 - 1:55 PM	**Keynote | Foundation concepts for offshore wind: geotechnical considerations** **Speaker** | *Avi Shonberg, Senior Lead Geotechnical Engineer, Ørsted*
1:55 - 2:05 PM	**Multiscale characterisation of Australian carbonate sediments** **Speaker** | *A/Professor Shiaohuey Chow, School of Infrastructure Engineering, University of Melbourne*
2:05 - 2:15 PM	**Optimising design and reducing risk for OWT foundations and anchors in Australian carbonate sediments** **Speaker** | *Professor Fraser Bransby, Fugro Chair in Geotechnics, University of Western Australia*
2:15 - 2:25 PM	**Discrete Element Modelling of granular seabed-structure interaction problems** **Speaker** | *A/Professor George Kouretzis, School of Engineering (Civil Engineering), University of Newcastle*
2:25 - 2:45 PM	**Afternoon Tea**
1:30 - 2:25 PM	**Session 4 | Metocean and Hydrodynamics** **Session Chair** | *Dr Guy McCauley, Oceans Institute, University of Western Australia*
2:45 - 3:10 PM	**Keynote | Australian wave climate and its implications on offshore wind structures - from monopiles to floaters** **Speaker** | *Dr Jana Orszaghova, School of Earth & Oceans, University of Western Australia*
3:10 - 3:20 PM	**Presentation | Assessment of Long-Term Trends and Variability of Wind Power Density off the Coast of Australia** **Speaker** | *Dr Rui Li, Department of Infrastructure Engineering, The University of Melbourne*
3:20 - 3:30 PM	**Overdesign in jacket substructures - Rethinking wave and current load assumptions for Australian offshore wind** **Speaker** | *Aidan Archer, Oceans Institute, University of Western Australia*
3:30 - 4:20 PM	**Session 5 | Panel Discussion** **Synthesis of Research and Development Needs to Enable Offshore Wind in Australia** **Moderator** | *A/Professor Alan Jordan, NESP Marine and Coastal Hub, University of Tasmania* **Panel Members** | *A/Professor Michelle Voyer, University of Wollongong; Mark Say, Director, Environment Regulation Division, DCCEEW; Dr Daniel Machado, Senior Manager Environment - Offshore Wind, Iberdrola Australia*
4:20 - 4:30 PM	**Closing** | *A/Professor Shiaohuey Chow, Director, ACOWE, The University of Melbourne*

Session 1: Marine Environment

Understanding the Effects of Energy Emissions from Offshore Wind Development on the Marine Environment

A. B. Gill[1], M. Parsons[1,2], Christine Erbe[2], D. McLean[1]

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[2]Centre for Marine Science and Technology, Curtin University, Perth, WA, Australia

Keywords: Environmental; pressures; assessments; integrated

1. INTRODUCTION

The large-scale development of offshore wind brings with it a number of distinctive changes to the marine environment (Gill 2005). Understanding the effects of these changes both to focal species and the wider ecosystem that the species are part of is a major global question associated with offshore wind development (Isaksson et al. 2024).

The harnessing of wind energy resources results in associated energy emissions in the form of sound/noise, electromagnetic fields, light, heat, radiation, and other pollutants. Using lessons learnt from over two decades of offshore wind and subsea power cable development in Europe, we show how energy emission pressures could be considered, within the context of assessing potential environmental impacts in Australia, to illustrate the important factors that have been identified and explore the limits to these factors.

The European experience has been focused on single pressure-single receptor considerations, and whilst these have their place, there have been calls and now moves towards more integrated, spatio-temporal and cumulative approaches (Degraer et al 2020; Gill et al 2020). We propose that the new development of offshore wind across Australian waters could learn from the European experiences with energy emission environmental effects and build upon them.

2. APPROACH

Energy emissions associated with offshore renewable energy development are grouped together within strategic marine policy in Europe to deliver on the requirements to achieve Good Environmental Status. We will introduce the range of Energy Emissions and the sources relating to offshore wind installation and operation that are required to be addressed, namely sound/noise, electromagnetic fields, light, heat and radiation. We will then highlight the single pressure-receptor approach using underwater noise (e.g., Figure 1) and electromagnetic fields as the main examples, primarily because these have been the focus of attention and also the patchy nature of evidence-based knowledge for other energy emissions.

For noise, we will detail underwater sources and receptor groups and set out the rationale currently used to assess potential environmental impacts. The focus is on the effect on sensitive marine mammal receptors of sound pressure during the construction phase of offshore wind development that can extend over many kilometres. The cause-effect pathways are relatively well defined (Figure 1), but determining the impact that is of biological significance requires knowledge of a number of factors. These include the prediction of instantaneous and cumulative sound exposure levels (over a frequency band that the receptor is sensitive to) that an animal will experience as it moves through the area, along with the likely behavioural context at the time of exposure. It also requires having previously identified the species hearing thresholds (or having developed a reliable acoustic weighting function) within that frequency band, and in the case of communication masking, the source levels of the sounds that the animal uses to communicate with conspecifics. We highlight the key data and evidence requirements that are needed in the determination of impact significance.

The focus on marine mammals is a result of statutory requirements, but there is also a need to assess impacts on other species with different hearing modes. Most of the teleost, elasmobranch, and invertebrate species respond to particle motion in the water column or vibration in the seabed rather than the sound pressure in the water column that marine mammals respond to, and knowledge is much scarcer for these species' groups. The large number of conservation designated species in Australian waters and the importance of noise effects on fisheries species requires knowledge on both sound pressure and particle motion to enable confident assessment of the environmental impact; we provide some thoughts on how this evidence need should be approached.

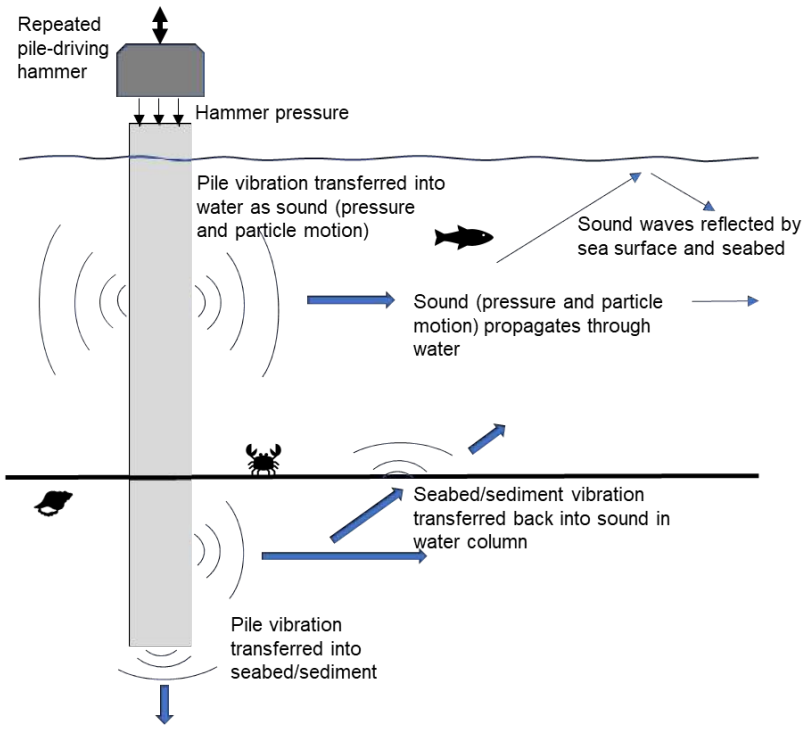

Figure 1: Summary of sound sources during offshore wind turbine installation, highlighting the various sources and pathways of sound propagation within the marine environment ©ABGill

For electromagnetic fields (EMFs), the knowledge base is less comprehensive than for noise, however, recent studies have provided sufficient direction to consideration of potential impacts (Hutchison et al. 2020). There are two main considerations, the first is that some species groups are adapted to detect and use the widely occurring natural magnetic or electric fields or both and although the sensory modes are still debated, studies have shown that some species respond to anthropogenic sources of EMF, such as subsea power transmission cables. The second is that exposure to EMFs over periods of time is implicated in affecting early life stages, such as developing embryos in eggs, leading to physiological and biochemical changes – regardless of whether the species is receptive to electric or magnetic fields. Most of the evidence is experiment-based and a critical aspect of assessing any environmental impact is the probability that the receptor of interest encounters the EMFs in the environment as EMFs propagate up to 10s of metres, much shorter distances than sound. We will present results from a recent study that we conducted that shows that subsea power cable EMFs extend further than current models predict.

Whether noise, EMF, one of the other energy emissions or a combination of emissions, it is important to consider the perspective of the animal encountering the changed environment. Predicting the probability of exposure and the level or duration that is experienced by an animal, from one or more emissions, requires knowledge of species distribution for different life-stages. We show an example an integrated approach for exposure to EMF, which takes the perspective of the receptor animal and at

the same time determines the parameters of the energy emission source that affect the intensity, frequency, duration and extent of the environmental pressure (Figure 2).

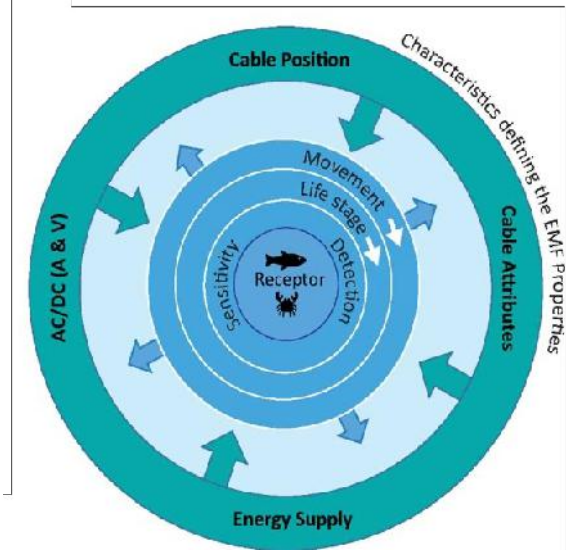

Figure 2 Taking the perspective of the receptor. The sensory capabilities and detection thresholds are at the core of receptor species attributes and must be considered through the integration of life history ecology. Simultaneously, EMF source characteristics must be known so that exposure levels can be determined and the likely encounter rate and potential consequences of exposure. A = Current (amps), V = Voltage (volts). Adapted from Hutchison et al., 2020, Oceanography [1].

3. CONCLUSION

The integrated animal-centric approach we promote lends itself to application for each energy emission and has the potential to enable assessments to look at pressures together and cumulatively therefore moving away from the single pressure-receptor approach that currently predominates.

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Safeguarding marine mammals in Australia's offshore wind future: building robust impact assessments and mitigation strategies

T. Al-Hashimi[1]

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Keywords: marine mammals, underwater noise, risk-based mitigation, adaptive management, lessons learned

1. INTRODUCTION

Australia's offshore wind sector is entering a critical growth phase, with multiple projects proposed within Gippsland Declared Area. While this transition supports national decarbonization goals, it also introduces potential risks to marine mammals, particularly large baleen whale species such as the southern right whale (*Eubalaena australis*) and blue whale (*Balaenoptera musculus*). These species are subject to Recovery and Conservation Management Plans that impose specific requirements which must be considered in project planning and execution to ensure consistency with management plan requirements.

A key challenge for developers and regulators is the current lack of robust baseline data needed to assess and manage the impacts of underwater noise on these species. This data is essential for informed regulatory decision-making, accurate environmental impact assessments, and the development of effective, proportionate mitigation strategies that support sustainable development.

2. Key Impacts and Mitigation Needs

The primary area of impact to marine mammals from offshore wind development is from underwater noise from pile driving during construction, and vessel noise throughout all project phases (construction, operation and decommissioning). Understanding species-specific presence, behaviours (i.e. how they use the area e.g. feeding, calving, migration), and seasonal patterns enables developers to implement targeted, risk-based mitigation strategies that avoid or minimise ecological impacts whilst enabling long-term industry viability. Consequently, a reliable, robust and accurate means of predicting and assessing the environmental effects of noise is needed whilst providing an iterative process for engineering teams in developing an optimum design for the foundation construction.

3. International lessons and Australian context

Some key lessons learnt from international projects include the importance of defining the spatial extent of potential impacts to guide baseline data collection, assessment of impacts in a population-level context to determine biological significance, monitoring programs during construction to evaluate disturbance and avoidance, and leveraging learnings from other industries to enhance assessments and mitigation effectiveness, for example effectiveness of monitoring technologies (e.g. infra-red cameras, unaccompanied automatic vehicles (UAVs)) for whales.

International projects, such as Vineyard Wind in the U.S. Atlantic, have demonstrated the value of real-time acoustic and aerial monitoring to support dynamic mitigation protocols. In Australia, areas identified as biologically important for pygmy blue whales include the Bonney Upwelling and all waters eastwards off the Victorian coast and in the Gippsland Declared Area. For southern right whales, the coastal reproduction corridor is identified as habitat critical for the survival of the species and all offshore waters off Victoria are important for migration. Strategically designed baseline studies are key

to collecting appropriate data to inform assessments and development of biologically meaningful mitigation zones and timing windows.

4. CONCLUSIONS

The assessment and mitigation of underwater noise impacts from offshore wind development on marine mammals are critical to ensuring regulatory compliance and ensuring consistency with recovery and conservation management plan objectives. Early investment in high-resolution baseline data enables developers to develop robust and defensible impact assessments. Ultimately, a science-driven approach to underwater noise impact assessment not only safeguards marine mammal populations but also streamlines environmental approvals and enhances the social license of Australia's offshore wind industry.

Assessing cumulative impacts on priority species from new and existing maritime activities in Bass Strait

K. R. Hayes[1*], E. A. Fulton[1], C. Erbe[2], C. Langlais[1], C. Tollefsen[2], D. Peel[1], E. Wilson-Mayne[3], G. R. Hosack[1], J. P. Garate[1], J. Myers[1], J. Williams[3], L. R. Lloyd-Jones[4], M. Mongin[1], M. El-Hachem[1], M. Parsons[5], M. X. Lacharité[3], N. J. Beeton[1], P. K. Dunstan[1], R. Treblico[1], S. Nicol[4], S. N. C. Woolley[1], T. A. Paterson[1], W-H. Yang[1], A. Jordan[3]

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Keywords: risk assessment, cumulative risk, offshore wind, Bass Strait

1. INTRODUCTION

In considering the environmental acceptability of wind energy projects, the Department of Climate Change, Energy, the Environment and Water (DCCEEW) will assess potential risks to (among other things) the recovery of populations listed under the Environment Protection and Biodiversity Conservation Act (EPBC Act 1999).

The assessment process will consider cumulative environmental impacts at a regional or even ocean basin-scale, in addition to environmental factors specific to wind energy projects. Additionally, the National Offshore Petroleum Safety and Environment Authority (NOPSEMA) has identified the need for improved understanding on species, processes and industry activities to support impact and risk assessment.

This presentation will summarize the approach and progress to date of the National Environmental Science Program Project 4.7: Development of regional modelling and risk assessments to inform offshore renewable decision-making.

2. APPROACH

NESP Project 4.7 is developing a quantitative cumulative risk assessment framework based on whole-of-ecosystem modelling and individual species modelling to estimate the impacts and risks to priority species following the installation of offshore wind infrastructure in Declared Area OEI-04-2024 (Bass Strait off Northern Tasmania) and Declared Area OEI-01-2022 (Gippsland). The risk assessment structure, approach and methods have been designed to address each of the impact pathways defined by DCCEEW [1].

2.1 Whole of ecosystem modelling

Some of the impact pathways identified by DCCEEW are best addressed through a whole-of-ecosystem approach to exposure/effects assessment. This includes the physical effects of wind farms on hydrodynamics and sediment transport (seabed disturbance and loss of/harm to benthic habitats) and the multiple pathways leading to possible impacts on Australian Marine Parks.

The project is developing new regional-scale hydrodynamic and biogeochemical models to predict how climate change and offshore wind farms will influence the oceanographic and biogeochemical properties of the GDA out to 2040, and to help parameterise the physical components of Atlantis [2] and Ecopath with EcoSim [3] models that will be used to predict for example: (i) the potential effects of displacing other commercial fishing activities; and, (ii) the trophic effects that may occur due to the attraction of fish and other fauna to offshore infrastructure.

2.2 Direct impact modelling

The project will develop population models for key threatened and migratory species, building where possible on existing models, to estimate population level effects of exposure to offshore wind impact pathways. The exposure assessments will predict animal movements through the proposed GDA license areas, and the potential for encounters and behavioral changes that present a risk to individuals.

The exposure assessments will examine potential impact pathways such as: (i) collisions between turbines and birds (or between vessels and marine fauna): (ii) the effects of underwater noise and electro-magnetic fields: and (iii) the displacement or attraction of animals due to noise, light or the physical presence of new infrastructure.

2.3 Cumulative risk

To assess cumulative risk the project will define a limited number of plausible "development scenarios" that describe the possible distribution of existing maritime activities and new renewable electricity generation infrastructure, both onshore and offshore, within the model domain of each priority species. Under these development scenarios the project aims to quantify the expected change in the mortality or morbidity endpoints attributable to new and existing maritime stressors, under a range of plausible climate change projections, and thereby enable managers to assess what additional mortality might be attributable to offshore wind infrastructure in the GDA.

ACKNOWLEDGEMENTS

This project is being undertaken for the Marine and Coastal Hub, a collaborative partnership supported through funding from the Australian Government's National Environmental Science Program (NESP).

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Predicting Far-Field Underwater Noise Exposure from Large-Diameter Pile Driving in Calcarenite Seabeds Offshore Victoria

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Keywords: Acoustics; Underwater Noise; Pile Driving; Marine Impact; Offshore Wind Farm

1. INTRODUCTION

The construction of offshore wind farms using large-diameter monopiles generates high-intensity impulsive noise from hammer strikes, with peak sound pressure levels exceeding 200 dB re 1 µPa [1]. Unlike continuous noise sources, such as vessels, which produce noise near or at the surface, predicting underwater sound from pile driving requires hybrid acoustic modelling approaches to account for complex interactions between the driven section beneath the seabed and the rest of the environment. Compounding the complexity, much of the Australian continental shelf, including offshore Victoria, consists of calcarenite seabeds, which require additional modelling capability to predict their higher dissipative effects on underwater noise compared to typical sandy seabeds [2].

2. BACKGROUND

The modelling of sound propagation has been an established discipline for decades, however there remains several modelling approaches that have been developed, each with differing suitability according to acoustic frequency range, water depth, seabed properties, computational requirements and ability to account for spatial variability in the environment. Sound propagation modelling includes the ability to model spreading, attenuation loss, refraction, reflection and understand their associated influencing parameters.

Fixed offshore wind turbines are usually attached to a monopile or jacket structure when installed in shallow water of < 40 m [3]. The noise for driving piles into the seabed is generated through impulsive strikes of the pile with a hammer. Noise transmission in water depths < 200 m (defined broadly [4]), is greatly increased due to the proximity of the seabed to the ocean surface. The ocean surface effectively reflects the noise source, resulting in cylindrical spreading in shallow water, which has reduced transmission loss compared to spherical loss in deep water applications [2]. Broadly, with all environmental parameters constant, spherical spreading results in a loss of 60 dB/km, while cylindrical spreading is 30 dB/km.

There is a big push for larger wind turbines with capacities at or exceeding 15 MW to be used in wind farms. These large turbines require large monopiles with diameters approaching 10 m [3], and the largest known pile diameter in use for a fixed offshore wind turbine is the 9.5 m “XXL monopile” at Parkwind’s Arcadis Ost 1 wind farm [5]. Impulsive pile driving operations are typically louder than noise associated with vessel and marine operations, and the large-diameter piles will emit larger SPLs (Sound Pressure Level) and LPeaks (Peak Sound Pressure Level) due to the installation of these large piles [1]. Furthermore, a pile being driven into the ocean floor may need to be struck as much as 2000 times for full installation with instantaneous SPLs exceeding 200 dB re 1 µPa [1] and thus can have a substantial impact on the resultant Sound Exposure Level (SEL) which factors in the duration of exposure. Considering the above is combined with the shallow water depths required for fixed-bottom wind turbines, the noise produced from the installation of these monopiles will be quite significant.

Marine life will be greatly affected by these operations as they mostly have auditory injury (AUD INJ) impulsive SEL weighted thresholds < 190 dB re 1 μPa^2s as defined in the latest US industry guidelines [6]. It is very likely that the noise due to pile driving can exceed this limit kilometres away from the source, depending on the bathymetry at the site [3]. For an accurate prediction of noise transmission, accurate modelling of the noise source, bathymetry, sea sound-speed profile and seabed properties is required.

3. CALCARENITE SEABEDS

The Australian continental shelf, particularly the southern section, is generally a calcarenite substrate [2]. Methods to specifically model underwater sound accurately over the calcarenite seabeds of Australia have been reported in the literature since late 2008, and reports on underwater sound measurement are also available, offering means for validation. Calcarenite (hard) seabeds absorb more sound than sandy bottoms which would appear contradictory at first. The reason is that calcarenite seabeds absorb and propagate both compressive and shear acoustic waves, whereas a sandy-type substrate which doesn't have shear strength cannot propagate shear acoustic waves. It is the propagation and *absorption* of energy in propagating the shear waves that generally results in greater sound loss over calcarenite seabeds than sandy seabeds over a range of frequencies. Without accounting for the absorption, underwater sound predictions will generally overestimate the noise levels, making for unnecessarily large marine observation regions around the noise sources.

4. APPROACH

Noise modelling approaches for pile installation operations already exist, but these are either limited to the noise immediately in the vicinity of the pile (within 50 m), or measured noise taken from hundreds of metres away from the source [2]. It is important for large scale modelling of pile operations to correctly model the far-field transmission, of the order of kilometres, of piles [11].

Underwater noise from pile driving operations can be characterised using either near-field impact modelling or hydrophone measurements. Near-field modelling relies on numerical methods—primarily finite element (FEM) or finite difference (FD) approaches—to simulate the vibro-acoustic interaction between the pile, seabed, and surrounding water. These models resolve the pressure wavefield within approximately 50 m of the pile and can capture critical dynamics such as seabed elasticity and secondary wave propagation, as discussed by Tsouvalas et al. [3].

Pile driving generates impulsive noise with transient, decaying waveforms that vary over time and with pile embedment depth. This results in the generation of a time-decaying sound wave which will have a peak noise level, as shown in Figure 1 from [7]. The noise produced by a pile strike will change depending on the embedded depth of the pile in the seabed.

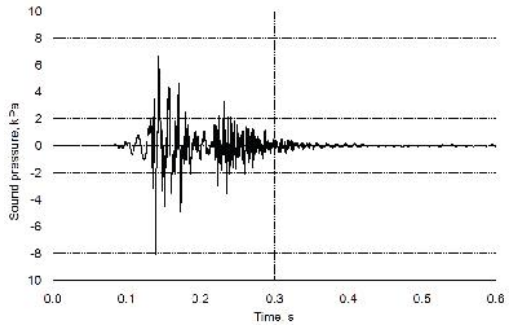

Figure 1 Underwater noise impulse caused by an impact pile driver. Distance = 700 m, pile diameter = 4 m, blow energy = 850 kJ [7]

For regulatory compliance and conservative impact assessments, the peak strike noise is often used as a representative source level. Acoustic energy from pile strikes spans a wide frequency band, typically from 1 Hz to 100 kHz, but for offshore wind turbine applications, most relevant energy is concentrated between 1 Hz and 50 kHz [3]. This necessitates the use of hybrid noise propagation models that can accurately simulate broadband transmission across shallow water environments.

To address this, multiple noise modelling tools (e.g., parabolic equation (PE), Normal mode, wavenumber integration (WNI) and ray tracing) can be used in combination, each suited to different frequency regimes, propagation distances and ability to model varying properties with distance ('range dependent'). The presence of limestone (calcarenite) layers in Australian seabeds must be considered when selecting the appropriate acoustic models. For example, the WNI model SCOOTER, is typically considered the benchmark model for noise modelling of elastic seabeds, however is a range-independent model and can therefore only be used for underwater noise propagation over flat seabeds. To accurately predict the underwater noise from the installation of Australian offshore wind farm infrastructure, model selection should be done carefully, and benchmarking studies such as [2] should be performed. Site-specific measurements of the underwater noise levels produced by a characterised noise source would also be valuable for benchmarking studies and validation of acoustic model predictions. This hybrid modelling approach enables prediction of both near-field and far-field acoustic behaviour, facilitating accurate estimations of cumulative noise exposure at ecologically sensitive ranges.

5. DISCUSSION

This extended abstract reviewed the modelling and measurement of underwater noise generated by offshore pile driving, with a focus on its environmental implications and the importance of accurate prediction. Pile driving produces impulsive, high-intensity broadband noise that can propagate over large distances, particularly in shallow water. The noise spectrum of a pile strike can be obtained through near-field vibroacoustic modelling or hydrophone measurements, both of which are sensitive to variables such as pile diameter, strike energy, and ram mass. Hybrid sound propagation loss prediction models are essential to capture far-field acoustic effects and verifying compliance with regulatory thresholds, while near-field models must account for local seabed and bathymetric features to improve accuracy.

Seabed characteristics - especially elasticity and layering - play a significant role in sound transmission close to the pile. The most accurate predictions are likely to be realized by using a hybrid near and far field modelling approach with the models including the capability to represent the dissipative effects of noise propagating as shear waves in calcarenite seabeds.

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Biofouling in a coastal aquaculture setting

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Keywords: Mussel; percent cover; temporal; multivariate; Jervis Bay

1. INTRODUCTION

Biofouling, defined as the "unwanted" growth of organisms that attach to artificial hard surfaces that are immersed for substantial time in typically marine waters, poses problems for underwater infrastructure, including those for aquaculture of farmed fish and invertebrates (Fitridge et al., 2012), vessels and port facilities, and potentially offshore wind farms (MacLeod et al., 2016). These problems can be physical, such as extra weight and thus underwater drag leading to equipment loss/failure, and which can require further processes or treatment to minimise such biofouling. In terms of ecological functioning of coastal marine systems, such biofouling assemblages can (1) enable potentially invasive species to establish new populations (ref), (2) act as artificial reefs that can attract other fishes, potentially recreational fishers and other larger predators (ref) and (3) loss of organisms to the seafloor can alter benthic ecosystem function (Fitridge et al., 2012; MacLeod et al., 2016).

The type and extent of biofouling is difficult to predict in any given environment, as the processes governing the arrival of organisms as larval forms prior to settlement are complex, and there is scant knowledge on such assemblages, their taxa nor their life cycles. However, biofouling can pose significant economic duress to any operators of underwater infrastructure, through modification of processes/adoption of new processes and equipment loss and there is therefore a need to understand its potential prior to their deployment.

This study aims to describe the biofouling assemblages on aquacultured blue mussels which are close to harvest size and have therefore been submerged for 9-12 months in the coastal marine waters of the east coast of Australia. The main taxa will be identified and analyses used to determine whether their percent cover on the mussel shell differs with water depth and/or time of year. Assessments will also be made as to whether biofouling affects the final condition of aquacultured mussels.

2. METHODS

Samples of approximately 30 blue mussels were obtained from two water depths (2 and 4 m) from suspended longlines in waters of 10-14 m depth at the Callala mussel lease operated by South Coast Mariculture in Jervis Bay (35.0481° S, 150.7447° E). Sampling occurred at six-weekly intervals from September 2021 to January 2023. For each mussel, biofouling taxa were identified, their percent cover estimated, and total percent cover for all taxa determined. The mussel condition index (Davenport and Chen, 1987) was used to determine this index, representing a measure of market quality.

Total percent cover was subjected to two-way ANOVA, testing for differences with time and water depth. Percent cover of different biofouling taxa were square-root transformed and analysed by multivariate approaches, using the Bray-Curtis measure to create a similarity

matrix. This matrix was analysed for differences with time and water depth using a permutational ANOVA and patterns visualised using nMDS scaling ordinations of centroids.

3. RESULTS & DISCUSSION

Thirty seven biofouling taxa were identified, with the most prevalent being a filamentous red algae *Polysiphonia* sp., the large branching hydroid *Solanderia fusca*, and juveniles of the cultured blue mussel *Mytilus galloprovincialis*, with two barnacle species making moderate contributions. One of those barnacle species, *Megabalanus* sp., possibly represents an introduced species. Although these taxa can all be removed from harvested mussel shells by physical means post-harvest, the added weight while *in situ* contributes to stock loss and potentially damage/loss to suspended infrastructure.

Total percent cover of biofouling taxa for different times (6-weekly intervals) and water depths (2 and 4 m) reflected the accumulation of those taxa that settled and grew in the prior 9-12 months. Two-way ANOVA of total percent cover found a significant difference with time ($F=12.104$, $P<0.001$) but not water depth ($F=1.60$, $P=0.207$), and there was an interaction between time and depth ($F=2.50$, $P=0.04$). When examining time overall, total percent cover was low (<10%) in Time 1, 7 and 10, but essentially tripled (25-30%) in Times 3, 6 and 11. The interaction showed that this pattern varied slightly with water depths, e.g. in Time 4, percent cover at 4 m (13%) was less than half that at 2 m (28%), while for the next time, this pattern was reversed but to a lesser extent. The considerable variability in this coarse measure of biofouling during both the study period and with water depth highlights the lack of consistently-detected patterns in biofouling. This variabilility presumably reflects temporal differences in the supply of settling larvae and any other resource limitations.

Calculations of mussel condition index revealed no consistent relationship with total percent cover, implying that the biofouling percent cover (5-30%) had no apparent effect on mussel marketability during the study period (September 2021 – January 2023).

Multivariate analysis, using a similarity matrix based on the percent cover of the various biofouling taxa showed that the difference between Time was greatest (Pseudo-F=33.9), followed by Water depth (Pseudo-F=11.1) and the interaction (Pseudo-F=4.6), with all being highly significantly different ($P=0.001$). Focussing on differences with time, nMDS ordination showed differences among those centroids, with that for Time 7 to the far right, those for Times 4 and 6 to the upper left, those for Times 11 and 12 in a tight group in the top middle, and the other times forming a loose group in the lower left part of the plot. Overlaying of the percent cover of three key taxa showed that two were present throughout the study, e.g. *Polysiphonia* sp. and *S. fusca,* but were least in the most distinct time (Time 7), while that of another algae (*Cystophora* sp.) was greatest in that period (Figure 1a,b,d). The blue mussel showed relatively high percent cover in Times 4,6, 11 and 12, but were low at other times (Figure 1c). These patterns, which differ among these four taxa, indicate different periods of settlement and/or potential success thereafter and point to complexity in the potential biofouling assemblage.

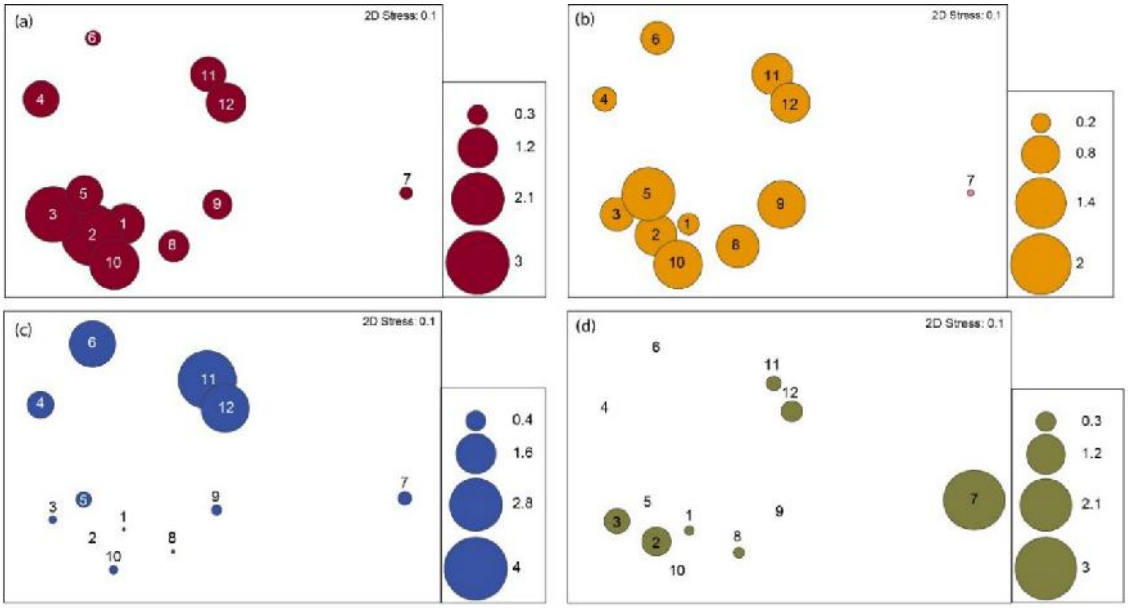

Figure 1. Bubble plots of percent cover for four taxa with Time coded sequentially from 1-12, representing Sept 2021 to Jan 2023 for (a) Polysiphonia *sp., (b)* Solanderia fusca*, (c)* Mytilus galloprovincialis *and (d)* Cystophora *sp. (Legend for size of bubbles is show on the right).*

4. CONCLUSION

Although this study describes biofouling patterns on the shells of aquacultured mussels, it is clear that extrapolations of both the approaches and research outputs can be made to any submerged infrastructure, including offshore wind farms and other aquaculture settings. Results demonstrate considerable variability in the extent and characteristics of the biofouling assemblage during this 16-month study, and which differs to that within a further mussel farm within another marine embayment in Australia. The biofouling assemblages are also well characterised, such that introduced species can be readily detected, noting that one species (*Megabalanus* sp.) may already represent such an introduction.

There is clearly a potential for these biofouling assemblages to contain fauna that can attract other fish predators and thus affect ecosystem function. Although the extent of cover (5-30%) did not apparently affect mussel condition, this may not hold true under increased biofouling scenarios arising from natural variability or other local environmental stressors.

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Windfarms and fisheries in Australia: Learning from the United Kingdom to plan for the future

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Keywords: Offshore wind farms; Fisheries; Conservation; Marine Spatial Planning; Conflict resolution

1. INTRODUCTION

Offshore wind (OSW) is seen as one of the key ways to meet a growing global demand for renewable energy. OSW has been in place for decades in several countries where it continues to grow, while in others such as Australia it is only just emerging. The benefits of OSW for generating green energy are obvious, but the placement of large amounts of OSW infrastructure into previously undeveloped marine environments can create spatial challenges for existing users. Like all resource use challenges, limited planning and/or opportunity for stakeholder engagement can make matters worse. One of the key stakeholder groups potentially challenged by the rapid growth of OSW is the commercial fishing industry (Szostek et al., 2025). This is particularly the case for fisheries towing trawl nets or dredges, which are often banned or impractical to operate within OSW farm arrays.

In the United Kingdom (UK), the first OSW farm was given permission in 2001 and completed at the end of 2003. Wind electricity has increased over 700% in the UK in the last 10 years, and OSW now provides 15.9GW, capable of powering 52% of UK households. This constitutes 41% of all OSW capacity within European waters. The UK has a legally binding target of Net Zero by 2050 and hence has highly ambitious plans for further growth. In July 2024, the new government set a target for OSW to provide 60GW of operational capacity by 2030, almost four times current levels (Wind Europe, 2024). There is also an ‘ambitious but achievable goal’ for floating wind to provide 5GW of this capacity. However, against this backdrop of growth in OSW are grave concerns from the UK fishing industry. Indeed, one recent analysis concluded that by 2050 up to 49% of the UK seabed could be off limit to bottom towed fishing gear due to growth in both OSW and Marine Protected Areas. This is colloquially known as ‘spatial squeeze’ (ABPmer 2022).

Given the 25-year history of OSW development in the UK compared to the emerging state in Australia, this study aimed to use the UK experience to inform the development of OSW in Australia, particularly with respect to reducing conflicts between OSW and fisheries.

2. APPROACH

Using a combination of existing literature and interviews with key stakeholders in UK, we examined how OSW development has affected fisheries and other sea users to date and their recommendations for OSW in Australia. This included exploring how development might be done differently in the future, and whether there are opportunities for the co-location of wind farms with the interests of other sectors (e.g. fisheries, conservation, and aquaculture). We also explored the needs, concerns and perceived knowledge gaps of stakeholders and managers in Australia through a workshop and meetings focused on the planned OWF development and to contextualize these with the UK experience.

Twelve interviews were conducted in the UK during January and February 2023. Participants included representatives from the commercial fishing industry (3), academics (2), environmental consultants (3), environmental groups (2), offshore wind energy companies (1), and a government regulator (1). Key questions are listed below. These were designed to both evaluate the UK experience, and to guide the future development of OSW in Australia.

- Briefly describe your involvement with or interest in windfarm development
- Has the development of wind farms to date adequately accommodated the needs of your sector?
- If the process of wind farm development started again from scratch, would you like to see things done differently?
- Do you see opportunities for the co-location of wind farms with the interests of other sectors (e.g. fisheries, conservation, aquaculture)?

The Australian workshop was run online in March 2023. Attendees included key fisheries stakeholders, managers and funders (AFMA, SE Trawl Fishermen's Association, Seafood Industry Australia, Southern Rock Lobster Ltd, and FRDC). We also held a meeting with a key OSW company involved in projects in Australia. After a presentation on the results of the UK interviews, attendees at the Australian workshop were asked for their views about two key elements:

- Their perceptions of the interactions between OSW and fisheries and how concerned they are about them.
- What key knowledge gaps exist with respect to managing interactions between OSW and fisheries in Australia.

3. RESULTS

None of the respondents in the UK interviews said that OSW development had adequately accommodated the needs of their sector to date (apart from the energy company representative). However, of particular relevance to the Australian situation, they all provided ideas for how OSW development could have been done differently and identified opportunities for co-location of OSW with the interests of other sectors.

The following points provide a summary of the main findings:

- Government/planning policy to date in the UK appears to have given priority to OSW development over fisheries and other sea users which has led to numerous challenges and conflicts
- Fisheries and OSW have different attitudes to the seabed and marine management which had led to different priorities and conflict
- A lack of data / evidence has been available to establish the level of impact of OSW on the fishing industry. This has included impact on individual species and on the economic viability of current fishing boats and gear.
- A lack of evidence on impact (inc. baseline ecological data and economic viability) has resulted in:
  - A lack of confidence and trust of the fishing industry in OSW
  - Problematic decision making that has had negative impacts on the fishing industry
- The speed of OSW development has led to both challenges and opportunities including greater collaboration between stakeholders and greater impetus to find solutions
- Whilst early intervention presents opportunities for spatial planning to separate OSW from fishing grounds, enabling co-location is likely to become essential in the longer term
- Moving energy offshore has proved costly both financially and environmentally because of the busy nature of the coastal fringe
- Offshore floating windfarms present different challenges because of the additional pressures posed by the mooring technology used which necessitates larger no fishing areas around them.
- Compensation programs to date have been contested as both 'greenwashing' and not representative of true financial costs
- Examples exist of successful co-location where fishing has been able to continue within OSW sites

- Timing is everything – there needs to be a much longer design period to allow for meaningful co-development rather than one industry being favored while the others just accommodated.
- Planning for the 'end-of-life' of OSW infrastructure needs to integrated into planning from the start.

Participants in the Australian workshop demonstrated a high degree of awareness of the potential conflicts between OSW and fisheries, but were also relatively positive that these could be minimised if careful planning was adopted from an early stage (Figure 1). Ten key knowledge gaps were also identified by participants including; how to set up a consultative process that equitably addresses the needs of all relevant stakeholders, how the impacts of OSW on the marine environment combined with other potential stressors such as oil and gas and aquaculture, and how much the design of OSW infrastructure can be adapted to meet the needs of fisheries.

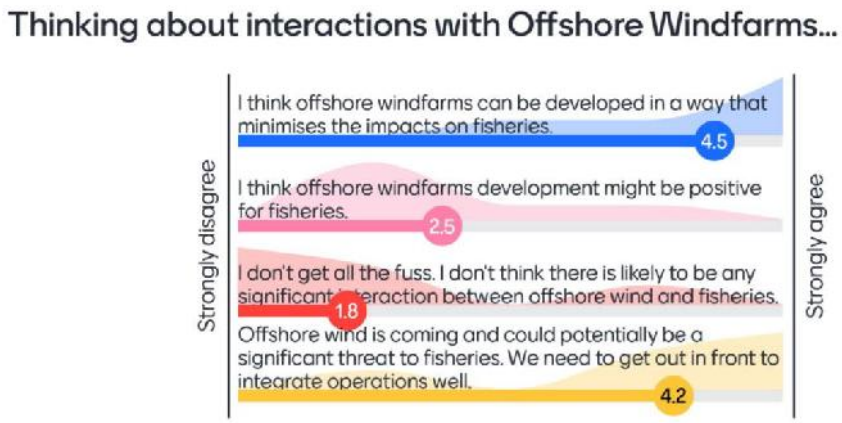

Figure 1.Mentimeter results from the workshop with Australian stakeholders held in March 2023.

4. CONCLUSIONS

The UK experience has provided a wealth of information about how Australia could develop OSW in a way that helps mitigate effects on the commercial fishing industry and potentially enhances their needs. However, setting up the structures and processes necessary for that to happen needs to be done at the earliest possible opportunity. We encourage more dialogue between the OSW sector and the commercial fishing industry (and other relevant stakeholders) in Australia with their counterparts in other countries with a longer history of OSW development. If done well, Australia has the potential to develop an OSW wind sector that provides a global model of best practice for stakeholder engagement and accommodation that informs other countries as they increasingly turn to offshore wind in their journey towards a low carbon future.

ACKNOWLEDGEMENTS

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Environmental Impact Across Life Cycle Stages of Offshore Wind Farms - A Systematic Review

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Keywords: Environment Impacts; Offshore Wind; Renewable Energy; Review

1. INTRODUCTION

Offshore wind farms (OWFs) have emerged as a key technology towards the global renewable energy transition, offering significant potential for mitigating climate change and reducing dependence on fossil fuels (Rezaei et al., 2023). The rapid expansion of OWFs, driven by the need for clean energy, has been accompanied by growing concerns about their environmental impacts at different stages of their life cycle (Ouro et al., 2024). While OWFs are considered as clean energy source, their development and operation raise various environmental issues, including habitat disruption, emissions from production, and risks to marine ecosystems (Amponsah et al., 2014; Kouloumpis & Azapagic, 2021). Previous studies have highlighted that the environmental footprint of OWFs varies significantly across different life cycle stages, including material extraction, manufacturing, construction, operation, maintenance, and decommissioning (Pena et al., 2023). Understanding the full scope of these impacts is crucial for optimizing OWF designs, improving sustainability practices, and guiding informed policy decisions (Rezaei et al., 2023). Despite their promise to reduce greenhouse gas emissions, there is a lack of comprehensive studies that systematically evaluate the environmental impacts across these stages, thus highlighting the need for a review (Ouro et al., 2024). By synthesizing findings from existing research, there is a thriving need to analysis the environmental impacts of OWFs. This review provides an in-depth analysis of the environmental impacts of offshore wind farms across their life cycle, focusing on the key stages from material extraction to decommissioning. By collating data from literature, this review aims to investigate the environmental impacts of OWFs across life cycle stages.

2. METHODOLOGY

A systematic review of studies is adopted in this Research to determine what environmental impacts have been identified for OWFs. This systematic review involved an extensive analysis of peer-reviewed articles from the Scopus database. Initially, this study screened 4,075 papers on offshore wind energy, narrowing them down to 2321 by limiting the selection to articles and reviews published between 2010 and 2025, and written in English. By identifying the importance of the environmental impacts of OWFs, further screening based on titles and abstracts reduced the number of papers to 199. PRISMA was identified as the most appropriate methodology to investigate specific areas of interest. A systematic review, following PRISMA guidelines, involves a thorough and structured process of collecting all relevant data based on predefined eligibility criteria (Sohrabi et al., 2021). Manual content analysis was used to analyze the data.

3. RESULTS AND DISCUSSION

The systematic review encompasses articles from a diverse range of countries, with the United Kingdom contributing the highest number of studies (68), followed by the United States (29), Spain (19), and France (17). In addition, notable contributions include those from Germany, Italy, and the Netherlands, each with 15 studies, while China and Norway have 14 and 13 studies, respectively. Australia has also represented with around 9 studies. This geographic distribution highlights the global interest and research efforts focused on offshore wind farms, with Europe and North America leading the field, but with growing contributions from Asia and other regions.

Offshore wind energy is a fast-growing industry; long-term effects on the marine environment are unknown (Kirchgeorg et al., 2018). Understanding this environmental impact is essential for making strategies to minimise the impact. However, Chen et al. (2018) listed visual impact, activities during construction, decommissioning, and ecological impacts under the term "common environment impacts". In addition to ecological effects, studies have identified that visual intrusion, noise pollution, and other human-centred concerns are often included under environmental impacts, highlighting the social dimension of offshore wind development. Ouro et al. (2024) argued that the environmental impacts of OWFs can be broadly categorized into atmospheric, hydrodynamic, and ecological effects. Alternatively, Moussavi et al. (2023) employed Life Cycle Assessment (LCA) to quantify the environmental impacts associated with OWFs and categorize them into LCA impacts and ecological impacts. Therefore, to provide a comprehensive assessment, this review specifically focuses on the environmental impacts of OWFs, encompassing ecological, atmospheric, and hydrodynamic effects, while limiting the scope of life cycle stages to construction through to decommissioning.

The construction phase introduces habitat disruption, marine pollution, and noise disturbance as key environmental impacts. The installation process can disturb marine habitats, particularly benthic environments, and generate considerable noise, both underwater and above water, which impacts marine life, including species reliant on sound for navigation (Ouro et al., 2024; Pena et al., 2023). Some authors argue that habitat destruction is one of the most significant short-term environmental impacts during this phase, highlighting the need for more effective mitigation measures (Rezaei et al., 2023). During the operation and maintenance phases, offshore wind farms have a relatively low carbon footprint but still present risks to marine life, particularly in terms of collision with turbine blades, underwater noise, and electromagnetic disturbances (Pena et al., 2023). The operation of turbines creates underwater noise pollution, which can disrupt the behaviour and migration patterns of marine animals, especially marine mammals and fish species (Kim et al., 2025). Additionally, electromagnetic fields generated by the turbines and cables can interfere with the natural behaviour of marine organisms (Ouro et al., 2024).

Decommissioning involves dismantling and removing turbines and other infrastructure, leading to waste disposal issues and environmental disturbance if not properly managed (Rezaei et al., 2023). Studies highlight the need for eco-friendly disposal methods and efficient recycling processes to minimize the environmental footprint during this phase (Ouro et al., 2024). Sustainable practices, such as reusing materials and restoring marine ecosystems post-decommissioning, have been emphasized as critical for reducing environmental harm (Amponsah et al., 2014; Pena et al., 2023). In addition, the authors noted that OWFs infrastructure often functions as artificial reefs, promoting the development of new biodiversity. Consequently, these habitats may be displaced or lost during the decommissioning phase. Figure 1 shows the summary of findings.

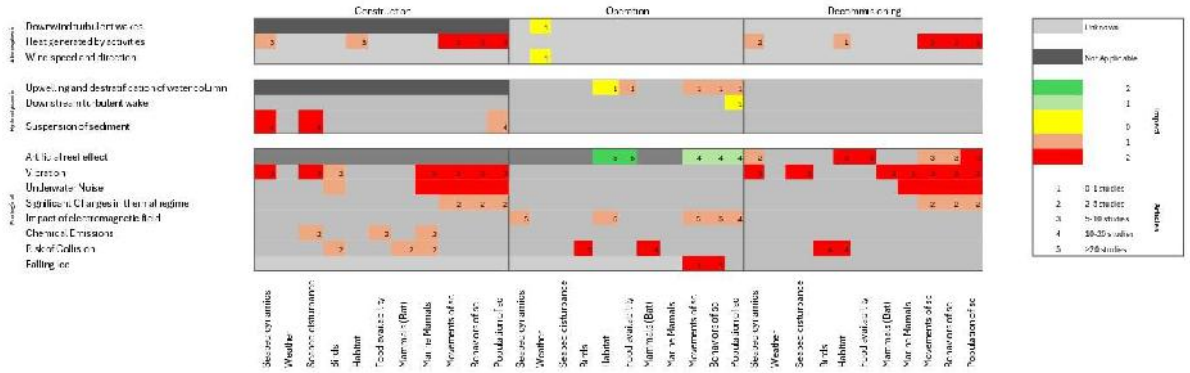

Figure 1: Summary of findings

Figure 1 summarises the findings of 40 articles on environmental impacts, which are continuing. The 14 impacts summarised have been categorised into atmospheric, hydrodynamic, and ecological effects in line with Ouro et al. (2024). As shown at the bottom of Figure 1, the affected factors are distributed under three life cycle stages of OWFs. The five different colours used in the figure represent the impact scores identified in the literature, indicating whether the impact is positive, negative, or neutral across various environmental categories, based on empirical data. The effects on sea creatures (sc) are often categorised in the literature into impacts on their movement, behaviour, and population dynamics, as many studies have analysed these aspects separately. Construction and decommissioning contribute the highest environmental disturbances among all life cycle stages, with vibration and noise being particularly impactful on marine organisms, as frequently reported in the literature.

4. CONCLUSIONS

The environmental impacts of OWFs are multifaceted, but manageable with proper mitigation strategies. Although the environmental costs associated with the construction, operation, and decommissioning of offshore wind farms are considerable, these impacts can be minimized through advanced technology, strategic planning, and better design practices. The long-term environmental benefits of OWFs, such as reducing GHG emissions, mitigating climate change, and supporting the transition to renewable energy, outweigh the potential risks when proper mitigation measures are implemented. Offshore wind farms play a critical role in achieving global renewable energy targets, but their development must be managed to minimize adverse environmental impacts. This review has highlighted the importance of conducting life cycle assessments to evaluate and mitigate these impacts across the construction to decommissioning stages of offshore wind farm development. By adopting a holistic approach incorporating environmental impact mitigation strategies throughout the life cycle, the offshore wind industry can contribute more effectively to sustainable energy goals while preserving marine ecosystems and minimizing the negative impacts on human and environmental health.

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Session 2: Logistics

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Navigating supply chain challenges: Port strategies for Australia's offshore wind industry

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Keywords: Renewable energy; offshore wind farm; supply chain; port strategy; multiport

1. INTRODUCTION

Australia has committed to decarbonising its electricity systems, with a federal target of sourcing 82% of electricity from renewables by 2030 [1]. Offshore wind has emerged as a cornerstone of this ambition [2]. The federal government has declared six priority offshore wind areas [3], and currently there are 11 feasibility licences granted in the Gippsland area (Victoria) [4, 5], totalling a possible capacity of 23 gigawatts (GW). If realised, assuming a conservative capacity factor of 40% [6], this 23 GW could produce approximately 80.6 TWh per year, which accounts for 28.4% of Australia's total 2024 electricity generation of 283.920 TWh, of which 64% (181.518 TWh) relies on fossil fuels [7]. These figures illustrate the transformative potential of offshore wind to decarbonise Australia's electricity sector and significantly displace fossil fuel-based power generation.

The deployment of such large-scale offshore wind capacity will require a highly coordinated and capital-intensive supply chain that integrates global manufacturing, international and domestic logistics, specialised vessels, port infrastructure, and skilled labours [8-15]. Ports are unquestionably critical to the construction and operation of the offshore wind energy supply chain [16-18]. A port may also serve as a fabrication, assembly, and/or operations hub. In all cases, it acts as a key point in the supply chain, facilitating the movement of components or services to offshore wind farms [19]. The first step in offshore wind farm development is selecting primary ports, either with existing facilities or those requiring upgrades. In the Bass Strait, four major ports—two located in Victoria and two in Tasmania—are considered capable of supporting offshore wind farm construction.

A central challenge is determining how these ports' resources can be allocated most efficiently to manage the installation of multiple large-scale projects within overlapping timelines. The choice of port utilisation strategy has direct implications for project sequencing, resource bottlenecks, and overall delivery timelines. This study addresses the question: *Which port utilisation strategy—independent or shared—offers greater efficiency in terms of storage utilisation and construction timelines for large-scale offshore wind projects in the Bass Strait region?*

2. PORT STRATEGY ANALYSIS FOR OFFSHORE WIND CONSTRUCTION

This research evaluates two distinct port utilisation strategies:

- **Independent Port Use Strategy** – Each project is assigned a dedicated port. This simplifies coordination and eliminates competition for port resources among concurrent projects. However, it can lead to underutilisation of port capacity at larger facilities, overburdening smaller ones, and constrains the number of projects that can be built simultaneously.
- **Shared Port Use Strategy** – All projects draw on the combined resources of a network of ports. This pooling of capacity allows better balancing of uneven port resources and can enable more projects to proceed concurrently. The trade-off lies in more complex coordination, increased scheduling interdependence, and potential delays for individual projects if berth or storage capacity is saturated.

The study's methodology involved developing a model that incorporates port capacities, project specifications, turbine component characteristics, and transport logistics. The model examined scenarios involving 4 to 8 concurrent projects, each with a capacity of 2 GW, requiring 111 turbines with 18 MW capacity each. Components were assumed to be delivered in three equal batches, with storage requirements dynamically replenished as items were transported offshore.

The four case-study ports (see Figure 1) were assigned the following capacities:

- **Port A**: 25 hectares storage
- **Port B**: 40 hectares storage
- **Port C**: 25 hectares storage
- **Port D**: 17 hectares storage

Figure 1 The four case-study ports.

Under the independent strategy, smaller ports such as Port D become bottlenecks, with utilisation rates exceeding 90%, while larger ports operate below capacity. In contrast, the shared strategy pools the total 107 hectares across all ports, effectively supporting up to six concurrent projects with an 89.48% utilisation rate. Beyond six projects, storage requirements exceed combined port capacity, necessitating more frequent deliveries or infrastructure expansion.

The installation rate was modelled at 15 days per turbine using two jack-up installation vessels and two feeder vessels per project. Transport times from port to site ranged from 0.48 days (Port C) to 3.20 days (Port B), all significantly shorter than installation times, allowing for operational overlap and minimal vessel idle time.

For **independent port use**, a maximum of four projects can be executed concurrently, with each taking 2.45 years. Additional projects must wait for earlier ones to finish, leading to cumulative timelines of up to 4.73 years for eight projects.

For **shared port use**, all projects can commence simultaneously, with efficiency gains peaking at 45.67% for five concurrent projects. The advantage diminishes as project numbers exceed port capacity, with efficiency gains falling to 22.43% at eight projects due to berth congestion and the need for more delivery batches.

3. CONCLUSIONS

This study demonstrates that the choice between independent and shared port utilisation strategies is not one-size-fits-all but depends on project scale, resource distribution, and delivery priorities.

The **shared port use strategy** is particularly advantageous for large-scale offshore wind build-outs in the Bass Strait region, where maximising concurrent project execution is critical to meeting ambitious renewable energy targets. By pooling resources across four ports, it allows for more efficient use of infrastructure and can reduce cumulative construction timelines significantly. Its optimal performance is observed with up to six concurrent projects; beyond this threshold, resource constraints—particularly in storage area and berth availability—necessitate either capacity expansion or operational adjustments, such as increasing delivery frequency to reduce storage demand.

The **independent port use strategy**, while less efficient in total build-out time, may be preferable when the primary goal is to deliver electricity from the first projects as quickly as possible. Dedicated resources per project reduce the risk of scheduling conflicts, but this comes at the cost of extended total construction periods for multi-project programmes.

In practice, a hybrid approach could be adopted, combining the advantages of both strategies: early-phase projects using dedicated ports to accelerate initial energy delivery, followed by a shift to a shared

model as more projects enter the pipeline. This would balance the need for speed in initial output with the efficiency gains of pooled resources in later phases.

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Strategic Multi-Use Port Infrastructure: Enhancing Australia's Offshore Wind and Maritime Capabilities for a Sustainable Future

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Keywords: Offshore wind energy; port capability, supply chain; port capacity, multi-use port

1. INTRODUCTION

The National Port Strategy 2012[1] is overdue for revision given the complex and dynamic changes that are occurring globally. It no longer holds currency for the current and predicted future demands which include major renewable infrastructure developments, such as offshore wind, and large oil and gas decommissioning projects. Ports play a critical role in supporting the supply chain lifecycle of offshore wind projects, from manufacturing and assembly to installation, operation, and maintenance. This research will provide important insights to inform effective future policy.

This paper presents results from a systematic literature review of international best practice for multi-use ports supporting offshore wind energy. It will focus on the supply chain for offshore wind infrastructure. We will also present the interim findings of interviews with key stakeholders involved in offshore wind energy projects in the Illawarra and Gippsland regions of Australia.

The current system of Commonwealth leasing of Offshore Wind Zones to stakeholders leads to individualism in approaches. Stakeholders are left to negotiate port requirements and individual access to port real estate and infrastructure. There is little incentive for ports to provide any purpose- built infrastructure to facilitate access and efficiencies in offshore wind energy projects when approached on an individual project basis.

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Early project-life treatment of export and inter-array cable risks

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Keywords: cables; crossings; risk; on-bottom stability; installation

1. INTRODUCTION

The development of offshore wind farm (OWF) infrastructure in Australia is at an early project-life stage. Projects in the Gippsland Zone have commenced site characterisation activities, including seabed survey and metocean studies. These studies are conducted with some flexibility in the routes for cable infrastructure, and findings will play an important role in finalising the export and inter-array cable (IAC) routes, and the selection of cable design. In this abstract, we introduce four focus areas for cables (both export and IAC) that should be treated at the early project-life stage to de-risk Australian OWF projects: seabed conditions with implications for cable installation and lifetime, cable design selections, cable crossings of existing subsea infrastructure, and cable specific metocean conditions. Each of these focus areas are discussed in detail in the context of the Gippsland Zone, including relevance to submission of Transmission Infrastructure License (TIL) applications. Examples from extensive experience on OWFs globally are given, and opportunities for cost & design optimisation are identified.

2. SEABED CONDITIONS & IMPLICATIONS FOR CABLES

The engineering for stable subsea behaviour of IAC and export cables in OWFs is primarily driven by near-surface properties of the seabed - in particular surficial soil or rock conditions. In mature offshore wind regions such as the North Sea cables are buried on areas of mobile (sandy) seabed. However, immediate burial post lay-down of the cables may not always be the preferred installation sequence. Furthermore, where rocky seabed features exist cable burial may not be an option.

Where a time delay exists between laydown and burial, the tri-partite interaction of the cable, the mobile seabed, and the prevailing metocean conditions must be considered to determine cable stability (*Figure 1*, (left) [7]), and this is treated using the STABLEpipe methodology (see *Figure 1*, right [5]).

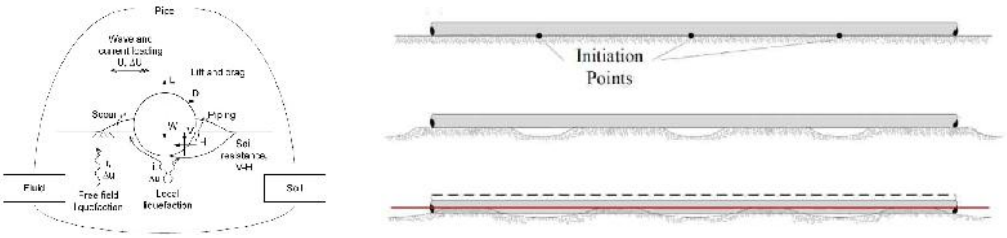

Figure 1 STABLEpipe considers the tri-partite interaction of cables with the seabed and fluid motion (left, [7]) to develop a picture of cable self-embedment over time into the mobile seabed (right, [5])

Consideration of self-embedment leads to assessment of much lower stability utilisation than would be expected using traditional absolute stability assessment under DNV-RP-F019 [4]. The STABLEpipe methodology is referenced in the 2021 edition of DNV-RP-F019, and has been applied to cables across numerous OWFs globally. The presence of potentially mobile seabed sediments in the Gippsland Zone ([10], [11]) suggests that the application of STABLEpipe to the IAC and export cables could benefit OWF developers. To apply for a TIL the *"proposed installation and burial methods, including stability controls, if relevant"* [14] should be defined. Safely decoupling laydown and burial activities can lead to cost savings, broadening windows for laydown and giving developers flexibility for install plans.

Parts of the seabed within the Gippsland Zone may present with shallow or no sediment coverage on rocky features [10]. The prevailing approach may be to select cable routing to avoid laying over such features. The COREstab methodology [8] has been developed to assess cable stability on rocky seabeds,

where the cable may not be buried for operational lifetime. The forthcoming British Standard 10009 [1] references the COREstab methodology to provide a framework for design of cables on rocky seabeds. The premise is that cables are of a scale to interact with rocky seabed features, which can provide support and enhanced lateral resistance. AOE have experience applying the COREstab methodology on seabed features similar to the Gippsland Zone in the Otway Basin in Western Victoria. Cable protection measures, such as rock bags or rock dump, can be used to protect the exposed cable. Analysing such solutions at an early project stage may allow developers to consider optimised cable routes, and providing necessary inputs for TIL applications which require consideration of stability controls [14].

3. CABLE SELECTION

A further consequence of cable stability during installation periods is the differing risks when selecting preferred cable designs. Cables with copper cores (Cu cables) are generally heavier per unit length than cables with aluminium cores (Al cables), leading to more stable on-bottom behaviour. However, Al cables (for similar voltage and current rating) are cheaper on a capital basis [9]. Analysis of cable installation stability between laydown and burial on mobile seabeds may provide justification to use Al cables over Cu cables, when enhanced embedment under the STABLEpipe methodology is applied. Such comparisons can be completed at an early project life phase, to feed into the TIL application, which requires information on the *"nominal outside diameter, number of conductors and core area/material, insulation, screens, and protective sheath/armour/coatings"* of the export cable [14].

4. CABLE CROSSING ENGINEERING

Subsea cable routes for both IAC and export cables in the Gippsland Zone may need to traverse existing seabed pipeline and cable infrastructure, such as the Tasmanian Gas Pipeline and Basslink Interconnector. Some of this infrastructure may be buried shallow under, or installed on, the seabed - such as the TGP (*Figure 2*, right [6]). *Figure 2* (left) presents a summary of existing infrastructure, with oil (green) & gas (red) pipelines, fibre optic cables (magenta), and electrical transmission cables (dashed maroon). The crossing of this existing infrastructure will require specific design considerations influenced by the crossing agreements between the OWF developer and existing infrastructure owner.

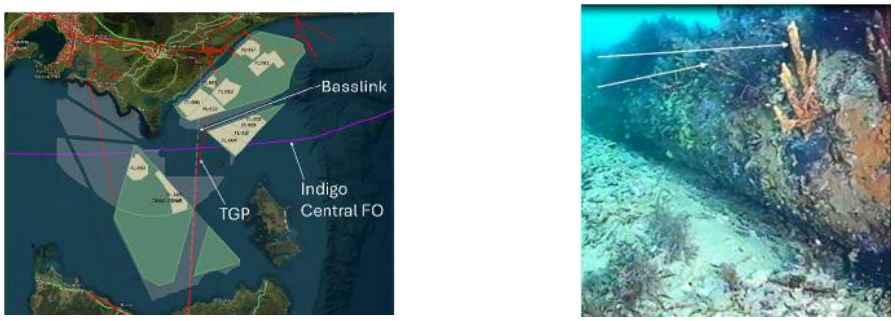

Figure 2 Gippsland Zone overlaid with existing subsea infrastructure (left, adapted from Offshore Renewable Energy - General Portal, Geoscience Australia 2022. This product is released under the Creative Commons Attribution 4.0 International Licence. http://creativecommons.org/licenses/by/4.0/), and the TGP on the seabed in proximity to Tasmanian landfall (right, [6])

The challenges of safely implementing crossings, and providing for on-bottom stability, are described in [15]. Relative motion of the crossing over the existing asset can lead to degradation of the mechanical separation systems (generally constructed of polyurethane). Crossings are recognised as a risk to the cable and the existing asset to the extent that the TIL guideline notes that *"Applicants should avoid cable crossings, where possible"* [2]. Where crossings cannot be avoided, there is a need to ensure safe and reliable crossing design. Work in [12] has addressed the application of the STABLEpipe Method C approach to assess crossing stability for export cables on a Dutch Sector North Sea OWF, with the separation system free to roll the cable over the seabed. Enhanced stability at the crossing was achieved via support of crossing shoulders embedding into surrounding mobile sediment. AOE has subsequently applied similar analysis to other OWF cable crossings. Recommended improvements to crossing design, include increased weight of mechanical separator, and restriction of separator rolling.

5. CABLE SPECIFIC METOCEAN CONDITIONS

As the STABLEpipe methodology considers time-evolving cable embedment it is critical to understand the evolution of the metocean for a given site. The work in [13] describes a typical STABLEpipe analysis process, from initial cable lay, through ambient conditions, concluding with the onset of the design storm condition. Characterisation of typical ambient and storm conditions for a OWF site allows for a comprehensive analysis of cable embedment, from laydown onwards. In particular, [13] has shown that the use of hindcast storm ramp rates at a given site is necessary in place of generic profiles from standards such as [3]. This is especially apparent when considering directional evolution of a storm. Prevailing conditions in the Gippsland Zone come from the SW, with some significant storms coming off the Tasman from a SE direction. OWF lease area on the western and eastern flanks of the Zone will require bespoke consideration of storms to ensure local metocean conditions are suitably captured.

6. CONCLUSION

Opportunities exist for Gippsland Zone OWF developers to make early project-life decisions for IAC and export cable design that will provide benefit during the installation and operational phases. With projects commencing site characterisation activities and TIL application guidance explicitly requiring an export cable design basis, it is essential to consider four key areas: seabed mobility & rocky features, cable specific metocean conditions localised for the site, cable design selection influenced by seabed & metocean, and cable crossings of existing infrastructure. Leveraging experience from mature OWF regions globally, and applying local knowledge relevant to the Gippsland Zone sites, developers can optimise cable decisions, mitigate later stage risks, and provide flexibility for installation decisions.

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The Critical Role of Local Supply Chain Integration in Offshore Wind Planning: Tailoring the Sector to the Australian Context

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Keywords: OEM, infrastructure, supply chain

1. INTRODUCTION

As Australia moves toward large-scale offshore energy development, operational success will depend on adapting global best practices to meet uniquely Australian regulatory, environmental, and industrial conditions. While international offshore models offer useful benchmarks, local suppliers already active in the renewables sector bring essential, context-specific expertise that is critical to project success across all areas.

For developers, OEMs and stakeholders, early engagement with the local supply chain is key to derisking projects and ensuring long-term operational efficiency. Local partners offer a deep understanding of workforce dynamics, labour relations, union agreements, technological constraints, stringent HSE standards, and the logistical complexities of operating across Australia's diverse landscape, factors that, if overlooked, can significantly drive up costs and complexity compared to similar projects in alternate regions.

Lessons from onshore renewable integration have demonstrated that simply importing international models is insufficient. Instead, a balanced approach combining global capability with trusted local experience will be vital. Strategic partnerships between international suppliers and local supply chains demonstrate how local capability can be effectively integrated to enhance service delivery and accelerate the transfer of knowledge from past and current projects into Australia’s emerging offshore energy market.

This discussion highlights the critical importance of early and proactive stakeholder engagement in integrating local content to support the development of Australia's offshore energy supply chain. It also emphasizes the need to recognize and align with mature partners who have invested in, and integrated with, local supply networks enabling the creation of a scalable, self-sufficient, and sustainable offshore energy industry

2. BACKGROUND

Australia’s experience with onshore renewable energy integration offers key lessons, particularly around the risks of neglecting local content. Early attempts to fit Australia’s unique landscape into international delivery models and an overreliance on international supply chains resulted in cost overruns, project delays, and missed opportunities for local job creation and economic growth. Many international suppliers struggled to adapt to Australia’s regulatory and industrial environment, ultimately withdrawing from the market, unable to make the generic wind business model work.

In response, Australian businesses adapted, investing in local talent, equipment, and compliance to fill the gap left by international suppliers. These local capabilities have been essential in both delivering new projects and maintaining existing developments, supported by a skilled, locally-based service provider pool. However, challenges such as misaligned costs, extended timelines, and operational discrepancies with global markets created risks for local suppliers and hindered the supply chain’s growth. Despite this, increased collaboration, albeit delayed between developers, OEMs, and the supply chain has enabled market adaptation and growth.

As focus shifts to offshore wind development, these lessons call for a fundamentally different approach that emphasises early investment and collaboration. In the formative stages of the offshore market, international delivery models must be adapted to local conditions rather than applied as blanket solutions. Central to this strategy is the development of local capability, in partnership with trusted offshore suppliers. This approach will ensure projects meet global standards while fostering a self-sufficient, competitive offshore wind sector within Australia.

3. DISCUSSION

Integrating local content from the outset of offshore wind development through research, planning, and strategic execution is essential for achieving long-term objectives, including community engagement, economic resilience, employment growth, workforce development and strong sector forecasts. Establishing a developmental roadmap that recognizes the importance of local capability is central to building a scalable, self-sustaining offshore wind industry within the Australian context. This requires prioritising domestic supply chain engagement over reliance on imported delivery models.

Australia's offshore wind sector faces unique and multifaceted challenges ranging from complex regulatory requirements and strict environmental protections to highly unionised labour frameworks and geographically dispersed project locations. Local suppliers have built robust businesses incorporating these dynamics and coupled with their ongoing involvement in onshore renewable projects, are best positioned to address these challenges for the offshore sector effectively. Their established familiarity with compliance standards, environmental governance, logistics, and workforce culture makes them critical contributors to the success of offshore initiatives.

Maximising the value of offshore wind development requires a deliberate shift from transactional procurement to strategic, early engaged long-term partnerships. Current collaborations within the market highlight how local expertise in heavy logistics and infrastructure can be effectively integrated with international experience, established operational frameworks, and pre-existing delivery networks. These collaborative models enable targeted capability transfer, enhance sector and workforce readiness, and ensure continuity in project execution while mitigating risk through the combined use of proven international service providers and locally attuned partners. Critically, they also offer developers the opportunity to build a supply chain that not only drives economic value but also advances broader national interests.

The adaptation of technological capability and reference alone is not sufficient for the effective planning, development, and execution of offshore wind projects in the Australian market. Success depends on establishing a coordinated and integrated supply chain strategy that prioritises local content from the outset and fosters long-term, structured partnerships between domestic and international stakeholders.

Failure to support strategic partnerships and leverage the commitment of the local supply chain in these early stages risks repeating the mistakes made during the integration of the onshore market. Overreliance on foreign supply weakens project resilience and increases vulnerability to global market shifts effecting long term market presence and ongoing serviceability. Misalignment with local regulatory, environmental, and industrial frameworks can lead to costly delays, while sidelining local businesses limits opportunities for skills development, capability growth and places limitations on serviceability by narrowing the pool of experienced contractors. Lack of local engagement may also erode social licence particularly when communities and industries feel excluded from economic benefits. These oversights ultimately slow sector maturity and increase lifecycle costs. To mitigate these risks, policy and industry priorities must focus on supporting both local and international businesses that demonstrate a commitment to early engagement and proactive investment. Existing partnerships should be acknowledged across all facets of the sector and leveraged for their proven capabilities and contextual expertise throughout every stage of project development. This includes early-phase activities such as feasibility assessments and front-end engineering design (FEED) studies, through to

infrastructure and port development, and ultimately the execution of transport and lifting operations, equipment procurement, labour mobilisation, and workforce planning. Embedding local content from the outset and enabling strategically aligned, collaborative delivery models will position Australia to develop a resilient, competitive, and nationally beneficial offshore wind industry that is technologically advanced, socially inclusive, and economically sustainable.

4. CONCLUSIONS

A sustainable and self-sufficient offshore wind industry in Australia hinges on a balanced approach that blends global best practices with local expertise, coupled with the commitment of developers, OEMs, and stakeholders to integrate this from the early development and feasibility stages. Successful collaborations/ partnerships demonstrated throughout the market showcase how local knowledge can enhance internationally recognized experience, creating resilient, operationally-ready projects tailored to Australia's unique climate and regulatory landscape. This approach ensures technical and operational success while fostering a competitive, scalable, and inclusive sector that can meet Australia's distinct needs. As the offshore wind industry progresses, the focus must be on early investment in local content and the formation of long-term, strategic partnerships. By prioritizing local engagement from the outset, Australia can avoid past pitfalls, enhance project outcomes, and unlock long-term economic, environmental, and social benefits. This is the foundation for building a globally competitive, locally integrated offshore energy industry.

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Establishing a Trusted Environmental Data and Information Supply Chain to support impact modelling of offshore renewable energy infrastructure

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Keywords: Environmental data supply chains; FAIR data; Impact modelling; Decision support systems; Stakeholder engagement

1. INTRODUCTION

Assessing the potential environmental and social impacts for the emerging Offshore Renewable Energy (ORE) sector in Australia presents a challenge due to the complex nature of cumulative impacts, nature positive activities, their associated outcomes, and the need for ongoing monitoring and adaptation. Core to meeting this challenge will be access to reliable, fit-for-purpose and trustworthy data, science, and models to drive assessment and decision-making processes. A collaborative approach to designing and building data sharing and analytics infrastructure across government, research and industry sectors will achieve the highest levels of efficient and effective analytical and evidence-based decision support at the lowest possible cost. A new project running from 2025 through 2027 at the Institute for Marine and Antarctic Studies (IMAS), University of Tasmania, funded by the Australian Research Data Commons (ARDC), and in collaboration with the National Environmental Science Program (NESP) Marine and Coastal Hub will attempt to address some of these challenges.

2. OFFSHORE RENEWABLE ENERGY TRUSTED ENVIRONMENTAL DATA AND INFORMATION SUPPLY CHAINS

This project aims to establish trusted, standards-based, Findable, Accessible, Interoperable and Reusable (FAIR) environmental data and information supply chains using the Shared Analytic Framework for the Environment (SAFE 2.0) as a guide to provide analysis-ready data products (Figure 1) and support evidence-based decision-making in the ORE sector. Using the Gippsland declared offshore wind zone as a regional exemplar, the project will deliver scalable infrastructure and practices that can be adapted nationally.

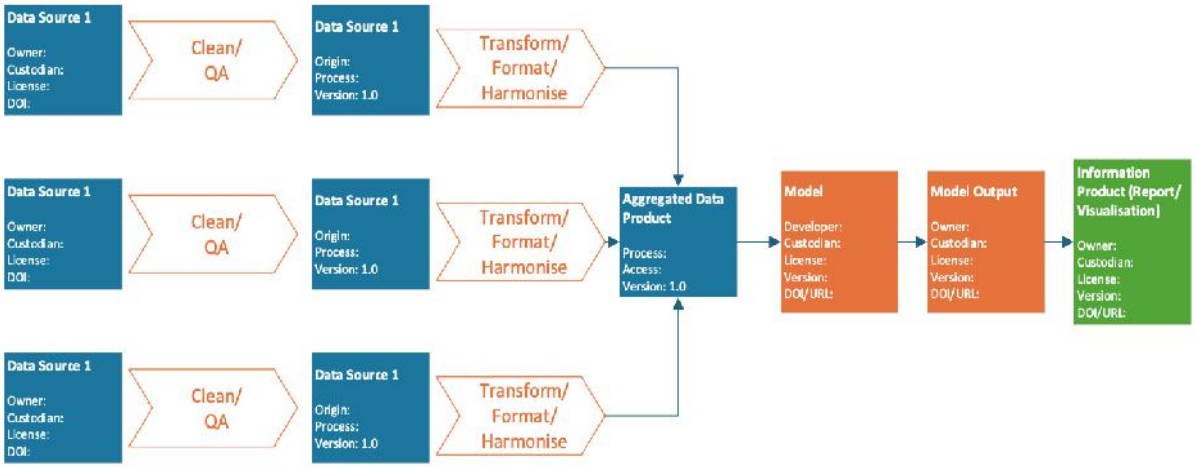

Figure 1: A high level, conceptual information supply chain, showing three data pipelines that support a single aggregated data product, and a model that is used to derive an Information Product. Note the inclusion of clear provenance metadata. As standardized data collection and management practices evolve, the need for cleaning, QA, transforming, formatting and harmonising steps will be dramatically reduced leading to increased efficiency and cost reduction.

The project team will collaborate with modelers from the National Environmental Science Program (NESP) Marine and Coastal Hub Project 4.7: "Development of regional modelling and risk assessments to inform offshore renewable decision-making"[1] to identify and deliver two information products that best reflect the needs of Government and industry. These may include data and information on seabirds and cetaceans, seabed mapping and marine habitat, oceanography or anthropogenic factors.

The project will aim to be platform independent and will adopt the common architecture and standards currently in use by the Australian Ocean Data Network (AODN) and its partner organisations, including those developed by the Open Geospatial Consortium (OGC) and ISO19115 metadata. Initially working with only open access data sources, the platform design will aim to ensure a high degree of interoperability with more secure platforms such as the Shared Environmental Analytics Facility (SEAF) and the Australian Agricultural Data Exchange (AADX).

3. GOVERNMENT, INDUSTRY AND RESEARCH ENGAGEMENT

The advent of the emerging ORE industry in Australia has yielded many environmental baseline and research studies, including those supported directly by the Renewable Energy Research Initiative (RERI). Of the 28 RERI projects awarded as of June 2025, over 35% aim to identify or develop 'best practices' or 'standards' as related to environmental assessments for ORE. These new projects are emerging at the same time as ORE research from NESP, IMAS, AIMS, ACOWE and other research institutions, and environmental baseline surveys are already underway by industry and associated consultancies (e.g. Star of the South).

Although the definition of what makes a best practice or standard in these projects remains unclear, these projects will almost certainly require engagement with proponents, researchers, and government representatives. There is a recognised need for national coordination of these approaches to increase the relevance and consistency of recommended practices and standards for both industry and government, as well as to enable efficient use of time and resources (McLean et al. 2024). Fragmentation of practices and data across disciplines, regions, and impact pathways will inhibit robust environmental assessments and sustainable development of this emerging sector (Hörstmann et al. 2021)

To meet this objective, our project will also involve a coordinated effort to 1) define what is meant by 'best practices' in the context of environmental ORE and 2) provide advice for those engaged in the development of marine and environmental ORE practices and data standards.

4. CONCLUSIONS

As an emerging industry in Australia, this represents a once in a generation opportunity to establish strong baseline data and long-term monitoring for ORE from establishment to decommissioning. This project will also:

- Improve access to new and existing data for marine ecosystem researchers that will increase our understanding of environmental condition, processes and change relevant to ORE.
- Enhance research translation for improved management of marine ecosystems by government managers and policy makers.
- Establish collaborative relationships between government, industry and research sectors to achieve shared goals in ORE practices, including faster regulatory decision-making for industry.

[1] https://www.nespmarinecoastal.edu.au/project/4-7/

This project will demonstrate data and information supply chains for 2 priority issues. Along with the data collection and data sharing framework and a future development and investment roadmap, this demonstration will provide the groundwork for future investment in further work over 5+ years (Figure 2) to establish a comprehensive suite of trusted, sustainable data pipelines delivering a wider suite of data and products for ORE regulation, research and monitoring. This will ultimately lead to liberating large amounts of government and industry data for research, regulatory and monitoring purposes; reduce uncertainty and risk in decision-making; accelerate and increase transparency of decisions and increase public trust and social license.

Figure 2: This project (Years 1-2) will establish the groundwork for a longer term vision.

ACKNOWLEDGEMENTS (OPTIONAL)

We acknowledge the generous funding and support from the Australian Research Data Commons and contributions from partner organisations.

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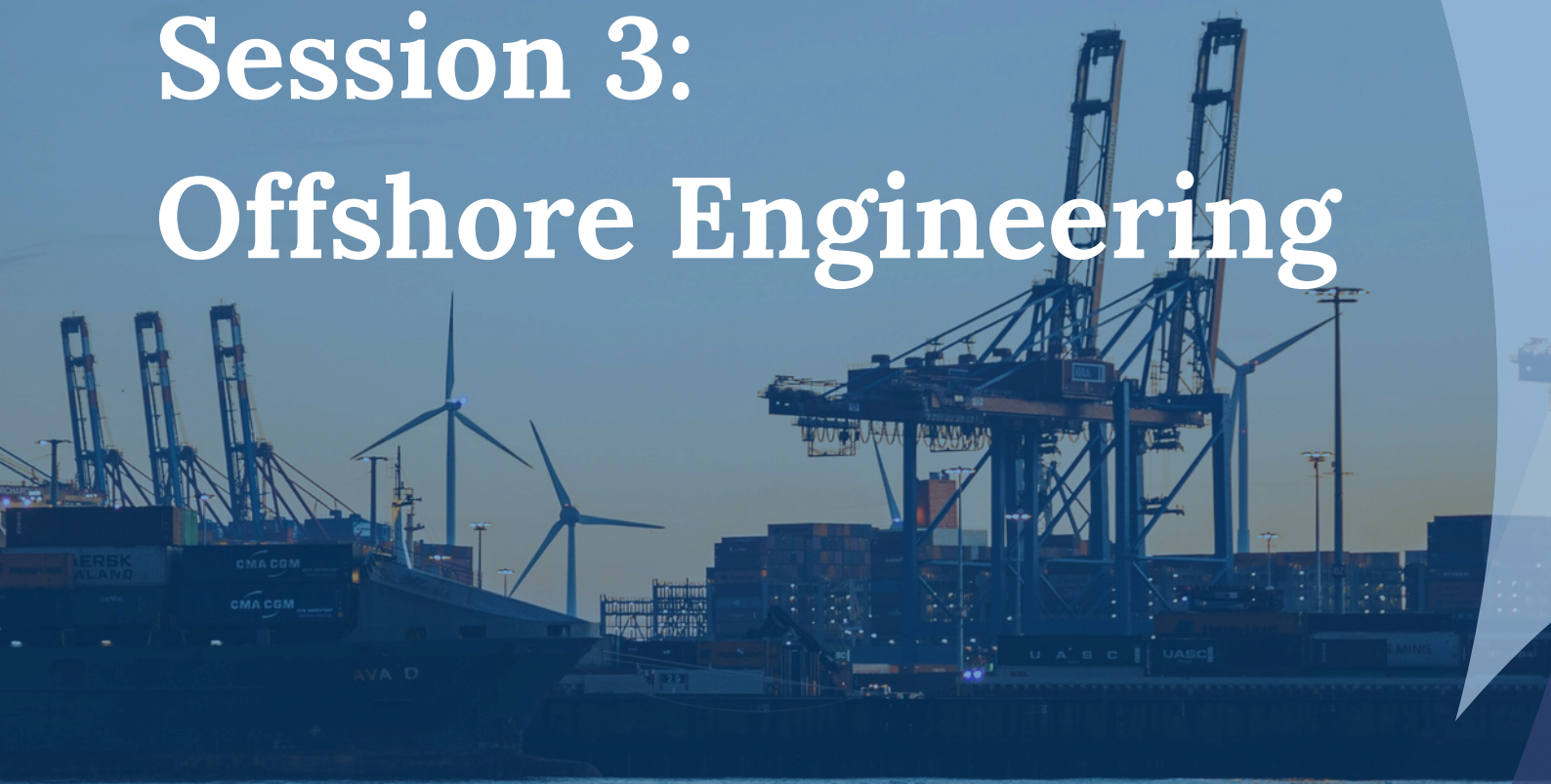

Foundation concepts for offshore wind: geotechnical considerations

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Keywords: offshore foundations; monopiles; suction bucket jackets; piled jackets, concept selection

1. INTRODUCTION AND BACKGROUND

Offshore wind energy is playing a crucial role in global efforts to reduce CO_2 emissions. For example, the UK has set a target of installing 50 GW of offshore wind capacity by 2030 [3], and similar energy transitions are in progress, or are being planned, in a number of regions around the world, including Australia.

The capacity of individual bottom-fixed offshore wind farms (OWFs) has risen steeply as developers install larger offshore wind turbine generators (WTGs) over larger areas at sites with increasingly deep waters. With WTG foundation costs potentially being up to 25-30% of the total OWF capital cost [6], these demands have led to a mix of foundation concepts being utilised across the industry with concept selection typically focusing on finding the most technically sound and economical solution given each individual project's specific requirements. Importantly, with the large number of foundations typically needed for OWFs, significant savings can be realised through simplification, optimisation (during all phases of the project) and industrialisation.

This paper explores the most common foundation concepts for bottom-fixed OWFs and shows how key factors - particularly ground conditions - can influence concept selection. Furthermore, case studies are used to demonstrate how ground-related risks have been mitigated and opportunities leveraged to develop technically sound and economical foundation solutions.

2. FOUNDATION OPTIONS FOR BOTTOM-FIXED OWFs

For bottom-fixed OWFs, the range of available foundation options is extensive. Fundamentally, the foundation's main purpose is to safely support the WTG and thereby transfer loads acting on both the WTG and the superstructure to the seabed, while ensuring compliance with all relevant tolerances. The different foundation concepts rely on different mechanisms with which to transfer the loads, including shallow foundations (e.g. gravity bases or suction bucket jackets) which rely on shallow bearing, intermediate foundations (e.g. monopiles) which rely on lateral/overturning resistance and deep foundations (e.g. piled jackets) which rely on axial resistance at depth. From an engineering perspective, the choice of foundation concept is heavily influenced by four key factors – water depth, loading conditions, WTG size and ground conditions. Other considerations, such as energy production (e.g. windfarm layout), fabrication, logistics and statutory requirements also undoubtedly have a significant influence on the foundation concept, with the interaction between these and the engineering factors often being optimised to find the most economical solution. A good example of these interactions is the West of Duddon Sands OWF, where shallow rock was anticipated across a significant portion of the site [5]. However, with the

remainder of the site featuring favorable ground conditions for monopiles [5] and the OWF site having "excellent wind resources (and) favourable water depths" [8], monopile foundations in combination with a layout avoiding the areas of shallow rock (where installation was not considered feasible) was the solution adopted.

3. MONOPILES

Since monopiles were first used for the Horns Rev 1 OWF in 2002, almost 80% of all installed WTGs are supported by monopile foundations [12]. Many early windfarm sites in Northern Europe (including Horns Rev1 OWF) utilised monopile foundations as they had shallow water depths and competent ground conditions; site characteristics which monopiles are typically well suited to. This led to the industry's early familiarisation with the concept and subsequent industrialised processes developed to support their further use. Whilst there has long been debate in the industry if a limiting water depth exists for monopiles [4], recent monopile designs continue to set new water depth records where ground conditions allow [7].

Monopiles are generally well suited to sites with competent soils near the mudline which provide support to the structure, in terms of both stiffness and strength, without being too 'hard' to preclude installation. In many areas where OWFs have been developed, ground conditions often consist of dense sands and stiff, overconsolidated clays at relatively shallow depths, which allow for relatively predictable installations and modest monopile embedments with low length to diameter ('L/D') ratios.

With offshore wind's expansion to sites with deeper waters and larger turbines, monopiles have remained the most common foundation choice due to their simplicity, scalability, versatility, potential for optimisation and the relative ease with which they can be fabricated, handled and stored. However, with the global footprint of offshore wind ever increasing, monopiles are also being utilised as foundations at sites with markedly different geological conditions to those previously seen in Northern Europe, and risks associated with these differences need to be considered carefully (particularly those related to monopile installation). However, mitigations for these risks are available, such as the drilled monopile concept utilised for the Saint-Nazaire OWF [9] where hard rock was present.

4. JACKETS – 'PIN PILED' JACKETS OR SUCTION BUCKET JACKETS

At OWF sites with deeper waters[1] or complex ground conditions, jacket structures have commonly been used given the efficiency with which they transfer loads to the seabed. However, they are inherently more complex to design, optimise and fabricate compared to monopiles and have thus not yet had the same degree of industrialisation.

Jackets supported by suction buckets (commonly referred to as suction bucket jackets, or 'SBJs') have been increasingly utilised in recent years [2], as they are relatively quick to install using suction and typically have small embedment depths (up to about 15 m below mudline). Therefore, they can potentially be deployed at sites where geo-hazards may preclude the use of intermediate or deep foundations. SBJs can be installed in many different soil types, including very dense sands, layered soils and very stiff clays [2], with installation trials having been undertaken at some OWF sites to reduce installation related risks [2].

[1] In this context, the deepest bottom-fixed offshore wind turbine foundations installed to date are those at the Seagreen Offshore Windfarm, with water depths up to approximately 60 m [11].

'Pin piled' jackets are relatively versatile for supporting WTGs given that the 'pin piles' can be extended to transfer loads to deeper, more competent, strata where necessary. Reducing ground-related uncertainties can therefore lead to significant risk reduction and pile length optimisation at OWFs where long piles may be required. For example, offshore pile load tests [1][10] have successfully been conducted to reduce costs and risks for a number of OWFs which utilised pin piled jackets, such as the Wikinger and Greater Changhua 01&2a OWFs.

5. CONCLUSIONS

A wide range of foundation concepts are available for supporting WTGs and various factors can influence the most economical concept for a given OWF site - from an engineering perspective, the most relevant factors are water depth, loading conditions, WTG size and ground conditions. For the majority of OWFs, monopiles have been utilised due to their simplicity, scalability, versatility and potential for optimisation, although risks associated with the ground conditions (particularly installation risks) need to be considered carefully. At sites with challenging ground conditions or deeper water, SBJs or pin piled jackets have been a common choice, with many projects incorporating practical strategies to optimise the foundations and reduce ground related risks. For each OWF, understanding the effect that ground conditions can have on the foundation (in terms of both risks and opportunities) is crucial to finding the most technically sound and economical foundation solution.

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Data-Driven Enhancement of CPT-Based Shear-Wave-Velocity Predictions for Offshore Wind Foundations

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Keywords: Offshore; Shear Wave Velocity; SVR; Machine Learning; Wind Foundation

1. INTRODUCTION

The design of offshore wind turbine foundations critically depends on precise characterization of subsoil stiffness at small strain levels. In particular, the shear wave velocity (V_s) profile (and corresponding small-strain shear modulus G_{max}) (Robertson & Campanella, 1983; Robertson, et al., 1986) is a key input for analyzing monopile foundation behavior and the dynamic response of the turbine structure.

Numerous studies have highlighted various factors that directly influence the value of shear wave velocity , which can be broadly categorized into six groups:a) soil type, b) cone tip resistance and sleeve friction, c) depth, d) stress level, e) soil age factor and f) cyclic stress ratio (CSR) and cyclic resistance ratio (CRR). Stuyts et al. (2024) analyzed S-CPT data from different locations in the North Sea and proposed a new formula to predict shear wave velocity in seabed profiles (Stuyts, et al., 2024). However, their formula only accounted for soil type, certain parameters, and stress levels, and did not achieve higher accuracy when applied to other profiles. Janzen et al. (2024) proposed two different correlations for shear wave velocity based on cone tip resistance, effective stress, and calibrated parameters using data from 30 locations in the German part of the North Sea (Janzen, et al., 2023).

Machine learning (ML) modeling has emerged as a powerful alternative to derive V_s from CPT data without relying on a prescribed empirical form. Unlike traditional regression equations that assume a specific functional relationship, ML algorithms can learn complex, non-linear relationships directly from data. This data-driven flexibility is advantageous for capturing the combined effects of multiple CPT parameters (e.g. tip resistance, sleeve friction, pore pressure) on V_s across different soil types. Recent studies have increasingly explored ML for CPT-based Vs prediction. For instance, Entezari et al. (2022) trained a random forest model on a global dataset of CPTu–Vs pairs and found it outperformed earlier empirical equations. They further showed that incorporating geotechnical domain knowledge improved the model – for example, by distinguishing between uncemented and cemented soils to account for microstructure effects. These developments motivate a thorough comparison between conventional and ML-based Vs prediction approaches, especially using a large North Sea-specific dataset where existing correlations have proven suboptimal (Entezari, et al., 2022). This study aims to review the geotechnical background of V_s estimation and the limitations of traditional CPT correlations for offshore soils, and present a comprehensive ML modeling framework (using XGBoost, Random Forests, GradientBoosting, SVR, Lasso, Ridge, ElasticNet, DecisionTree, and KNeighbors) for predicting V_s from CPT data, use optimization techniques to enhance model performance, and compare the accuracy of ML predictions against several conventional CPT–Vs correlations in North Sea soils. A case study from a North Sea site is used to illustrate the differences between measured V_s profiles, ML predictions, and empirical correlation estimates. The overall goal is to reduce uncertainty in offshore foundation design.

2. CPT-BASED CORRELATIONS OF SMALL-STRAIN STIFFNESS FOR OFFSHORE WORK

Shear-wave velocity (Vs) underpins critical offshore checks—from jack-up leg penetration to monopile drivability and pipeline–seabed interaction—but direct seismic tests are seldom feasible in deep water. Practitioners therefore rely on CPT-based correlations by Hegazy & Mayne, Mayne, Andrus et al., Robertson and McGann et al., which translate cone resistance, sleeve friction and the soil-behavior index into Vs. Their formulations and performance metrics are summarized in *Table 1*, providing a

rapid, low-cost route to offshore stiffness profiles when only CPT data are available (Hegazy & Mayne, 2006; Mayne, 2007; Andrus, et al., 2007; Robertson, 2009; McGann, et al., 2014).

Table 1 CPT derived V_s/G_0 correlations

Reference	Correlation	R^2	RMSE	MAPE
Hegazy & Mayne	$V_s = 0.0831 Q_{tn} \exp(1.7861 I_c)(\frac{\sigma_v'}{P_a})^{0.25}$	-1.368	97.045	26.170
Mayne	$V_s = 18.5 + 118.81 \log(f_s)$	0.2231	55.577	13.872
Andrus et al.	$V_s = 2.27 q_t^{0.412} I_c^{0.989} z^{0.033}$	0.0832	60.375	14.878
Robertson	$V_s = [z^{(0.55 I_c + 1.68)}(q_t - \sigma_v)/P_a]^{0.5}$	0.1971	56.498	15.100
McGann et al.	$V_s = 18.4 q_t^{0.144} I_c^{0.0832} z^{0.278}$	-3.204	129.284	39.277

3. COMPARATIVE ACCURACY OF MACHINE-LEARNING MODELS

Machine-learning regressors, hyper-tuned (using RandomizedSearchCV and GWO, 70% Train and 30% Test) on the same offshore CPT dataset, consistently achieve higher R^2 and markedly lower error metrics than the long-standing CPT correlations. The table ranks every method by RMSE, making the improvement in Vs prediction immediately clear. Machine-learning models—especially SVR—halve the prediction error compared with the best classical CPT correlation (Mayne), markedly improving Vs estimates for offshore design.

Table 2 CPT derived V_s/G_0 correlations

Rank	Predictor	R^2	RMSE	MAPE	Rank	Predictor	R^2	RMSE	MAPE
1	SVR	0.524	43.44	11.5	6	Ridge	0.509	44.14	11.8
2	XGB	0.511	44.04	11.8	7	ElasticNet	0.508	44.16	11.9
3	RF	0.51	44.07	11.8	8	K-Neighbors	0.499	44.56	11.9
4	GBM	0.51	44.08	11.8	9	DecisionTree	0.336	51.3	14
5	Lasso	0.509	44.14	11.8					

4. MODEL-TO-DATA COMPARISON AT IJV038 (IJMUIDEN VER)

According to *Table 3* and *Figure 1,* for the IJV038 borehole in the IJmuiden Ver offshore wind-farm zone, SVR delivers the most accurate site-specific Vs prediction, recording RMSE = 28, R^2 = 0.52 and MAPE = 8 %. Compared with the best empirical formula (Mayne 2007: RMSE = 30, R^2 = 0.46, MAPE = 9 %), SVR lowers the error by ~6 %. All other correlations lag far behind, with RMSEs of 38–100, MAPEs exceeding 10 %, and negative R^2 values, underscoring SVR's clear superiority for this profile.

Table 1 Site-Level Error Metrics (IJV038)

Model / Equation	RMSE (m s^{-1})	R^2	MAPE (%)
SVR	28.3	0.519	8
Mayne 2007	30	0.459	9.2
Andrus 2007	37.6	0.15	9.9
Robertson 2009	79.5	–2.801	22.6
Hegazy–Mayne 1996	88.2	–3.680	26
McGann 2015	99.7	–4.984	34.4

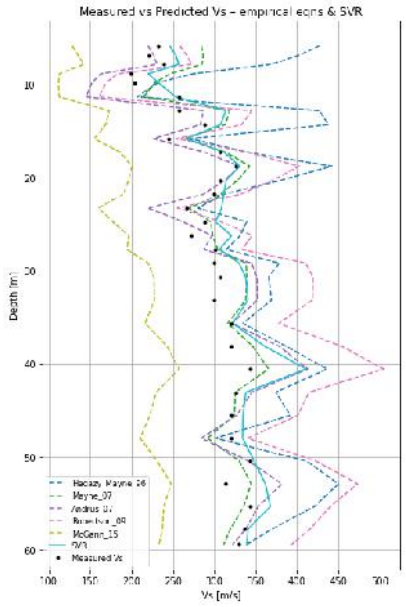

Figure 1 Measured versus predicted shear-wave velocity (Vs) profile for borehole IJV038

5. CONCLUSIONS

Machine-learning models trained on a comprehensive North Sea CPT database predict shear-wave velocity far more accurately than classical empirical correlations. Among the nine algorithms evaluated, support-vector regression (SVR) stands out, roughly halving the RMSE and keeping MAPE at or below 8 percent. Site validation at IJmuiden Ver shows that the model not only improves goodness-of-fit but also reproduces stratigraphic variations, sharpening small-strain shear-modulus estimates and cutting geotechnical uncertainty for offshore-wind monopiles.

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Optimising design and reducing risk for OWT foundations and anchors in Australian carbonate sediments

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Keywords: Seabed risk; carbonate sediments; Offshore foundations and anchors

1. INTRODUCTION

When designing, installing, and operating the infrastructure for offshore wind developments (e.g. offshore wind turbines and power cables), the seabed provides a project – and site – specific risk. For example, the most prevalent solution to fix offshore wind turbines in the rest of the world – driven monopiles – is unlikely to be feasible in at least some of the proposed Australian development areas. This is because Australian offshore wind farms carry a higher seabed risk, due primarily to the wide range of properties (ranging from very strong highly cemented calcarenites to very weak loose, fine grained carbonate muds), the way they are layered and their mechanical properties; all a result of how they were formed and the carbonate material they are made up of. This lesson was learnt (initially the hard way – see Senders et al., 2013) during oil and gas development on the North West Shelf and the Bass Strait, such that it is recognized that different considerations and design approaches are needed in these types of seabeds (e.g. Watson et al., 2019). Many of these findings are directly applicable to future offshore wind projects in Australia but need modifications to allow for the infrastructure types, their varying loading conditions, and limit states.

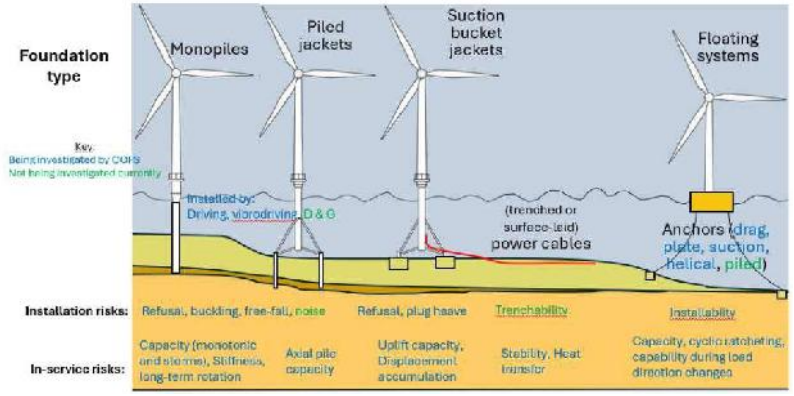


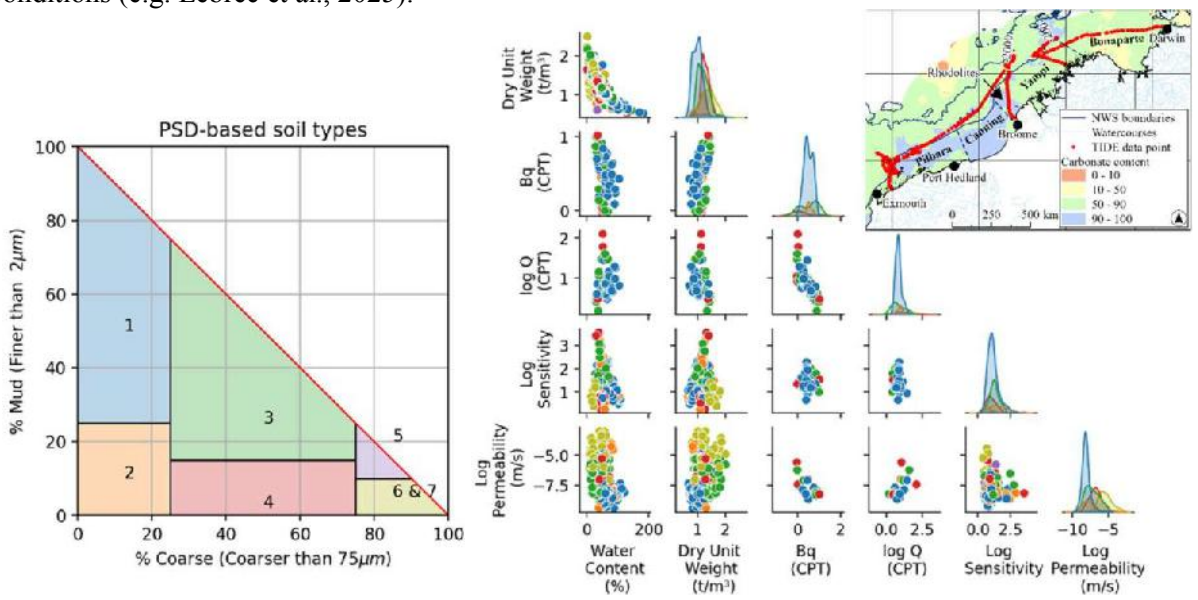
Figure 1 Infrastructure for offshore wind farms and their geotechnical challenges.

The Centre for Offshore Foundation Systems (COFS) at UWA has focused on carbonates since its formation in 1997, with emphasis on element response, approaches to characterise their properties, and the installation and in-place performance of a range of foundation and anchor types – with most conducted in collaboration with industry to ensure practical applicability and to facilitate uptake (Randolph et al., 2021). Our current work concentrates on providing inputs to offshore wind farm projects worldwide and connecting geotechnical research in Australia through the ACOWE initiative. This abstract summarises five pieces of ongoing work, selected amongst many ongoing projects to typify the research we are conducting on Australian carbonates, transitioning from the properties of the seabed itself, though to the installation and in-place performance of foundations for bottom-fixed turbines, and anchors for floating turbines.

2. ELEMENT RESPONSE

Information about specific areas of the seabed is obtained (at great cost) during every site investigation for every project. Typically, this information is retained by the Operator or Developer and so findings

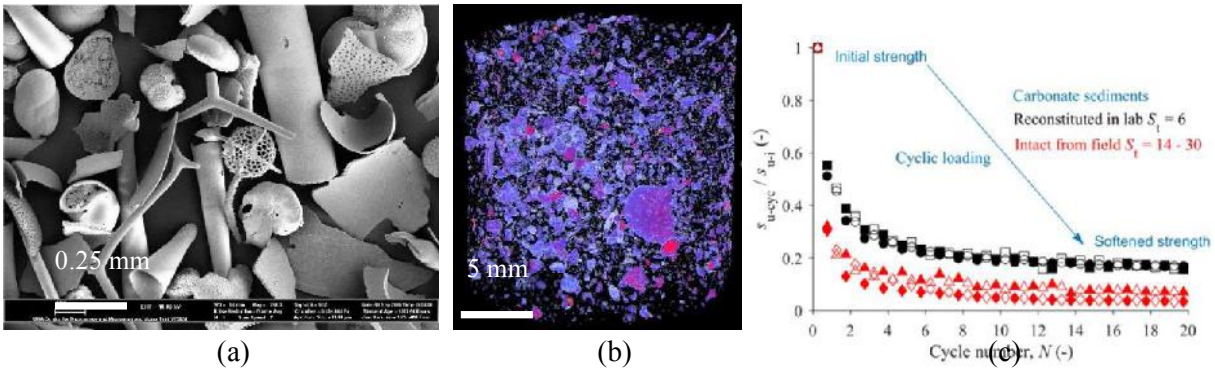
are restricted to providing direct inputs to the project. However, different areas of the seabed are likely to share similar characteristics because of their common geological origins (e.g. Lebrec et al., 2024). Therefore, collation of these findings has the potential to inform future projects by providing initial information (reducing initial risk) and reducing future site investigation scope (reducing cost and schedule). This process is underway with assembly of a data set comprising offshore in situ and laboratory element tests (including 1,545 PCPTs and 1,308 sampling locations). Figure 2 presents a proposed Particle Size Distribution (PSD)–based soil classification, which is being applied across the available data to identify potential patterns and correlations. Work is ongoing to link these to geological conditions (e.g. Lebrec et al., 2025).



(a) (b)

Figure 2 Preliminary findings from the carbonate soil database: (a) uncemented sediment types; (b) initial cross-correlations for the different materials (each dot represents a single data point with its colour depending on material type).

The mechanical behaviour of carbonate sediments arise from complicated grain behaviour – i.e. their irregular shape, ease of breakage and high compressibility, high void ratio and sensitivity, and variation of inter-particle bonding / cementation. Fig. 3a and b shows the typical skeletal remains of living organisms from Scanning Electron Microscopy (SEM) and a typical X-ray micro-CT scan of intact carbonate sand sample, where high intragranular porosity can be observed.



(a) (b) (c)

Figure 3 (a) SEM of carbonate sediments (after Watson et al. 2019) (b) X-ray micro-CT of carbonate sediments (c) cyclic strength degradation of intact and reconstituted carbonate sediments.

To explore the performance of geotechnical infrastructure, multi-million-dollar offshore tests could be performed. However, it is more effective to conduct small scale model tests, but to perform these tests different seabed types need to be recreated in the laboratory. Fig. 3(c) indicates the difference in soil behaviour between intact samples and reconstituted samples prepared from the same offshore sample, using conventional methods: the intact sediment shows significantly more softening

than the reconstituted sample. Ongoing work aims to develop new techniques recreating the physical and engineering properties of in situ carbonate sediments and use these findings to model a range of infrastructure types.

3. FOUNDATIONS FOR BOTTOM-FIXED TURBINES

One foundation option being considered in areas of seabed with cemented carbonates is piled jackets (see Fig. 1). Reduced-scale pile tests were conducted at a site at Pinjar, Western Australia where the geological and geotechnical properties are similar to those in Australia's planned offshore development areas. Cone penetration tests conducted at the site indicated a fairly consistent q_c = 55 MPa. The focus of the tests was on the drivability of impact driven piles and their post-installation shaft capacity during pile uplift. A total of 10 open-ended piles with diameter ranging from 114 to 324 mm and diameter-to-wall thickness ratios in the range 15 to 26 were driven to depths of either 2.5 m or 4.5 m. A Movax DH-35 hydraulic hammer was used with energy deliberately varied between 0.1 and 10 kJ, leading to a wide range in blow count per 0.25 m penetration. Tension loading of the piles after installation yielded ultimate shaft frictions in the range 33 to 159 kPa. The piles were subsequently extracted with the intact plug remaining in the pile, with subsequent dissection revealing varying degrees of plug breakage along the pile length, with maximum breakage occurring furthest from the tip.

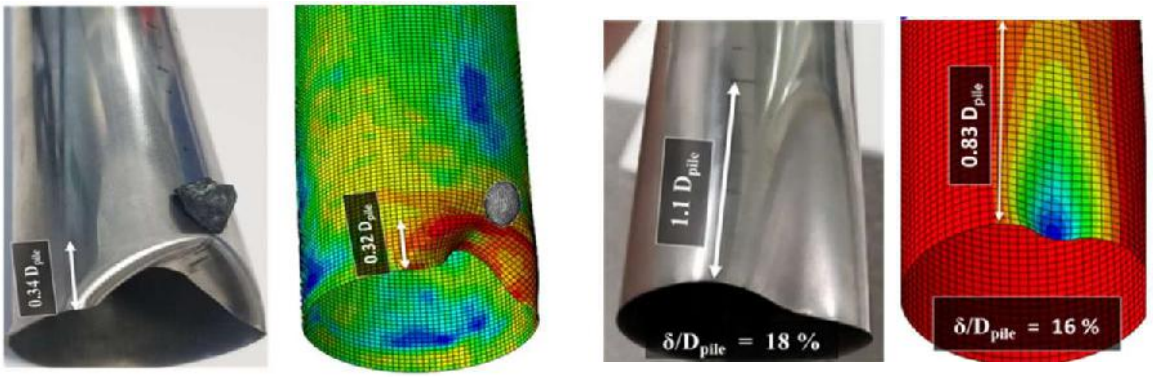
(a) (b)

Figure 4 Pile testing in cemented carbonates: (a) pile driving, (b) tensile loading

The presence of boulders or incompletely weathered soft rocks—such as the cemented limestones commonly encountered in Australian waters—poses a significant risk of pile damage during installation. This issue, first recognised by the oil and gas industry during the development of the North Rankin, a platform in the late 1990s on the North West Shelf, is expected to become more critical in offshore wind applications. Monopiles, being large-diameter and thin-walled, are particularly susceptible to tip damage and extrusion buckling. Such damage can lead to premature refusal, introduce uncertainty in the lateral response of the structure, and hinder post-installation operations such as drilling out the soil plug, if required. COFS have been addressing this issue through centrifuge modelling and large-deformation numerical analysis, forming the basis for an assessment framework to evaluate the potential for pile tip damage and extrusion buckling during installation (Figure 5; Nieteidt et al., 2023) so that this installation risk can be avoided in future projects.

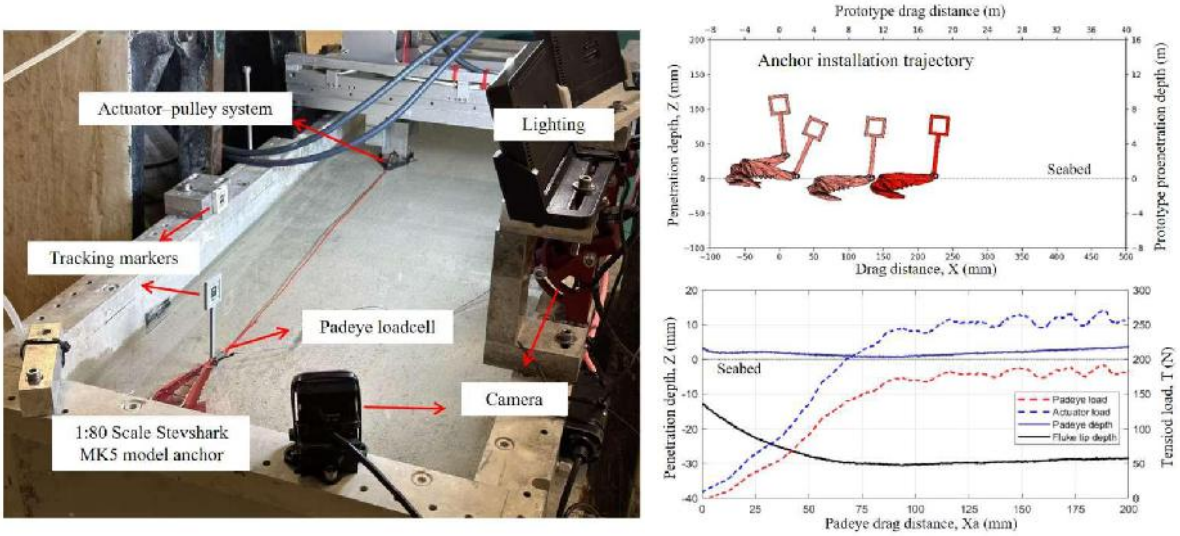
4. ANCHORS FOR FLOATING WIND

Both globally and in Australian waters, offshore wind farm developments are moving into deeper waters where the turbines will be floating, secured to the seabed using moorings and anchors. Much of the research effort at COFS therefore concentrates on the behaviour of drag anchors, plate anchors, helical anchors, suction anchors, and dynamically installed anchors in carbonate seabeds (Fig. 1). Although drag anchors are the most widely used anchor type, their performance in carbonate seabeds remains poorly understood, introducing significant uncertainty into their use in future Australian projects. To address this, centrifuge tests were conducted using carbonate sand samples and a 1/80th scale model of a 20-tonne Stevshark Mk5 anchor (Fig. 6a).



(a) (b)

Figure 5 Centrifuge and numerical modelling of pile tip damage and extrusion buckling: (a) Pile-boulder interaction; (b) progressive distortion



(a) (b)

Figure 6 Drag anchor tests in carbonate sand: (a) Experimental arrangement in the centrifuge, (b) anchor trajectory and holding capacity

The anchor trajectory and load response during the installation process are shown in Fig 6b, indicating that anchor penetration was very shallow, with the padeye essentially scraping along the seabed. This is considered to be due to the high friction angle of the carbonate sand, which limits penetration and so reduces the holding capacity. Work to reveal potential improvements to mitigate this issue (such as enlarging the shank–fluke angle, adding anchor weight, or reducing the surface area of the shank to facilitate deeper embedment) is ongoing.

5. CONCLUSIONS

This contribution provides an overview of some of the research activity being conducted (and some of the research methods being used) at UWA targeted to provide information for the Australian offshore wind industry. This and future collaborative research designed to reduce risks associated with carbonate seabeds should be conducted before entering key project design phases to avoid the costly lessons from early oil and gas developments in Australia.

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Multi-scale Investigation of Carbonate Sediments in Australia

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Keywords: Carbonate sediments; µCT imaging; particle shape; soil testing; centrifuge modelling

1. INTRODUCTION

Carbonate sediments are prominent in several of the declared offshore wind regions in Australia. Most of these offshore sediments are biogenic in origin, consisting largely of the skeletal remains of single-celled marine organisms, such as plankton and zooplankton [1]. As a result, these sediments tend to experience particle crushing and pose complex engineering challenges in the design, construction, operation and decommissioning of offshore foundations in these crushable sediments [2]. To provide a better understanding of the behaviour of these carbonate sediments, this study presents existing and ongoing investigations on several carbonate sediments in Victoria (VIC) and Western Australia (WA) across multi-scale (imaging and soil element testing). The location of these sediments is presented in Figure 1, with their carbonate content and mean particle size (d_{50}) summarised in Table 1. Among the six sediments, the Picnic Bay (PB), Norman Beach (NB), and Ledge Point (LP) sands were sampled from the coastal environment, while the Bass Strait (BS), Fine Carbonate (FC) and Goodwyn (GW) sands were sampled from offshore locations. The different depositional environment is known to produce different microstructure, thus mechanical behaviours [1]. It is also worth noting that the two Victorian coastal sands (PB and NB) have a low carbonate content of < 50%, which is considered as transitional sediments and generally do not exhibit the distinctive engineering properties attributed to carbonate sediments [2]. Nevertheless, they were included in the preliminary study due to their close proximity to the declared Gippsland offshore wind zone.

Figure 1 Origin of carbonate sediments considered in this study.

2. MULTI-SCALE INVESTIGATION OF CARBONATE SEDIMENTS

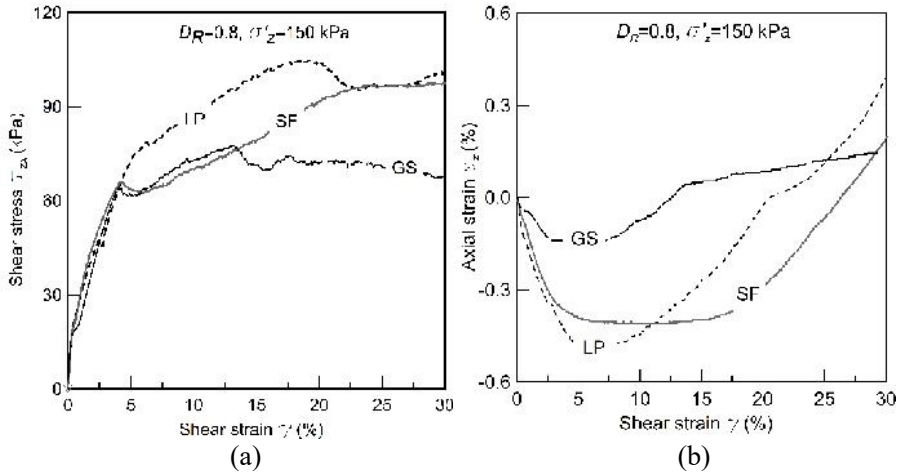
The micro-structure of the carbonate sediments was first investigated using X-ray micro-Computed Tomography (μCT) imaging technique at a high resolution of 5.5 μm/pixel in x and y directions at the University of Melbourne [3]. The images were then post-processed using an in-house developed algorithm to derive common 3D particle shape descriptors of the six sediments in Table 1. It is observed that the Sphericity (S_L) and Convexity (C) of the offshore sediments (BS, FC and GW) are smaller compared to the coastal sediments, while the opposite is observed for the Roundness Index (I_R). Other than these carbonate sediments, the imaging campaign was also extended to determine the 3D particle shape descriptors of several common silica sands and glass sphere for benchmarking purpose but not included here for brevity.

Table 1 3D particle shape descriptors of carbonate sediments in Australia.

Material	Origin	Carbonate content	d_{50}	3D particle shape descriptors (mean)		
				Roundness Index (I_R)	Convexity (C)	Sphericity (S_L)
Picnic Bay (PB)	VIC/coastal	8.8%	0.40	1.10	0.78	0.41
Norman Beach (NB)	VIC/ coastal	40.9%	0.14	1.07	0.75	0.45
Bass Strait (BS)	VIC/offshore	N.A.	1.20	2.00	0.34	0.05
Ledge Point (LP)	WA/ coastal	87.1%	0.26	1.15	0.58	0.21
Fine carbonate (FC)	WA/offshore	95.6%	0.15	1.58	0.44	0.08
Goodwyn (GW) [4]	WA/offshore	84.3%	0.32	1.58	0.48	0.12

To link the microscopic characteristics with mechanical behaviour, laboratory soil element tests were conducted to assess the effect of particle shape and mineralogy on shear strength and deformation behaviour of a carbonate sand, silica sand and glass sphere [3]. Direct simple shear (DSS) tests were conducted considering a range of relative densities (D_r = 40 to 90%) and effective normal stresses (σ'_z = 25 to 150 kPa). Due to the limited quantity of offshore samples, only the coastal LP sand was used in the DSS testing. As shown in Figure 2, the angular LP sand produced higher peak stress and deformation when when compared against a sub-rounded silica sand (SF) and rounded glass sphere (GS), although the same trend cannot be observed at lower σ'_z (not presented here for brevity).

To extend the study, ongoing work includes triaxial testing of LP, SF and GS samples at similar relative density and stress levels; along with targeted tests at high stress level to examine particle crushing in the LP sand. In addition, the fabric evolution of the three materials is being investigated considering two different stress paths and imaging techniques; (a) a modified DSS apparatus and synchrotron microtomography [5]; and (b) miniature triaxial apparatus and X-ray micro-Computed Tomography.



(a) (b)

Figure 2 Comparison of (a) shear strength; and (b) deformation behaviour of Ledge Point (LP) sand against UWA silica sand (SF) and glass sphere (GS) at D_r of 80% and σ'_z of 150 kPa [3].

3. CONCLUSIONS

This study has characterised the 3D particle shape descriptors of several coastal and offshore carbonate sediments in Victoria and Western Australia using X-ray micro-CT imaging. The particle shape descriptor of carbonate sediment is found to vary according to the different depositional environments. The effect of sand particle shape and mineralogy on the mechanical responses of selected carbonate sediment is then examined using laboratory direct simple shear tests. The carbonate sediment with complex particle shape is found to produce different mechanical response than the sub-rounded silica sand and rounded glass sphere.

Future works include the development of an advanced multi-surface constitutive model with particle breakage treatment to accurately capture the response of carbonate sediments. The model will then be implemented in commercial finite element software to model offshore wind foundations under monotonic and cyclic loading in carbonate sediments. The numerical model will be validated using physical model foundation tests using geotechnical centrifuge modelling technique.

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Discrete Element Modelling of granular seabed-structure interaction problems

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Keywords: Discrete Element Method; Calibration; Seabed-structure interaction

1. INTRODUCTION

Conventional continuum numerical methods, such as the Finite Element Method, often fall short when it comes to modelling complex granular seabed-structure interaction problems involving large deformations. Such problems include, but are not limited to, modelling the installation of piles and anchors, or predicting the reaction offered by the seabed to relative lateral and/or axial movement of underwater cables, mooring chains and pipes. The Discrete Element Method (DEM) is an attractive alternative to continuum methods for modelling these problems, as it can rigorously handle simulation of very large deformations, but also modelling strain-softening materials under low-to-very low confining stresses without suffering from mesh dependency issues. While there are several differences between continuum methods and the DEM, here we focus on the calibration of the necessary input parameters to mathematically describe the mechanical behaviour of the seabed. Continuum methods rely on constitutive models to describe soil behaviour, often incorporating a dozen or more material parameters, that are calibrated on measurements obtained during elements tests on soil samples, or determined empirically. On the other hand, the DEM relies on a handful of micromechanical parameters to describe the contact forces that develop between individual numerical particles, which depend on the adopted contact law. These micromechanical parameters are not directly related to any specific soil mechanics test. This renders their calibration cumbersome, as contact law parameters are interdependent and there may exist multiple parameter combinations that will yield similar macromechanical response.

In this abstract we present in brief a rigorous method for calibrating DEM contact law parameters. The method relies on the simultaneous use of different types of laboratory element tests to obtain a single set of contact law parameters that can successfully describe the mechanical behaviour of granular materials at different densities, subjected to different stress paths under varying stress levels. The merit of this approach is eliminating the need for "back-analysing" physical modelling experiments or resorting to tedious trial-and-error procedures. We have shown in earlier publications (Li *et al.* 2024, 2025) that the method can be used to "blindly" predict results of physical model tests on onshore pipes buried in soil. Here we demonstrate how our simulation method can be used to predict the reaction developing on an underwater cable laid on the seabed surface, during cyclic lateral movement episodes.

2. CONTACT LAW PARAMETER CALIBRATION PROCESS

The method we have developed to calibrate DEM contact law parameters is described in detail in Li *et al.* (2025) and is based on the Bayesian calibration framework "GrainLearning" (GL) of Hartmann *et al.* (2022). Its main feature is the simultaneous calibration of contact law parameters while considering multiple element test data, involving different confining stresses, material densities but also stress paths, in a consistent and structured manner. In this example we present the calibration of the parameters of a silica sand on the results of a series of Constant-Rate-of-Strain (CRS) one-dimensional compression tests, and isotropically-consolidated drained triaxial (TRX) compression tests. The tests were performed on dense (initial void ratio $e_0 = 0.558$) and medium dense ($e_0 = 0.656$) specimens. The confining stress applied during the consolidation stage of the triaxial tests ranged from $\sigma_c = 25$ to 100 kPa. The reference measurements selected for the calibration were those from the CRS test on dense sand, and from the σ_c

= 25 kPa and σ_c = 50 kPa TRX tests on dense sand. The remaining CRS and TRX test measurements were used for control purposes. DEM models were prepared to numerically replicate the CRS and TRX tests, each comprising up to approximately 25,000 spherical particles. The particle size distribution of the numerical samples was similar to that of the real sand, but the mean diameter of the spherical particles $D_{50,DEM}$ was scaled to be x10 larger than that of the real sand ($D_{50,DEM}$ = 3.6 mm), to reduce computational cost. An initial range of the adopted Hertz-Mindlin contact law parameters was entered as input, to sample parameter values from. The initial range of the parameters was: log$E$ = 8 to 10; ν = 0 to 0.5; φ_μ = 10 to 40; β = 0 to 0.05; η = 0 to 0.5 where E is the micro Young's modulus (in GPa), ν is the micro Poisson's ratio; φ_μ is the interparticle friction angle (in deg), β is the rolling stiffness coefficient; η is the rolling friction coefficient. The GL method is iterative. During each GL iteration we sampled N_p = 80 parameter sets and we performed N_p CRS and TRX simulation sets. Each simulation set consists of one CRS simulation and two TRX simulations (one for each confining stress). From each simulation set we collect predictions of vertical stress-axial strain from CRS models, as well as deviatoric strain-axial strain and volumetric strain-axial strain from TRX models. We compare these predictions with the reference measurements, and we accordingly update the probability distribution of each contact law parameter, to inform resampling of parameters from the input range for the next GL iteration. The process is repeated until we find an "optimal" parameter set, that minimises the absolute error between DEM predictions and measurements (see Li *et al.* 2024, 2025 for more details). Predictions of the DEM models incorporating the optimal parameter set are compared against indicative TRX and CRS test measurements in Fig. 1. The observed match suggests that the developed calibration procedure provides a single set of DEM contact law parameters that can replicate the behaviour observed during different types of tests (i.e., different stress paths), for different sand initial densities.

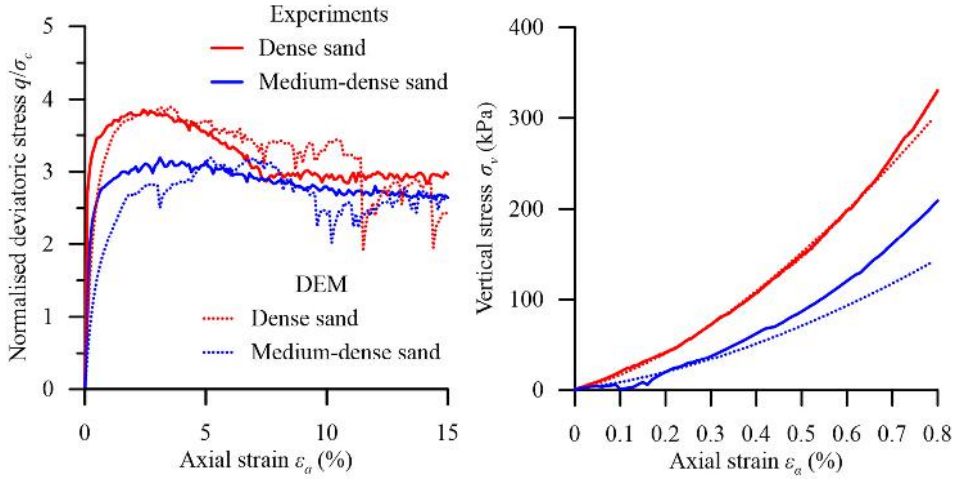

Figure 1 Comparison of test measurements and DEM predictions: (left) TRX for confining stress σ_c = 50 kPa; (right) CRS tests. Results for: E = 2.994 GPa; ν = 0.047; φ_μ = 24.114°; β = 0.017; η = 0.112.

3. SIMULATION OF CABLE-SEABED INTERACTION

An overview of the problem we simulated to demonstrate the potential of the method is provided in Fig. 2. A D = 50 mm diameter submarine cable of weight 48 N/m (corresponding to a polypropylene-coated cable with two layers of steel armor protection) is resting on the surface of a dense sand seabed, which is modelled by stacking "stress-free" Representative Volume Elements (RVEs) containing 1,000 spherical particles each. The interparticle and particle-cable contacts are modelled with the Hertz-Mindlin contact law, using the parameters listed in the previous section and soil-cable interface friction angle $\varphi_{\mu p}$ = 15°. To reduce the computational cost of this simulation we model the cable as rigid, and use a single REV in the out-of-plane x-direction with periodic boundaries to enforce quasi plane-strain conditions. The simulation consists of three stages: First, we apply a vertical velocity 0.02 m/s to the cylinder representing the cable to model laying of the cable. Then, the cable is dragged horizontally at rate 0.02 m/s until a lateral displacement of magnitude δ_h = 1D is reached. Accordingly, the sign of the velocity is reversed, and the cable is dragged along the opposite direction for δ_h = -2D, to simulate cyclic lateral movement. During the last two stages the cable is free to move vertically. Some indicative results

are presented in Fig. 3, which depicts the formation of a berm downstream of the cable during lateral movement, and the variation of the dimensionless reaction offered by the seabed during the cyclic movement episode. The presented results demonstrate that the analysis method can simulate large seabed deformations, and the reduction in the resistance offered by the seabed during cyclic movements.

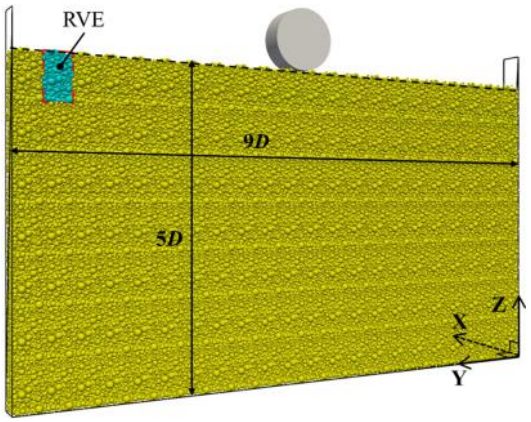

Figure 2 Overview of the simulated problem.

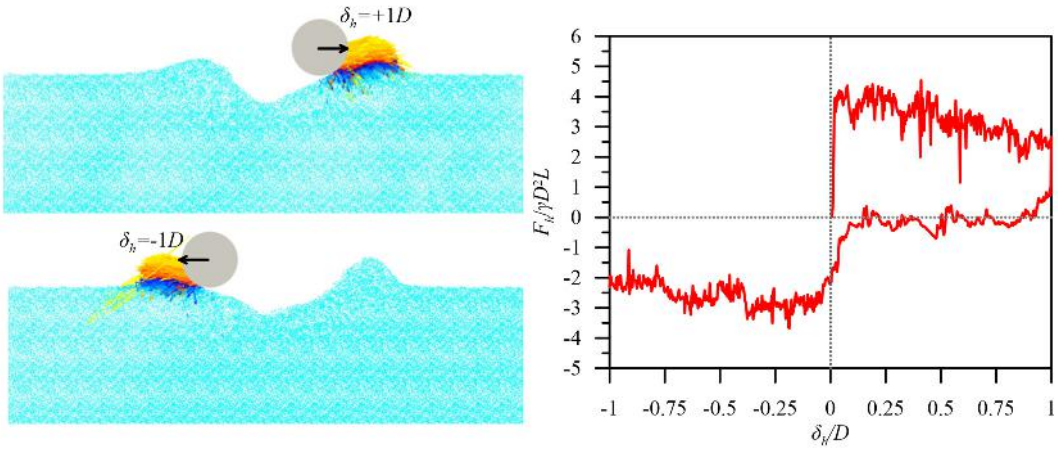

Figure 3 Indicative simulation results: (left) Incremental displacement vectors from different analysis stages; (right) Dimensionless reaction F_h on the cable as function of cable displacement δ_h. γ = 17 kN/m^3 is the dry unit weight of the seabed material and $L = 5.42D_{50,DEM}$ is the out-of-plane length.

4. CONCLUSIONS

We have presented an overview of a newly developed calibration method for DEM contact laws, that provides an optimal set of parameters to describe the mechanical response of coarse-grained seabeds under different stress paths and initial conditions. We have shown in earlier publications that the calibration method provides excellent blind predictions of the response observed in physical model experiments, without having to resort to "back-analysis". Here we have applied the method to derive the parameters required to simulate a typical offshore geotechnical engineering problem, and we have shown that our method can capture salient features of cable-seabed interaction.

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Resilient foundations in problematic deposits

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Keywords: Offshore wind energy, monopiles, problematic soil, vibratory driving

1. INTRODUCTION

Offshore wind energy development is expanding rapidly, especially in regions with complex seabed conditions. Among different foundation options, monopiles remain the most common due to their cost-effectiveness and structural reliability [1]. Traditional impact hammering has long been used for installation [2, 3], but this method faces serious limitations in dense sands, such as poor drivability, damage to pile heads, and harmful underwater noise. Vibratory driving, which uses low-amplitude axial vibrations, is increasingly considered a better alternative. It is quieter, causes less stress on the pile, and is more efficient in some aspect. However, its use remains limited, especially in soils with unusual mechanical responses.

Early studies in Germany and later experimental work demonstrated that vibratory methods could reduce shaft resistance significantly. Recent findings show that introducing a rotational vibration component can create greater shear stress in the surrounding soil, enhancing penetration. Still, the unpredictable nature of problematic deposits complicates installation. Calcareous sands, rich in calcium carbonate and common in regions like Australia, crush under load, reducing friction and triggering excess pore pressure. Glauconite sands behave even more strangely—initially granular, they transform under shearing and become cohesive-like, making driving and post-installation performance harder to predict [4].

To cover these uncertainties and to ensure a safe and cost-effective foundation system in problematic soils, this paper aims to explain how vibratory installation affects particle breakage (Br) around the pile and its drivability as the initial point of interest.

2. METHODOLOGY

To address this aim, a numerical modelling approach is selected for initial evaluations. To facilitate the solution procedure, the problem is divided into several packages: (1) Simulation of monopile penetration into a uniform regular soil using large deformation finite elements schemes, i.e. Coupled Eulerian-Lagrangian (CEL) analysis, (2) Element modelling of problematic soil behavior under cyclic/dynamic loading using an advanced constitutive model (i.e. SANISAND) and its calibration, (3) Combination of the two mentioned packages for solving a full boundary value problem. Each of these packages can include several sub-steps to achieve the final objectives. Although this paper does not cover all the above points, we will try to highlight some of the key challenges and any useful results for advancing this in-demand area further. The insights are then used to produce more realistic drivability charts.

At this stage, finite element model for analysis of pile penetration simulation models is being verified and refined for large-deformation problems. The geometry and loading of the reference model for verification was selected from Stuabach et al. (2022) [5].

For initial trials, a cap plasticity model was used. Calibration of the advanced SANISAND model [6] or its more recent variations is also under progress. Modelling and analysis are being undertaken in Abaqus [7].

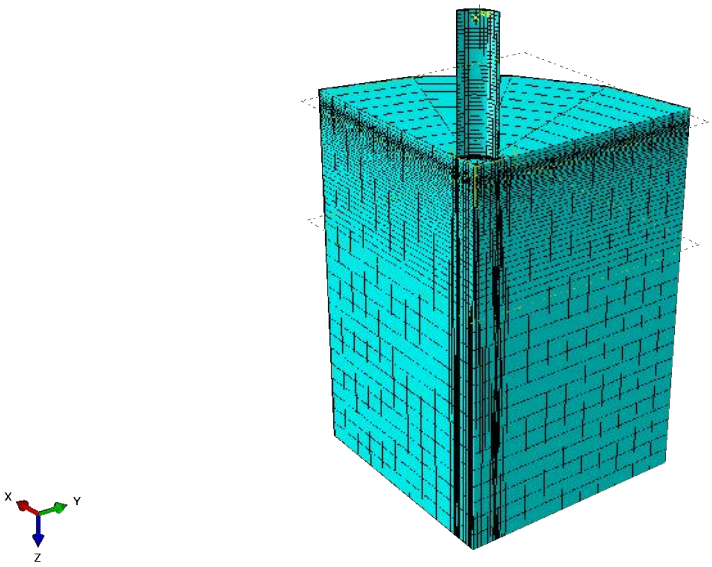

Figure 1 Finite element mesh of the monopile.

The Karlsruhe Fine Sand model parameters calibrated for the cap plasticity model are provided in Table 1.

Table 1 Cap model parameters for Karlsruhe fine sand

Material cohesion	**Angle of Friction**	**Cap Eccentricity**	**Initial Yield Surface Position**	**Transition Surface Radius**	**Flow Stress Ratio**
Pa	degrees				
18439	52	2.8	0	0.03	0.78

3. RESULTS

In Figure 2, a deformed mesh of the pile penetrated by vibratory driving is shown. The results demonstrate a promising base for development and implementation of sophisticated mechanisms including particle crushing and pore water dissipation in the future.

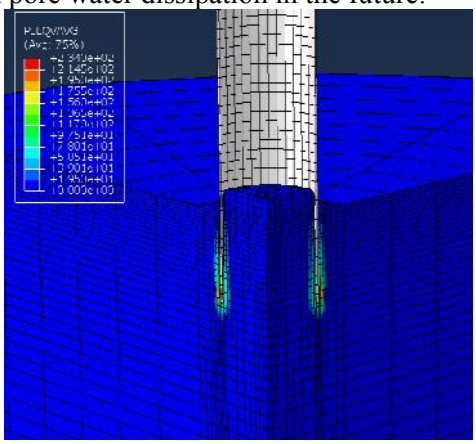

Figure 2 Eulerian volume fraction (evf) during the installation by vibratory driving.

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Session 4: Metocean & Hydrodynamics

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Australian wave climate and its implications on offshore wind structures – from monopiles to floaters

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Keywords: offshore wind, Southern Ocean, swell waves, wave statistics, wave force, design

1. INTRODUCTION

The six declared offshore wind zones in Australian federal waters have different wave climates, but are all influenced by the Southern Ocean. This makes the local wave conditions, which offshore wind substructures are designed for, rather different compared to the offshore north-west Europe where much of the existing offshore wind infrastructure has been deployed. The wave climate along the Australian southern margin is dominated by long-period swell waves approaching from the south-west. While the Bass Strait and the south-east coast are somewhat sheltered from the Southern Ocean swells, they are also influenced by other atmospheric drivers such as the East Coast Lows, for example. This work discusses implications of the unique Australian wave conditions on future offshore wind structures, drawing on existing studies and analysis of new wave data. The northern Australian coast is excluded.

Wave conditions are characterized by wave height, period and direction, and in a sea-state these are typically described statistically. Wave climate is then a long-term statistical description of these sea-state parameters.

2. WAVE HEIGHTS

A key characteristic of Australian wave conditions along the SW, S and SE coast is their **omni-presence** and **persistence** [1, 2, 3]. Significant wave heights H_s drop below 1 m rarely and only for short times, as strikingly illustrated by Figure 1. Though they exist, **seasonal effects are low**, very unlike the conditions in the North Sea with prolonged calm periods during summer which enable large-scale offshore installations and other operations. Another distinguishing feature are **low extreme values**.

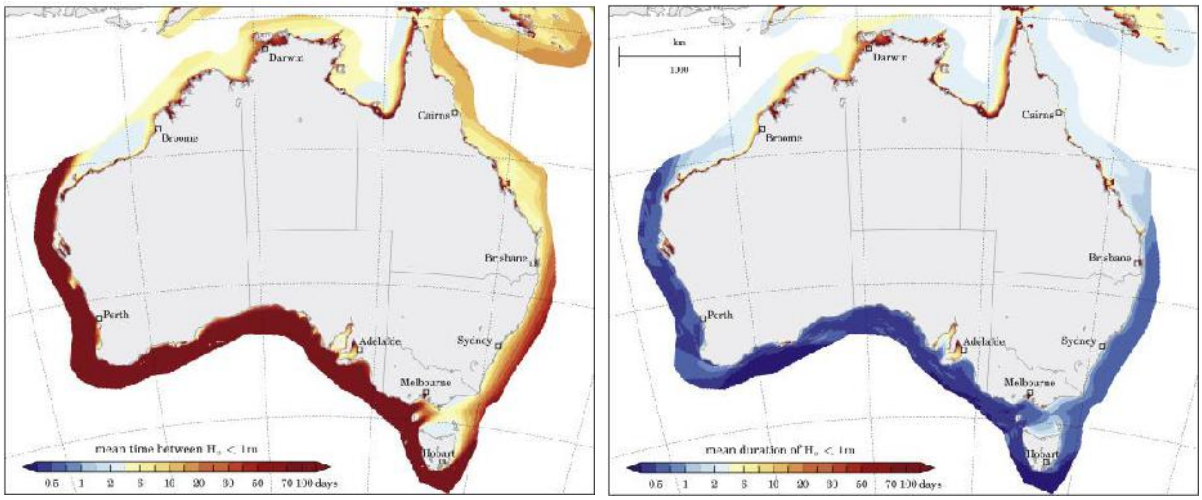

Figure 1: Mean time between (left) and mean duration of (right) instances with H_s < 1 m (both in days) [1].

As a specific example, a comparison between Albany on the exposed SW coast of Western Australia and the European Marine Energy Centre in the Orkneys, UK in the North Sea/North Atlantic Ocean is shown in Figure 2. Both locations are in 60 m water depth. At the Australian location, waves are always present and exhibit low intra-annual variability. Even though the long-term mean H_s is higher in Albany compared to Orkney, the extremes are remarkably low. [3] found wave heights at return periods of 1 in 100 years and above to be nearly twice as large at Orkney compared to Albany.

The different wave height characteristics have direct implications for design, installation and maintenance of floating and fixed offshore wind turbines in Australian conditions. Ultimate limit state extreme loading conditions may play a reduced role compared to fatigue loading, and support structures must be designed with easy installation and reduced maintenance opportunities in mind to enable deployment in an environment with limited calm weather windows.

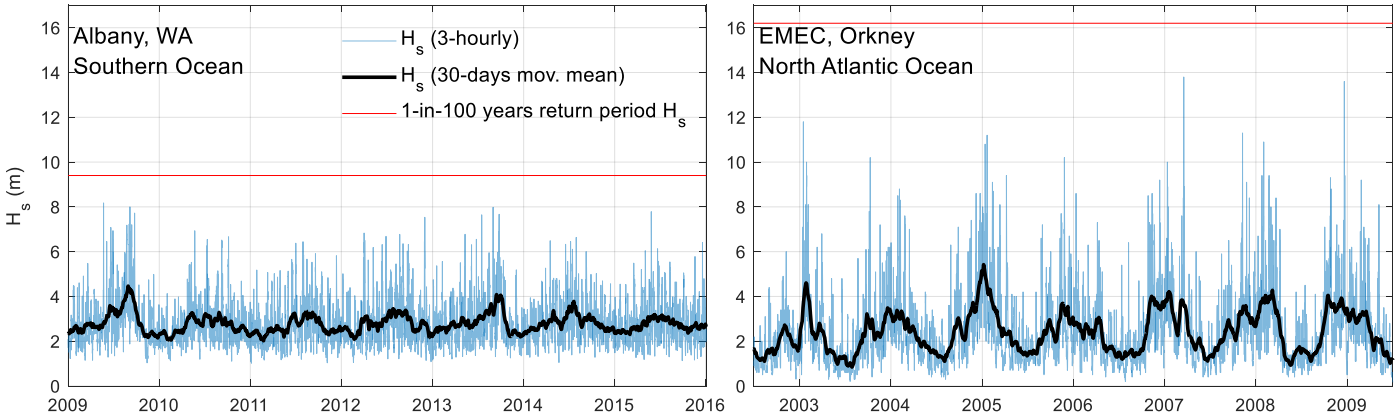

Figure 2: Timeseries of H_s (in m) from offshore Albany, Australia (left) and off the Orkneys, UK (right) [3].

3. WAVE PERIODS

The wave periods along the SW and S coast are **very long**, with mean energy periods T_e around 11 s, while considerably shorter waves of around 7-8 s are more typical in the SE waters (see Figure 3). Due to the quadratic relationship between wave period and wavelength, the SW and S waves are twice as long. Consideration of wave periods in design of offshore wind turbines is crucial due to their **potential to excite resonant responses**. As such, the tower-bending natural frequencies in offshore wind turbines are typically designed to fall in the super-harmonic high-frequency region, while the natural frequencies of rigid-body motions in soft-moored floaters, such as semi-submersibles and spars, target the sub-harmonic low-frequency range (see Figure 4).

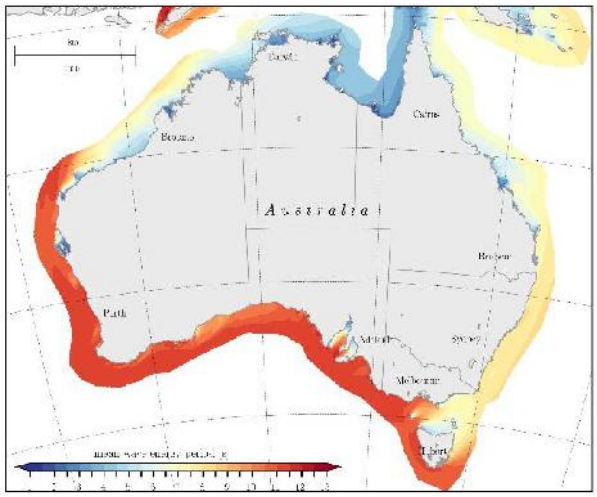

Figure 3: Mean wave energy period T_e (in s) [1, 2].

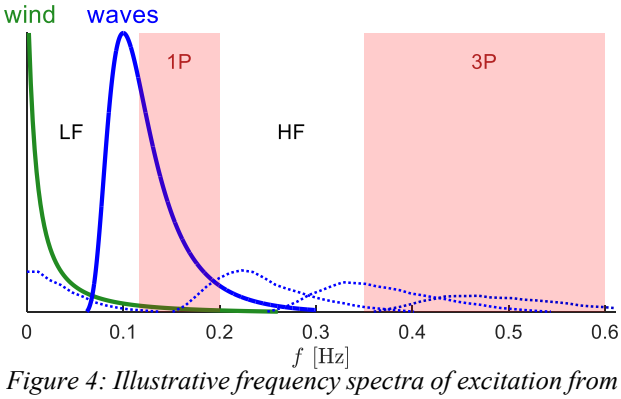

Figure 4: Illustrative frequency spectra of excitation from waves, wind and wind turbine rotor (1P and 3P). The low-frequency (LF) and high-frequency (HF) spectral gaps are typically targeted in design of offshore wind turbines, in order to avoid resonance. The dashed lines illustrate nonlinear wave forcing.

In addition to direct excitation by the main energy-bearing wave components, wave period is also highly relevant in nonlinear wave excitation, since under long-wave/shallow-water regime wave nonlinearity and the associated nonlinear wave forcing become amplified. As a specific example, Figure 5 shows linear and nonlinear wave forces exerted on a monopile foundation in 14 and 11 s waves (of the same steepness) in 30 m water depth [4]. The nonlinear wave forces are seen to be a significant fraction of the total forcing – they are thus important in estimating maximum design loads relevant to overload and foundation failure. Equally important is their effect on structural dynamics and fatigue damage due to their frequency content spanning natural frequencies (see Figure 4). The very long wave periods in Australian waters thus require careful account of nonlinear loading in design.

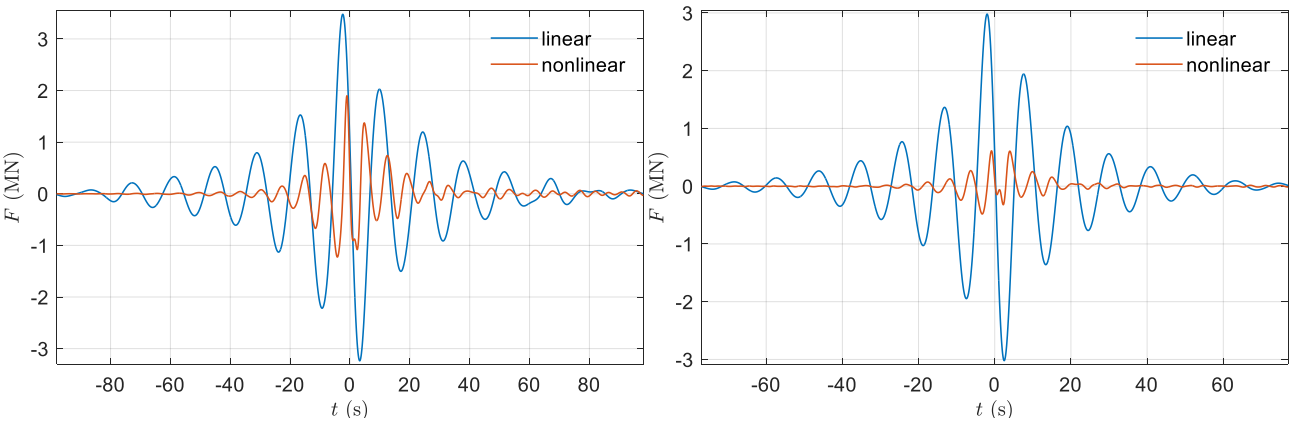

Figure 5: Horizontal wave force exerted on a monopile foundation in waves groups with peak period T_p of 14 s (left) and 11s (right)[4].

4. WAVE DIRECTIONALITY AND WAVES-WIND CO-OCCURENCE

Another unique characteristic of Australian wave conditions is their **weak coupling to local winds**, particularly along the S margin, due to the wave climate being dominated by swell waves from past, distant storms in the Southern Ocean. This has importance consequences in the design process as many design load calculations assume co-occurrence.

Wave directionality, both in terms of mean propagation direction and spreading about this mean, influence the dynamics of offshore wind turbines. Along the exposed S coast spreading is narrow and approach directions fairly constant [3, 5], while in the Bass Straight directionality is rather varied and location-specific [6]. Hydrodynamic loading in spread waves, as well as multi-directional combined wind-wave-current excitation, is an active area of research.

In summary, the Australian wave climate, with persistent long-period swell waves from the Southern Ocean, represents a new loading regime for offshore wind foundations, with further research and innovation needed for their safe and economic design, installation and maintenance.

ACKNOWLEDGEMENTS

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Overdesign in jacket substructures - Rethinking wave and current load assumptions for Australian offshore wind

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Keywords: Hydrodynamic forces, wave-structure interaction, current blockage

1. INTRODUCTION

Jackets are fixed, bottom-founded steel structures, comprising numerous slender cylindrical members and assembled as a spaceframe. From oil & gas origins, jackets are now an established support structure in offshore wind, used as foundations to support turbines (usually in deeper waters where monopiles are less cost effective) and used as electrical sub-stations (see figure 1).

It is forecast that jackets will be heavily utilized in Australia's offshore wind developments. Based on bathymetry, with jackets assumed best in water depths of 40-60 m, 55% of the Gippsland region and 44% of the Bass Strait will require jackets [1]. In addition, [12] highlighted the challenges of offshore wind foundation design in carbonate soils that are prevalent for Australian waters, for which jackets may offer advantages over monopiles. Moreover, electrical substations (which are required for most offshore wind farms) are almost always jackets, even for floating wind farms.

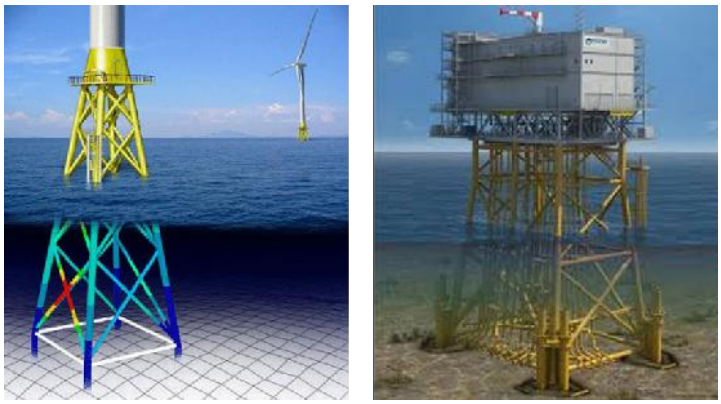

Figure 1: Offshore wind jackets. Left: Turbine-supporting lightweight jacket [9]. Right: Electrical substation jacket [10].

Cost is the enemy of offshore wind. Foundations like jackets make up a large percentage of the total capital cost (~20% according to [5]), so reducing the cost of jackets is highly beneficial. The cost of jackets is largely dictated by the amount of steel required, and this is sensitive to the assumed ocean wave and current loads that the structure must withstand. In regions known to have large wave and currents, like the Bass Strait, this cost sensitivity will only increase.

There is evidence to suggest that the present design approach to estimate these wave and current loads on jackets is overly-conservative, as some physical phenomena are not accounted for. Namely, the combined action of wave and currents on jackets has been shown to result in a dramatic reduction in hydrodynamic forces, an effect called 'wave-current blockage' [2,7,8]. Figure 2 estimates that, for a particularly extreme case with a jacket (that roughly resembles an offshore wind substation) subjected to (scaled) 1.25 m/s current speed and 17 m wave amplitude, properly accounting for 'wave-current blockage' results in a ~15% reduction in peak drag force over the present best practice blockage estimate [11]. Large cost savings could be gained if this effect is incorporated in design. The complication to this, however, lies in the fact that accurately accounting for 'wave-current blockage' is complex, likely too complicated for practical design purposes. It requires Computational Fluid Dynamics (CFD)

simulations that are time consuming to set up and run and difficult to validate. Advances must be made in better understanding 'wave-current blockage' and synthesizing this understanding into a simple recipe to incorporate into design standards.

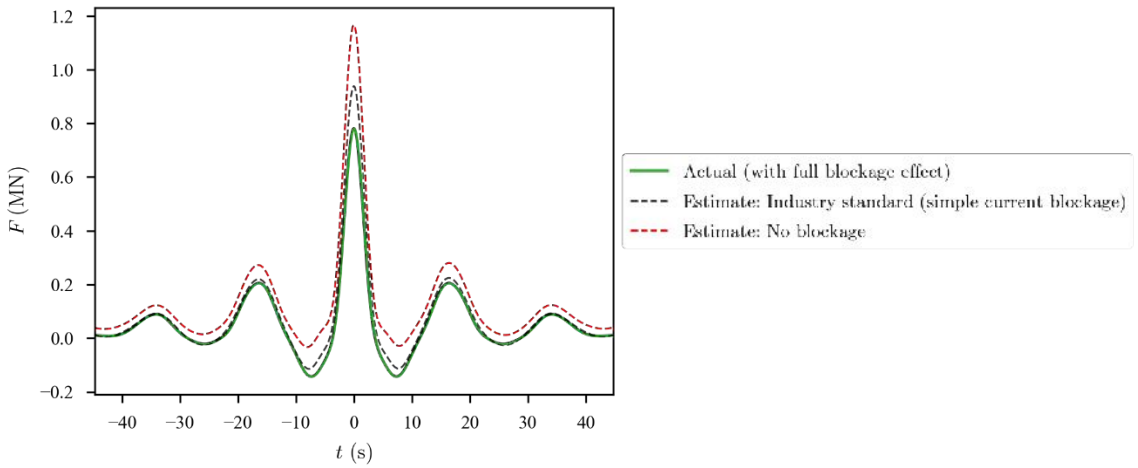

Figure 2: The effect that different assumptions of 'wave-current blockage' have on estimated drag forces, for a jacket subjected to 17 m wave amplitude and a 1.25 m/s in-line current (from [2]). Compared to measured forces, the industry standard method of simple current blockage [11], and no account of blockage, both dramatically over-estimate peak forces.

In this talk, we will cover a body of work that addresses these challenges, aiming to better understand 'wave-current blockage' to the point where a simple design recipe to estimate its effect can be confidently prescribed.

2. APPROACH

The presented works combine two fundamental approaches of physical experiments and CFD simulations. In this extended abstract, only the CFD simulations will be described.

The CFD simulations used the open-source software OpenFOAM and were set up to replicate the test conditions of the physical experiments. Jacket structures were represented in 3-dimensions (3D) as porous blocks, as previously done by [7,8], with different jackets (e.g., turbine-supporting jacket or electrical substation) represented by adjusting the porosity and flow resistance of the block. The waves2Foam toolbox [3] was used to handle the generation of focused waves and in-line currents. Mimicking the physical experiments, the 3D numerical tank (figure 3) had a water depth of 1.8 m and a width of 4.6 m. The length of the tank was truncated to save computational resources, with fully nonlinear free surface and wave kinematic information fed in at the inlet (x = 28 m), interacting with the centre of the jacket at x = 30 m, and dissipated by a numerical beach from x = 40 m to 50 m. The flow resistance of the porous block was defined with equivalent Morison drag and inertia components [6], using the approach by [4] (see [7] for more details on this equivalence).

3. RESULTS

Preliminary results support the large reductions in drag forces shown in figure 2 [2] when 'wave-current blockage' is properly accounted for. A further, more detailed set of results will be presented in this talk, including progress made to synthesise a simpler recipe for estimating this effect. This simpler recipe may be suitable for adoption in design standards and could yield a significant cost saving to Australian offshore wind projects.

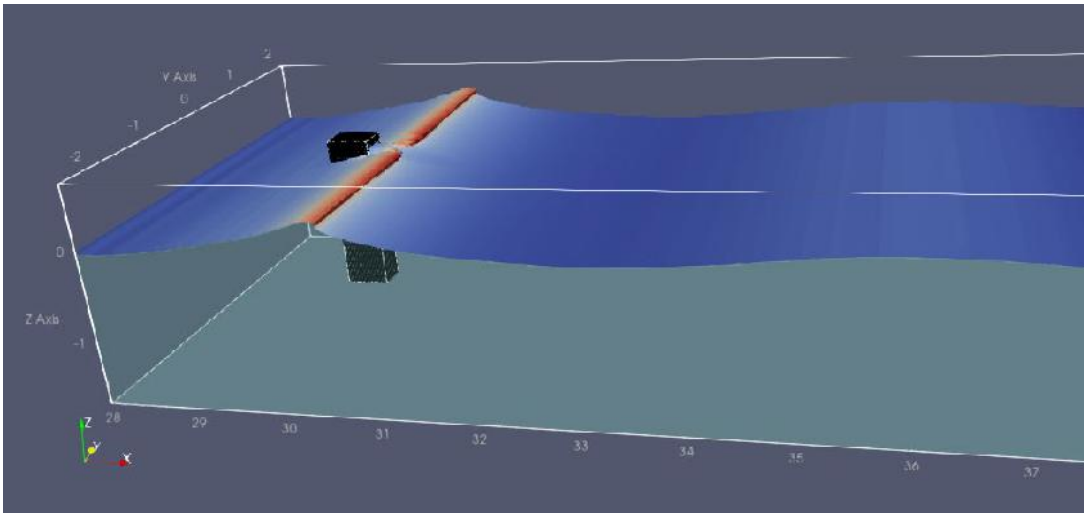

Figure 3: The 3-dimensional CFD solution domain (extends to x = 50 m out of frame). The porous block is shown in black at x =30 m, with its base at z = -1.33 m and extending above the maximum free surface.

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Assessment of Long-Term Trends and Variability of Wind Power Density off the Coast of Australia

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Keywords: wind energy; wind power density; Gumbel distribution; Australian offshore

1. INTRODUCTION

The southern coast of Australia is known for its strong and consistent winds, primarily influenced by the westerly belt(Li et al., 2021). It has been proposed that this region is well-suited for the implementation of wave energy converters to generate electricity(Hughes & Heap, 2010). However, there has been limited research on wind energy development in this area. It is crucial to conduct a comprehensive analysis of the wind energy potential in order to facilitate the future deployment of wind farms.

The assessment of wind energy has predominantly focused on evaluating the wind power density (WPD), the stability of wind energy, the historical trends of wind energy, energy storage, and resource classification(Capps & Zender, 2010; McKenna, Hollnaicher, & Fichtner, 2014; Soukissian et al., 2017; G. Xydis, 2015). Additionally, numerical models have been utilized for short-term wind energy forecasting(Tascikaraoglu & Uzunoglu, 2014; George Xydis & Mihet-Popa, 2016). Liu et al. (Liu, Tang, & Xie, 2008) produced WPD maps around Japan based on eight years of semi-daily Sea Winds data and made it clear that the WPD in the west of Izu Islands reached more than 600 W/m^2. Many studies have assessed offshore wind energy along the Australian coast (Briggs, M. Hemer, P. Howard, R. Langdon, & P. Marsh, 2021; Katsigiannis & Stavrakakis, 2014); however, very few have examined its long-term variability. Our study will provide a reference for the utilization of wind energy in Australia.

2. RESULTS

The spatial distribution and temporal variability of wind resources can be influenced by climate change. Based on the monthly WPD data spanning 40 years, Figure 1 illustrates the trends of zonal and meridional WPD. In terms of zonal direction, WPD in the Southern Ocean demonstrates an increasing trend, with a maximum rate of 1.40 W/m^2/year. Conversely, WPD in the southwest coast of Australia and coast of New Zealand indicate a weakening trend. A clear boundary line can be observed at 30°S, distinguishing the increasing and decreasing areas. North of 30°S, WPD growth is consistently positive. Moving on to the meridional direction, two areas with high growth rates in WPD stand out - one in the western Australian seas and the other in the northeast Australian seas. The maximum growth rates recorded are 0.52 W/m^S/year and 0.79 W/m^2/year, respectively. Overall, the rate of growth in the zonal direction surpasses the rate of growth in the meridional direction.

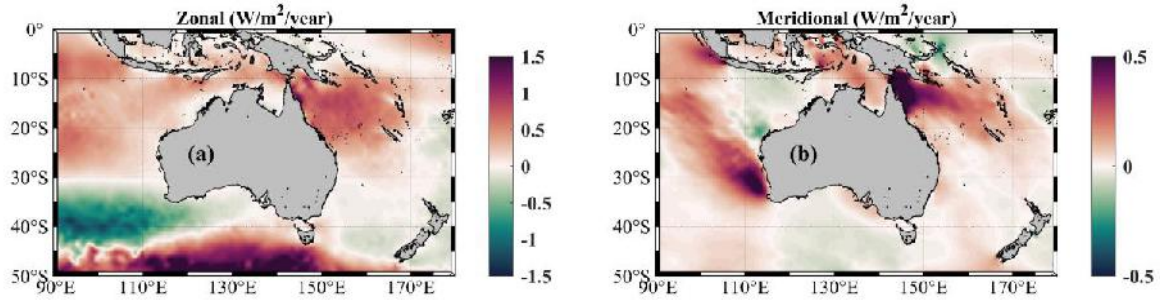

Figure 1 Trends of (a) zonal and (b) meridional WPD using the monthly means over the 40 years.

When studying wind energy, it is crucial to investigate the wind speed and WPD for the 50-year and 100-year return periods. In this study, we utilized the Gumbel distribution approach to calculate the annual extreme wind speed and WPD for these return periods, as illustrated in Figure 2. Unlike the assessment methods used for wind speed, the return period offers a distinct advantage in accurately determining the impact of extreme wind speed. Consequently, the spatial distribution characteristics of the long-term return period values are similar. For the 50-year return periods, the maximum wind speed can reach up to 10.4 m/s, while the maximum wind power can reach 689.5 W/m^2 in the Bass Strait. Similarly, for the 100-year return periods, the maximum wind speed can reach up to 11.7 m/s, and the maximum WPD can reach 988.4 W/m^2 in the Bass Strait. Along the coasts of Western Australia and Northern Australia, the maximum WPD for 100-year return periods can exceed 2000 W/m². This indicates that the wind energy in these regions is highly unstable, making them unsuitable for the construction of wind power generation equipment.

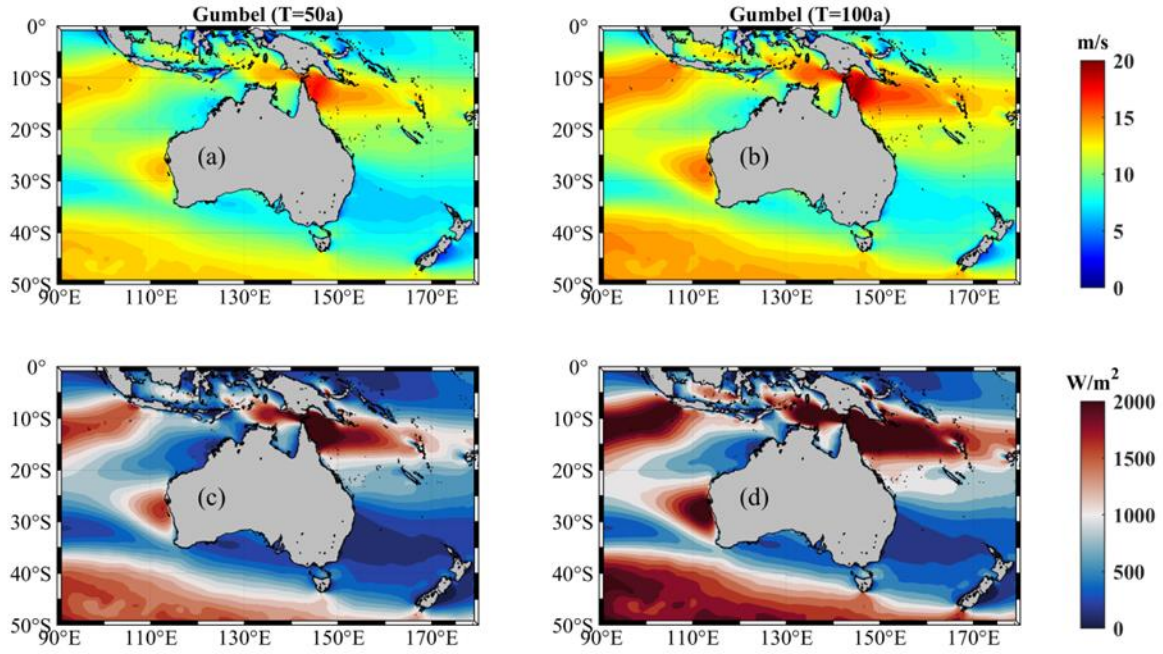

Figure 2. Long-term return period values calculated with the Gumbel distribution method using the monthly means over the 40 years. (a, b) are wind speed. (c, d) are WPD calculated from the results of (a, b).

3. CONCLUSIONS

Wind energy is a vital and sustainable renewable resource, offering significant environmental and economic benefits. This study assessed long-term trends in offshore wind energy around Australia, revealing key insights into regional wind power potential. Based on 10-meter wind speed data over a 40-year period, extreme values of Wind Power Density (WPD) were identified—reaching up to 918.9 W/m² along the northeastern coast and 1200.0 W/m² off the western coast. Notably, the Southern Ocean exhibits a rising trend in zonal WPD, driven primarily by the strengthening of the westerly wind belt. These findings underscore the strategic value of southeastern Australia for offshore wind development, given its consistent strong winds and proximity to high-demand energy markets. The demonstrated reliability and abundance of wind resources in this region support its viability for large-scale wind farm deployment. Overall, this study provides critical scientific evidence to guide decision-making in the planning, investment, and development of offshore wind energy infrastructure in Australia.

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Comparison of wave conditions for a floating wind turbine in the North Sea and Hunter offshore wind zone

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Keywords: Floating offshore wind turbine; metocean; wave statistics

1. INTRODUCTION

Floating offshore wind turbines (FOWTs) offer a promising solution to extract wind energy in deeper waters where typical fixed turbine foundations are no longer economically or technically viable. Current offshore deployments of FOWT are limited to small scale or demonstrator turbines due to prohibitively high costs, with only 121 MW of capacity deployed globally in 2022 [1]. Learnings from demonstrator FOWT deployments are vital to reduce costs and enable large scale deployment, but field data is tightly controlled and published studies using field data are limited. The University of Western Australia has been employed to study field data from the TetraSpar Demonstrator (TSD) floating wind turbine since 2021, including sensor validation studies and analysis of the motion and stress response. Here, a comparison is made between wave conditions experienced at the TSD location (off southwest Norway) to a likely location for FOWT deployment in Australia, the Hunter offshore wind zone.

2. TETRASPAR DEMONSTRATOR WAVE MEASUREMENTS

The TSD was deployed in the Norwegian Marine Energy Test Centre off the island of Karmøy in 2021 and uses a 3.6 MW Siemens-Gamesa turbine on the TetraSpar foundation. The TetraSpar foundation was designed by Stiesdal Offshore and consists of a tetrahedral structure stabilized by a keel suspended on Dyneema lines (see Figure 1). The keel may be raised for deployment from a shallow harbor, then lowered once installed at site. The TSD is equipped with a wide range of sensors measuring metocean conditions (wind, wave and current), turbine parameters and motions of the structure. Proper validation and quality control of these measurements is vital to ensure findings from the field data are accurate. The University of Western Australia is employed by the TSD investors (Shell, TEPCO RP, RWE Renewables and Stiesdal Offshore) to conduct quality control, validation and further study of the TSD measurements. Initial validation studies included assessment of measurements from a RADAC WaveGuide 5 wave radar installed on the TSD working platform. Full details of the wave radar and validation of measurements are given in [2]. Wave radar measurements were validated against both WAM and WaveWatch III models run by the Norwegian Meteorological Institute (NMI), as well as measurements from a Fugro Midi buoy positioned approximately 750 m to the south-west of the TSD location. The wave radar bulk statistical parameters compared well to the model predictions and Midi buoy measurements, particularly for significant wave height. This gives confidence to use WAM model predictions to compare metocean conditions to Australia.

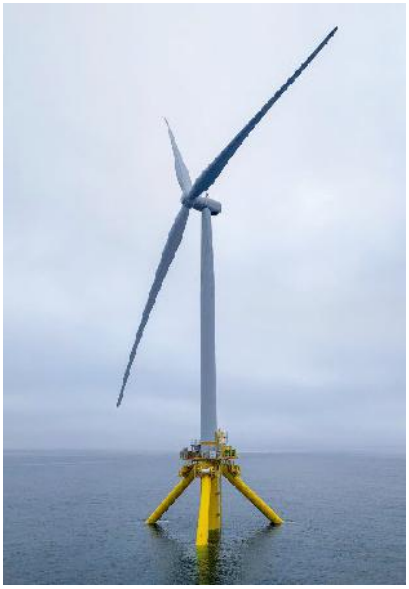

Figure 1. The TetraSpar Demonstrator FOWT deployed offshore Norway. Picture from www.stiesdal.com/offshore

3. COMPARISON TO AUSTRALIAN WAVE CONDITIONS

Having cross-validated wave measurements from the TSD against model predictions in [2], we now compare long term wave statistics from the TSD location to the wave climate in Australia and discuss the implications for FOWTs. Such comparisons have been made before for wave energy devices, e.g. [3], but it is of interest to compare wave statistics for a possible FOWT

deployment location. Of the six priority areas for offshore wind in Australia defined by the Australian Government, two will most likely require FOWTs due to depth constraints: the Illawarra region and Hunter region. The Bass Strait and Indian Ocean off Bunbury zones also contain some deepwater area that will require FOWTs but will likely initially host fixed offshore wind turbines. The only feasibility license awarded for a FOWT project to date in Australia is for the Novocastrian project in the Hunter region, hence this location is chosen for the present study to compare metocean conditions to the TSD location.

Wave data for the Hunter region is taken from the publicly available CAWCR WaveWatch III model data [4], which is run on a 4' grid for the Australian coastline. The nearest grid point was chosen as 33.133º S 152.400º E. Data for the TSD location is taken from the NMI WAM model [5] at the nearest grid point at 59.149º N 5.012º E. Approximately 8 years of wave data is used (limited by availability of the WAM model data). Figure 2 shows a timeseries of significant

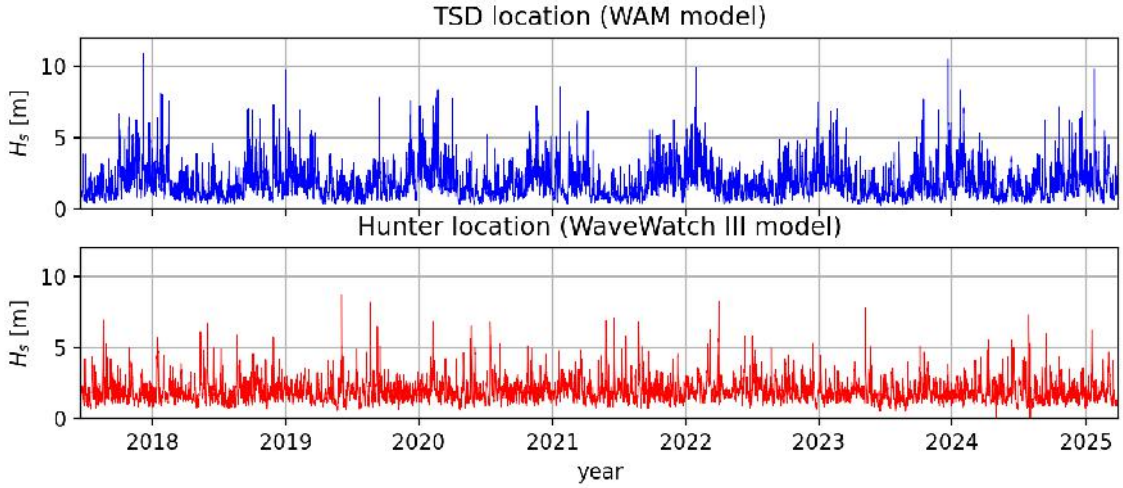

Figure 2. Timeseries of Hs from the TSD location in the North Sea and Hunter location in Australia.

wave height (H_s) from the TSD location (top) and Hunter location (bottom). It can immediately be noticed that there is much larger variability in H_s at the TSD location with substantially larger extremes compared to the Hunter location. The annual variability in H_s also appears to be much lower for the Hunter location. Figure 3 shows a probability density histogram of H_s for both locations. The distributions indicate that the Hunter region experiences much lower extreme H_s values than the North Sea, but conversely has very few periods with H_s< 1 m (note the log scale). Most of the time periods analysed for the Hunter region are in the H_s range 1.2 – 1.9 m. The low probability of H_s<1 m conditions in the Hunter region may have significant implications for installation and maintenance activities, as available weather windows will be reduced compared to North Sea deployments. To further illustrate the difference in extreme conditions, a peak-over-threshold analysis is conducted on H_s for both locations. A 95th percentile peak threshold is used in both cases, with minimum separation of 24 hrs between storm peaks. Figure 4 shows the result of this analysis for both locations (crosses) and fitted Weibull

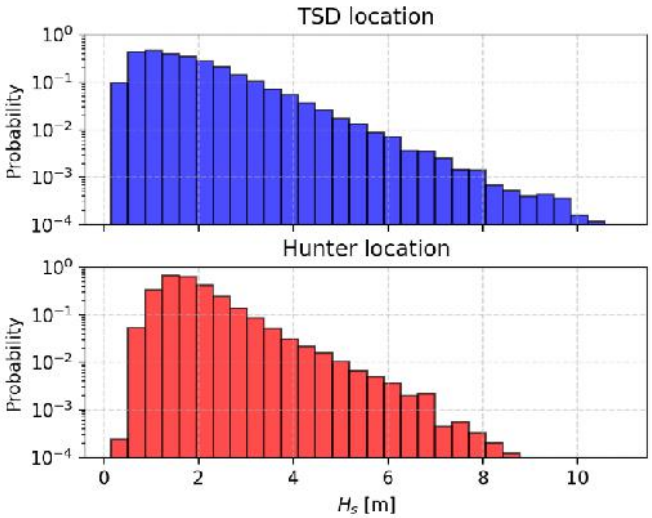

Figure 3. Histogram of significant wave heights

distributions (lines). It is clear that extreme wave conditions at the Hunter location are much less severe than at the TSD location. Probability density of H_S and energy period is plotted for each location in Figure 5. The Hunter location experiences significantly longer wave periods on average that the TSD location, so the waves are both smaller and less steep – less nonlinear. It would be of interest to examine the difference in spreading about the mean direction for the two locations – but it is well known, and we have confirmed for the TSD location in [2], that phase-averaged models like WAM deliver poor estimates of spreading.

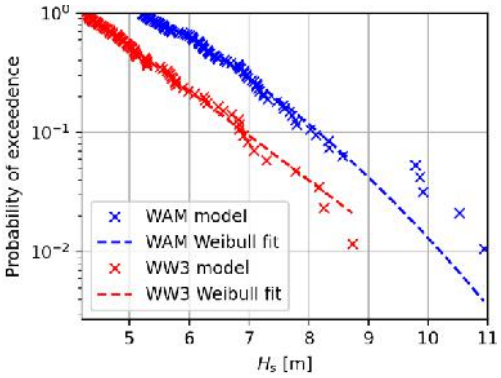

Figure 4. ***H_S*** *exceedance probability from peak over threshold analysis*

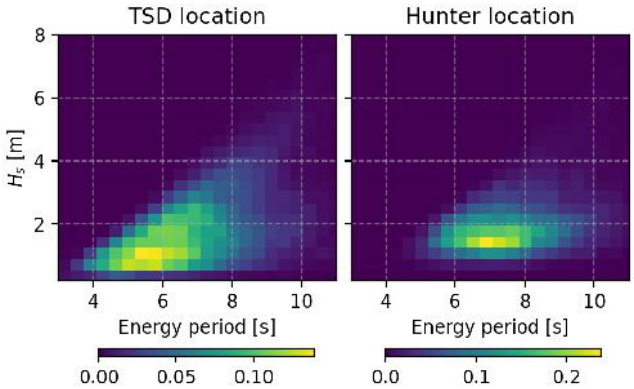

Figure 5. ***H_S*** *vs energy period, the color indicates probability density.*

CONCLUSIONS

Wave height hindcast predictions for the location of the TSD FOWT and for a proposed FOWT location in the Hunter region have been compared using eight years of historical data. The results indicate that extreme wave heights at the Australian location are much less severe than in the North Sea, but that time periods with H_S<1 m are significantly reduced. Additionally, the annual variability of H_S appears much lower at the Australian site. The differing wave climates will have significant implications for the design, installation and maintenance of FOWT for Australian conditions. Ultimate limit state extreme loading conditions may play a reduced role compared to fatigue loading, and floaters/moorings must be designed with easy installation and reduced maintenance in mind to enable deployment in an environment with limited calm weather windows. Further study of the metocean conditions for FOWTs should also consider differing current and wind conditions, and misalignment between wind, wave and currents.

ACKNOWLEDGEMENTS

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