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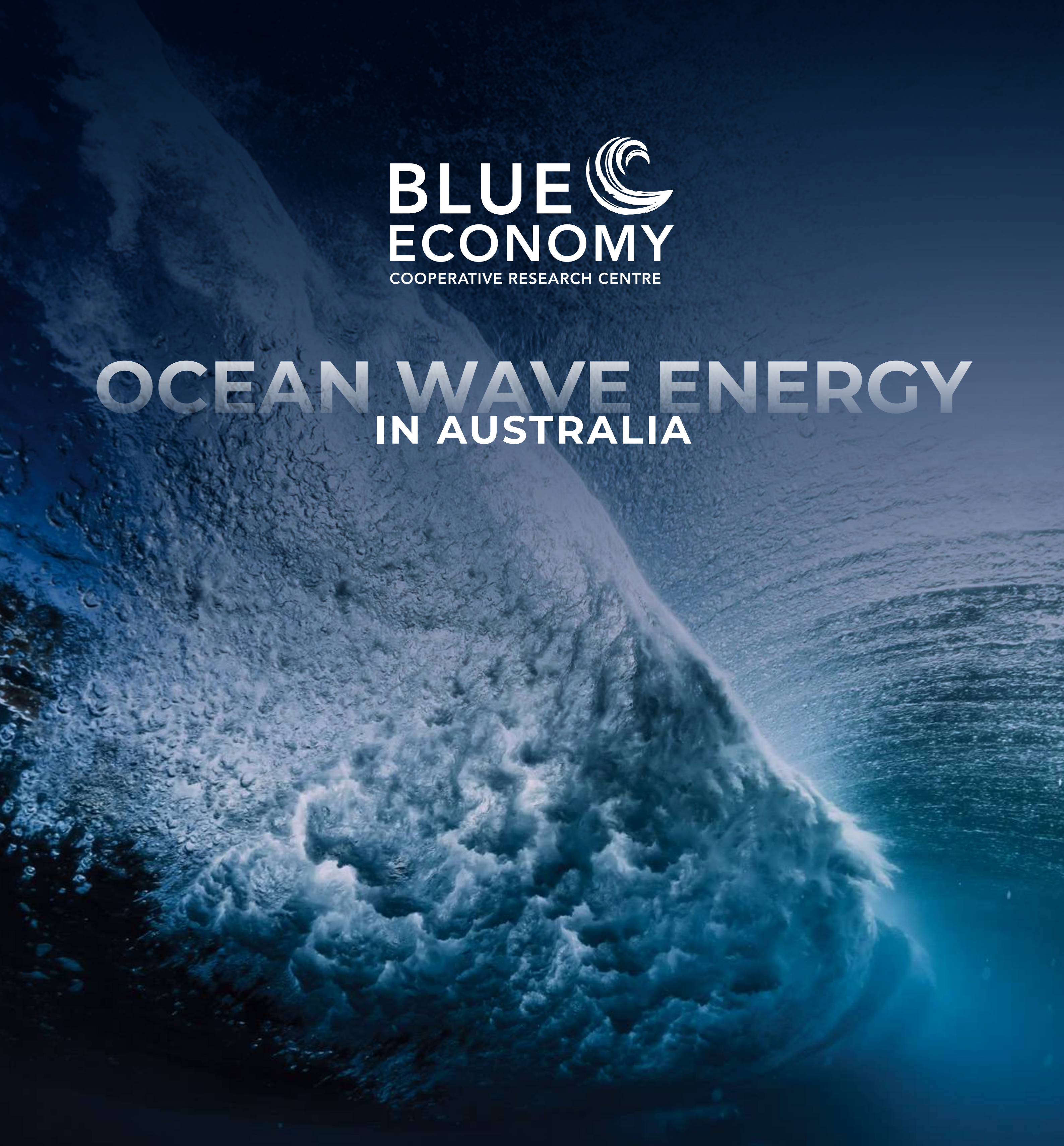

OCEAN WAVE ENERGY IN AUSTRALIA

Australian Government
Department of Industry, Science and Resources

Cooperative Research Centres Program

The Blue Economy CRC

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CONTENTS

Contents

Executive Summary 4

Authors: Christophe Gaudin, Hugh Wolgamot (University of Western Australia).

Chapter 1. Introduction 15

Lead Author: Hugh Wolgamot (University of Western Australia).

Contributing Author: Richard Manasseh (Swinburne University of Technology).

Chapter 2. International Trends and Developments 23

Lead Author: Adi Kurniawan (University of Western Australia).

Contributing Authors: Nataliia Sergiienko (University of Adelaide), Phillip Marsh (University of Tasmania).

Chapter 3. Australian ocean wave resource 56

Lead Authors: Kathy McInnes (CSIRO), Jana Orszaghova (University of Western Australia), Richard Manasseh (Swinburne University of Technology).

Chapter Reviewers: Amir Etemad Shahidi (Griffith University), Daniel Machado (BMT).

Chapter 4. Market opportunities, applications and integration 77

Lead Authors: Peter Osman (CSIRO), Richard Manasseh (Swinburne University of Technology), Nataliia Sergiienko (University of Adelaide).

Contributing Author: Hugh Wolgamot (University of Western Australia).

Chapter Reviewers: Jenny Hayward (CSIRO), Mohammad Sanjari (Griffith University), Ryan Lowe (University of Western Australia).

Chapter 5. Developing a Wave Energy Industry 137

Lead Author: Wiebke Ebeling (University of Western Australia).

Contributing Authors: Brighid Jay (Carnegie Clean Energy), Tom Denniss (Wave Swell Energy)

Chapter Reviewer: Chris Shearer (BMT).

Chapter 6. Environmental and social aspects 153

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Dedication

This report is dedicated to two wave energy pioneers who passed away in 2024. Stephen Salter and Johannes Falnes laid much of the groundwork for the modern wave energy industry and their vision continues to inspire innovators in Australia and worldwide.

EXECUTIVE SUMMARY

OCEAN WAVE ENERGY IN AUSTRALIA

Executive Summary

Ocean wave energy is undergoing a renaissance, with significant funding and effort worldwide devoted to this source of clean energy. This is driven by multiple factors, including the need for decarbonisation and renewable energy development in the face of climate change, the recognition of the diverse benefits of ocean wave energy as part of clean energy systems and a burgeoning Blue Economy.

The establishment of a global offshore wind industry provides an example and opportunity for the development and scaling up of other types of offshore renewable energy generation, including wave energy. With the world's largest national wave energy resource, Australia is uniquely well-placed to lead in this space, but is not keeping pace with global developments. Consequently, Australia is not realising the financial, social, and environmental benefits that could result from the development of a robust and sustainable ocean wave energy industry.

Australia has the largest wave energy resource of any country in the world.

The average power of the ocean waves crossing the perimeter of Australia's continental shelf is estimated at around 300 GW, ten times Australia's average rate of electricity consumption. The enormity of the national resource results from the extensive coastline directly facing the Southern Ocean. Persistent strong winds in this vast oceanic expanse concentrate energy in large waves which bring renewable energy towards the shores virtually continuously. The south and south-west mainland coastline and the south-west coast of Tasmania in particular experience the highest wave power levels, with exceptionally high-quality waves, exhibiting minimal intermittency and small extreme-to-mean wave height ratios, two characteristics essential for uninterrupted energy production.

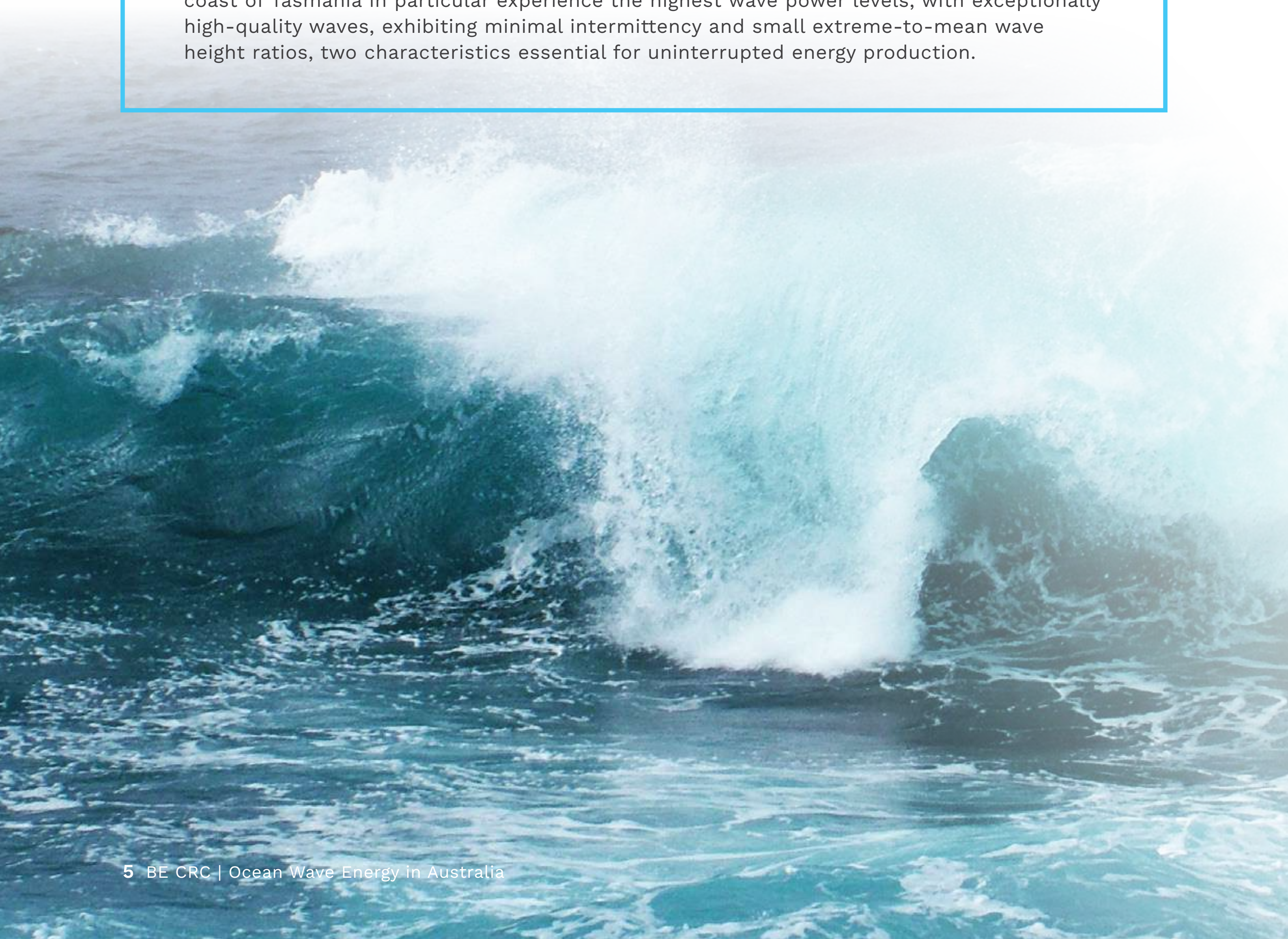
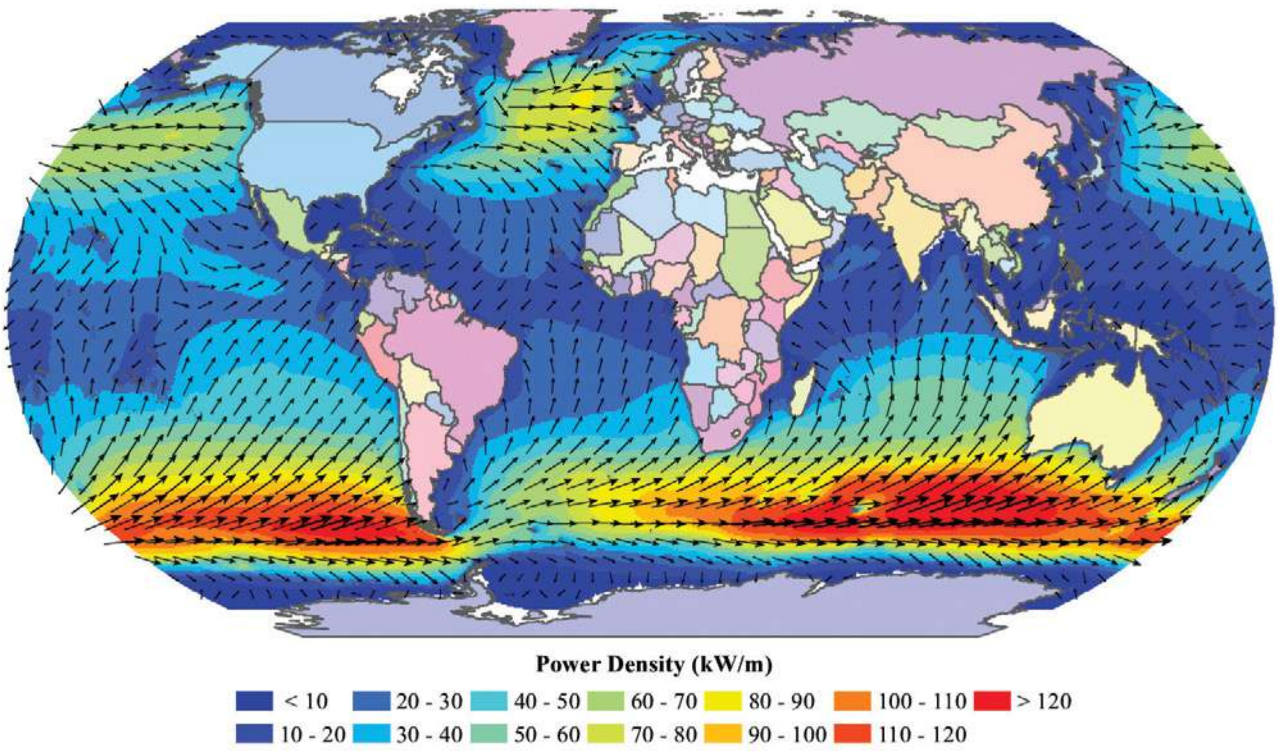
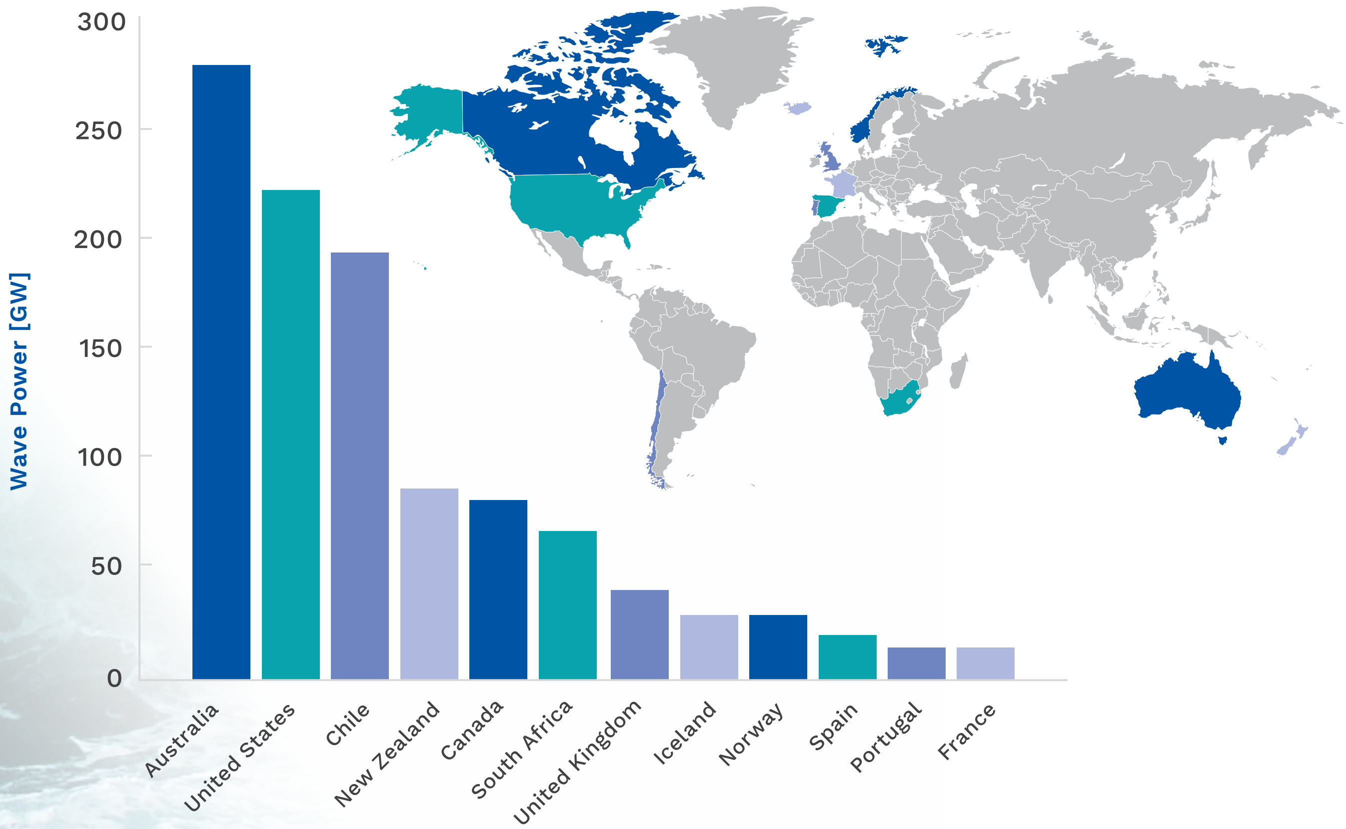


Figure 1. Australia has the largest wave energy resources in the world, based on data from Gunn and Stock-Williams (2012).

World map of wave power density.



Wave power resource for selected countries.



Wave energy is persistent and highly complementary to solar; it therefore has a role to play in the future energy mix.

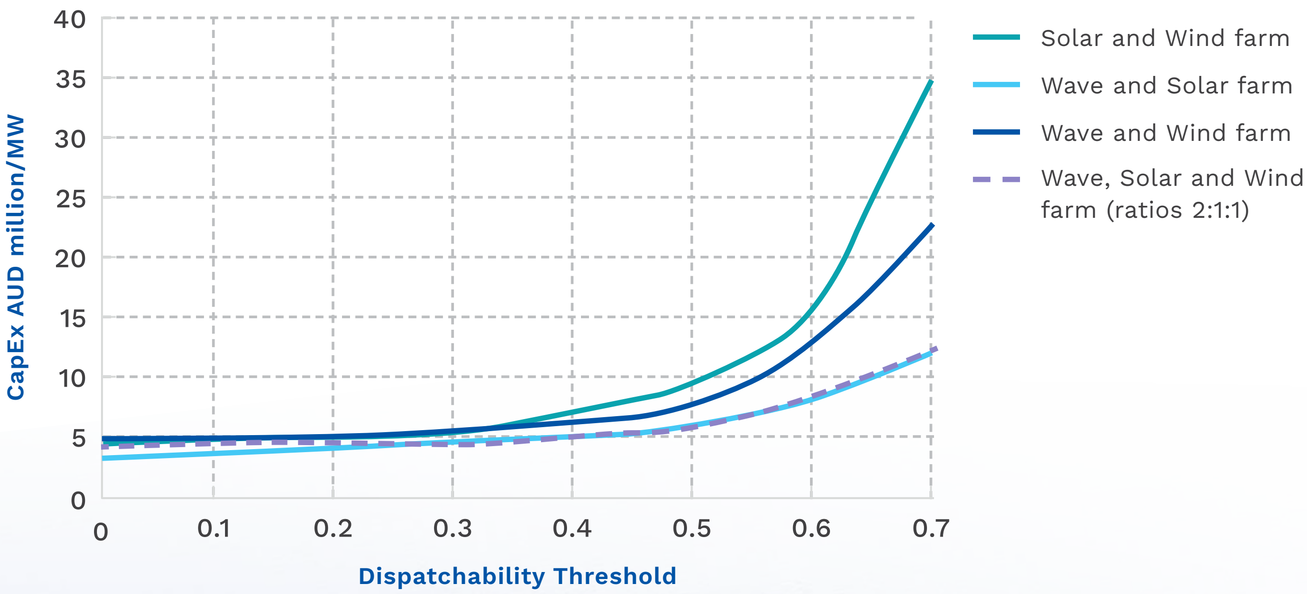
When combined with other renewables, wave energy decreases the cost of reaching a given level of dispatchability – the ability to guarantee power supply at a certain level. Results from Australia and around the world show that this is because combining the latest wave energy technology with wind and solar can cost-effectively reduce the need for energy storage. The example in Figure 2 shows a 50% reduction in the CapEx required to reach 0.6 dispatchability if wave is added to the energy mix, compared to solar and wind alone.

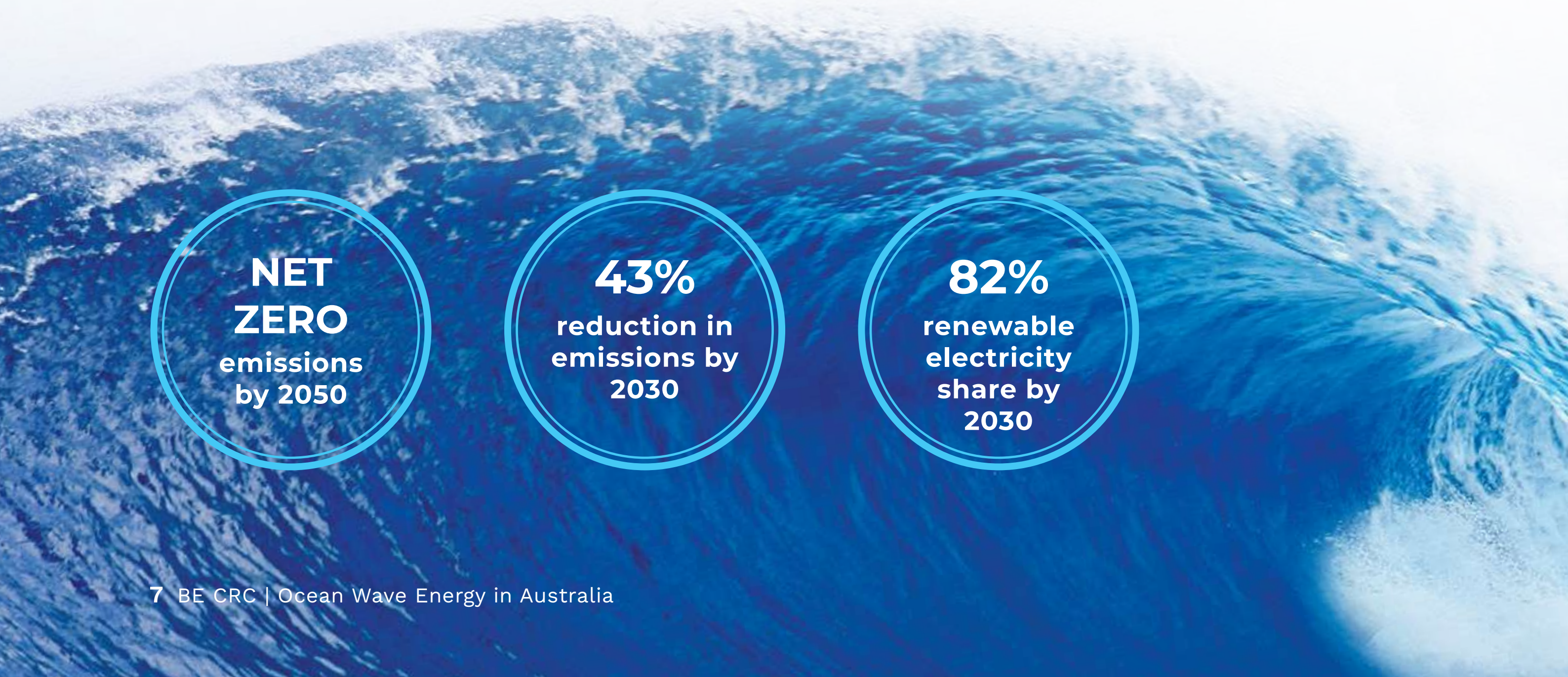
Promising electricity markets for wave energy in Australia include:

- introducing more cost effective dispatchability into national and State grid networks;
- combining wind, wave and solar for towns (particularly on the south and west coasts) which could provide standalone power or more opportunities to trade dispatchable electricity on the spot market.

Combined solar and wave systems can also provide standalone dispatchable power for remote communities on the east and west coasts.

Figure 2. CapEx 2050 estimates per MW average power, for a range of hybrid renewable energy resources to achieve dispatchability thresholds (ratio of guaranteed to average power) of 0.1 to 0.7. Location Carpenter Rocks, South Australia. As the dispatchability threshold increases, inclusion of wave energy dramatically reduces the costs compared to wind-solar solutions.





Wave energy can be a critical enabler in helping Australia achieve its net zero targets.

Australia's climate strategy focuses on achieving net zero emissions by 2050, with interim goals including a 43% reduction in emissions by 2030 and an 82% renewable electricity share by 2030.

The strategy includes initiatives like the Powering Australia plan, which aims to expand renewable energy and create jobs.

National Electricity Market (NEM) forecasts for 2050 suggest an enormous expansion in renewable energy capacity but also a shortfall in dispatchable power. Wave energy could therefore play a key role in future electricity grids.

Wave energy has the potential to support Australia's economy with world-class research and innovation capabilities and expertise, and a skilled workforce.

Australia has many elements necessary for wave energy, including existing skills in the workforce for offshore infrastructure and renewable industries.

High-level capabilities exist in Australia's research and innovation sector (e.g. in universities, CSIRO, industry, etc). Examples from around the world have demonstrated an economic value of wave energy industries, especially in coastal regions.

Wave energy has the potential to provide market and supply chain opportunities given the diversity in technologies, which range from grid connection to powering remote aquaculture facilities. Based on the few wave energy prototype projects completed, or currently conducted, Australia has an opportunity to leverage wave energy, supporting the growth of the AUD 118 billion Australia blue economy, especially in coastal regions, and utilise an existing skilled workforce to support fabrication, installations, and marine operations.

Image courtesy of University of Western Australia.

Photograph by Richard Manassen, with thanks to Wade Greenaway, Mid-West Ports Authority.

Wave energy converters may also be a useful tool in providing coastal protection, at the same time as generating electricity.

Waves are a key driver of coastal impacts due to flooding and erosion which will increase in frequency and intensity with climate change. Waves can be reduced or altered in a controlled manner by wave energy installations, protecting coastal communities and assets worth up to AUD 25 billion. Efforts are required to understand the interconnectivity between wave energy generation and coastal protection, as well as social acceptance to leverage this opportunity.

Wave energy developments in Australia can lead best practice in environmental impact assessment and social and cultural engagement.

Wave energy projects can leverage existing knowledge and data in environmental assessment and planning from other offshore developments.

Potential environmental impacts will be entirely dependent on the type, scale and location of the wave energy development, and other activities present and planned in the area.

Key areas likely to require some investigation in relation to smaller projects include interactions with seabed habitats and marine life during both construction and operation, particularly those associated with underwater noise, entanglement risk with mooring systems and potential interactions with other sea users. For larger developments, other potential interactions that may need to be addressed include those associated with changes in physical oceanography and displacement of sensitive species.

Coordinated strategic environmental and social research and monitoring programs developed through collaboration between Government, regulators, industry, and academia can de-risk the approvals process and help facilitate the sustainable and equitable development of the sector. Early and ongoing engagement with local communities, including Indigenous Peoples in places of cultural significance, is critical to gaining and maintaining the Social and Cultural Licences to Operate.

Image courtesy of Corpower.

Meanwhile, Europe and other regions are advancing wave energy with support and policy, anticipating significant growth by 2050.

With rapid technological advances and the International Energy Agency Ocean Energy Systems (IEA-OES, 2023) roadmap projecting 300 GW of ocean energy by 2050, the wave energy sector is set to expand significantly – creating ~680,000 jobs, boosting economic value by USD 340 billion, and reducing carbon emissions by ~500 MT p.a. worldwide. Both market pull and technology push mechanisms have been identified as necessary if wave energy is to play a substantial role by 2050.

The EU leads in wave energy technology development, holding 44% of global patents and investing significantly in R&D, with projections for ocean energy contributing EUR 5.8 billion to the economy by 2030 and creating substantial economic activity and jobs by 2050.

Strategic roadmaps at both EU and national levels guide efforts in wave energy. The EU's offshore renewable energy strategy targets 100 MW of ocean energy by 2027, 1 GW by 2030, and 40 GW by 2050. The European Commission plans to support this through a robust legal framework, funding, and supply chain improvements.

The UK predicts the installation of 6 GW of wave energy by 2050. This development could meet 15% of the UK's electricity demand and contribute GBP 6 - 21 billion to the economy, creating up to 8,100 jobs by 2040. The UK holds 35% of Europe's wave energy resource and has significantly invested in the sector, with EUR 32 million in public funding from 2022 to 2025.

The US Government has substantially increased funding for ocean energy research, with a record USD 120 million allocated in 2023 and a total of USD 520 million since 2019, surpassing European investment. State-level support is also growing, with California and Oregon advancing ocean energy laws.

Major technology developers span across Europe, the US, Australia, Canada, and Asia, showcasing a diverse range of concepts. Grid-connected test centres worldwide, such as those in the UK, US, and China, support technology trials under real-world conditions.

Despite all its strategic advantages, Australia currently lacks the level of support and funding needed to match its immense potential.

Since its inception in 2012, the Australian Renewable Energy Agency (ARENA) has invested AUD 2.25 billion in 663 projects, with around AUD 44 million (<2%) allocated to ocean energy (wave and tidal) projects. Notable funded projects include the Australian Wave Energy Atlas, the Perth Wave Energy Project, and the UniWave200 King Island Project.

The Blue Economy Cooperative Research Centre has supported small-scale wave energy projects such as Carnegie Clean Energy's MoorPower and the M4 Albany Wave Energy Demonstration Project. However, there are currently no dedicated roadmaps for wave energy in Australia and it is not included in the latest Integrated System Plan. There is a mismatch between the scale of Australia's opportunity and the national funding support and effort in wave energy.

Compared to other jurisdictions, the lack of a focused strategy represents a missed opportunity to diversify the renewable energy portfolio and enhance the Blue Economy.

Rapid development of wave energy in Australia is possible.

Several Australian agencies have recently issued their strategic plans for renewable energy technology development, emission reductions, job creation, and infrastructure upgrades. The national Sustainable Ocean Plan is currently being drafted.

These initiatives show that significant momentum is building and that an opportunity to integrate wave energy within energy and coastal protection plans exists. No environmental, social or cultural barriers have been identified which would prevent a well-managed, sustainable and socially acceptable wave energy industry from developing. Streamlining and optimising regulatory and planning processes, including across jurisdictions, while providing incentives and early support to the wave energy industry, can accelerate the development of wave energy towards full commercialisation.

Australia has the capacity to be a leader in the wave energy sector and the time for action is now.

Image courtesy of Carnegie Clean Energy.

Recommendations

The overarching recommendation of this report is:

Federal and State Governments in Australia should take a strategic view of the wave energy industry in order to achieve the maximum national benefit from this potentially critical national resource.

Underneath this umbrella, this report details seven recommendations across three key themes for the development of wave energy in Australia:

Area	Detailed Recommendations
Wave energy should be incorporated into national and State planning.	**1. The Australian Renewable Energy Agency (ARENA) should fund a study to determine the national benefit of developing a wave energy industry, including benefits to economic and social development, sovereign capability, environmental sustainability and export capacity through the development of a leading domestic industry.** This report indicates significant benefits from wave energy in multiple areas. Further substantial work remains to more accurately quantify many of these benefits and to identify mechanisms to seed, support and accelerate the industry. The benefits of alignment with the considerable international momentum in wave energy should be considered, including Australian alignment with the International Energy Agency Ocean Energy Systems roadmap for 2050. This should include consideration of 'market pull' mechanisms to encourage long-term investor confidence in the sector. A domestic wave energy industry is aligned with government policies including Powering Australia, Future Made in Australia and Net Zero targets.
	2. The Australian Energy Market Operator's Integrated System Plan (ISP) should evaluate wave energy possibilities, and in particular include and evaluate the impact of wave energy on 2050 requirements for energy storage. The Australian Energy Market Operator's (AEMO) Integrated System Plan (ISP) presently does not consider wave energy in any form. The EVOLVE study of the UK market (EVOLVE, 2023) concluded that installing 10 GW of wave energy could lead to annual cost savings of up to AUD 2.76 billion (GBP 1.46 billion) by 2040 due to reduced needs for storage and other generation. Findings in the present report similarly show that for Australian conditions introducing wave energy is associated with large reductions in storage capacity required. This translates directly to lower cost through the reduced cost of storage. Modelling for the local grids of three locations on the south coast of Australia returns very similar dispatchability and cost results, while resource modelling shows a high degree of similarity in the wave resource across Australia's southern margin. This provides confidence that the results in this report can be replicated at a larger scale. The system-wide implications of wave energy can only be reliably assessed by an integrated approach.

Area	Detailed Recommendations
	3. Wave energy should be included in the Sustainable Ocean Plan and considered alongside other renewable energy technologies. Funding schemes for wave energy projects will revitalise the connection between Australia's technology developers, research institutions, markets and investors, regional councils, and planning bodies. With State and federal Government support committed and sustained, training and transitioning of jobs in the offshore energy sector towards wave energy and other marine renewables can create employment and revenue. Cross-sector and cross-departmental collaboration can increase impact and benefits through education, R&D, and business activity. Australia's rural, regional, remote (RRR) coastal areas can play a major role.
Funding effort should be consistent and at scale to de-risk and accelerate deployments.	**4. Projects on different scales and across different market applications should be funded to validate wave energy technology and to demonstrate its national benefits over longer periods.** A key benefit of wave energy is dispatchability. The Australian wave resource has exceptionally favourable characteristics, but projects to date have not been designed to demonstrate reliable supply over multi-year periods. Field demonstrations over an extended period with permanently connected device(s) should be funded at different scales: decarbonising offshore facilities such as aquaculture; small scale supply to an isolated community; at larger (perhaps MW) scale with solar and wind to a remote (but grid-connected) community to improve dispatchability of the local grid; and ultimately at larger scale to national or State grids. Such 'technology push' funding to accelerate wave energy development is identified as a key mechanism by the International Energy Agency Ocean Energy Systems roadmap. Further, multi-year deployments will offer a key opportunity to evaluate environmental and social impacts.
	5. An integrated study to establish national guidelines for using wave energy for coastal protection should be carried out. Coastal protection is typically dealt with by local councils without the resources to study the possible benefits of wave energy. National guidelines to enable rigorous assessment and ensure public confidence in decision making about whether and how to use wave energy for coastal protection would provide significant benefit and enable uptake of wave energy solutions. This can provide benefit in both climate change mitigation and adaptation.

CHAPTER 1
INTRODUCTION

OCEAN WAVE ENERGY
IN AUSTRALIA

CONTENTS

Contents

1. Introduction 17

1.1. Brief Introduction to wave energy 19

References 202

Figures

Figure 1.1. Ocean waves are generated by winds. Source: Pecher and Kofoed (2016). 19

Figure 1.2. Ocean wave fundamentals. 20

1. Introduction

Ocean wave energy is undergoing a renaissance, with significant funding and effort worldwide devoted to this source of clean energy. This is driven by multiple factors, including the need for decarbonisation and renewable energy development in the face of climate change, the recognition of the diverse benefits of ocean wave energy as part of clean energy systems, and a burgeoning Blue Economy.

The establishment of a global offshore wind industry provides an example and opportunity for the development and scaling of other types of offshore renewable energy generation, including wave energy. With the world's largest national wave energy resource, Australia is uniquely well-placed to lead in this space, but is not keeping pace with global developments. Consequently, Australia is not realising the financial, social and environmental benefits that could result from the development of a robust and sustainable ocean wave energy industry.

The International Energy Agency's Technology Collaboration Programme for Ocean Energy recently released a roadmap (IEA-OES, 2023) for deploying 180 GW of wave energy generation capacity worldwide by 2050. Together with 120 GW of tidal energy, meeting this target would deliver 680 000 jobs, USD 340 billion Gross Value Added and a 500 million tonne reduction in carbon emissions worldwide. Activity could be concentrated in 20 or fewer countries driving this new industry. Australia is not presently playing a large enough role to be one of these major players.

Australia has significant renewable energy resources in solar and wind, both on- and off-shore, meaning that wave energy has not been seriously considered in planning our future energy mix. However, motivated by recent developments from around the world, this report aims to establish and clarify the status of the wave energy industry and the potential benefits to Australia that could arise from developing an industry.

These include:

- A more reliable electricity supply, due to the different temporal profile of wave compared to other renewable resources;
- Co-benefits of electricity generation and protection of our vulnerable coastline by wave energy arrays in well-chosen locations;
- Increased value from offshore wind farm developments with co-location of wave energy;
- Easing land-use, planning and environmental constraints around onshore solar and wind by diversifying the locations where renewable energy can be installed; and,
- Providing employment for people transitioning from offshore oil and gas and for local manufacturers.

This report therefore aims to provide information to inform discussions and drive further investment and research by:

- Summarising the international and national wave energy landscapes;
- Reviewing, collecting and presenting the national wave energy resource;
- Identifying and discussing key applications or market opportunities for wave energy in Australia;
- Discussing the employment and industry landscape of the wave energy industry; and,
- Evaluating the environmental, planning, social and cultural context for the wave energy industry in Australia.

The study delivers clear summaries and recommendations for action, drawing on this work.

The report has been assembled by a team representing the research and innovation ecosystem of wave energy, including academics, researchers and industry from a range of institutions and discipline backgrounds.

Overall coordination and funding were provided by the Blue Economy CRC. Individual authors and contributions have been drawn from: The University of Western Australia, CSIRO, Griffith University, Swinburne University, The University of Adelaide, Australian Maritime College (University of Tasmania), Wave Swell Energy, Carnegie Clean Energy and BMT.

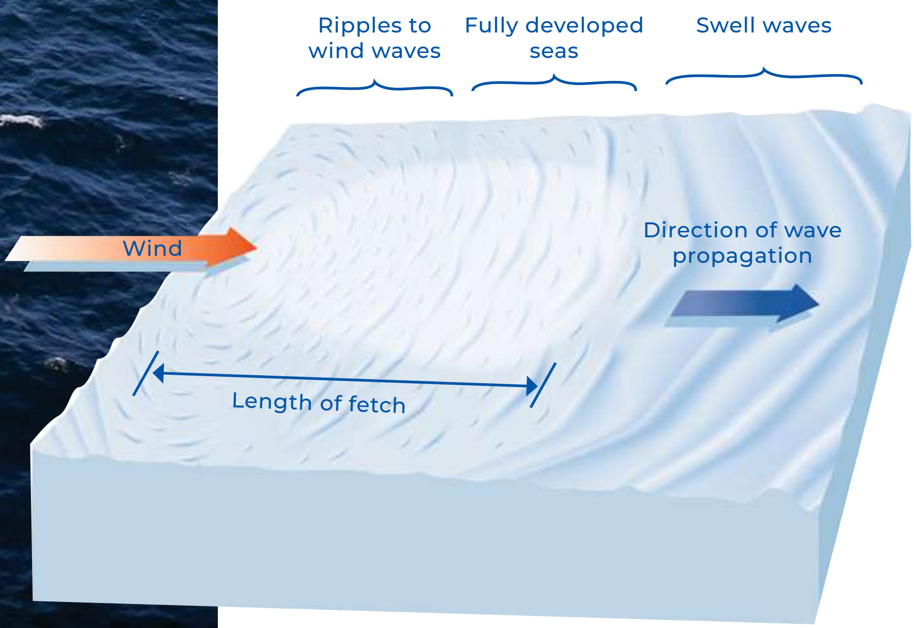
1.1. Brief Introduction to wave energy

Ocean waves are generated by winds. Therefore, ocean waves, like winds, are a source of renewable energy. Seventy percent of the Earth's surface is ocean, and thus most of the world's wind energy is blowing over the ocean, far from the continents on which we live.

Waves transport energy over thousands of kilometres of ocean, gathering energy and growing larger through each windy region, while travelling undiminished through calm regions. Thus, when the largest waves – the swell – reach our continent, they deliver concentrated wind energy, harvested from the windiest reaches of our planet.

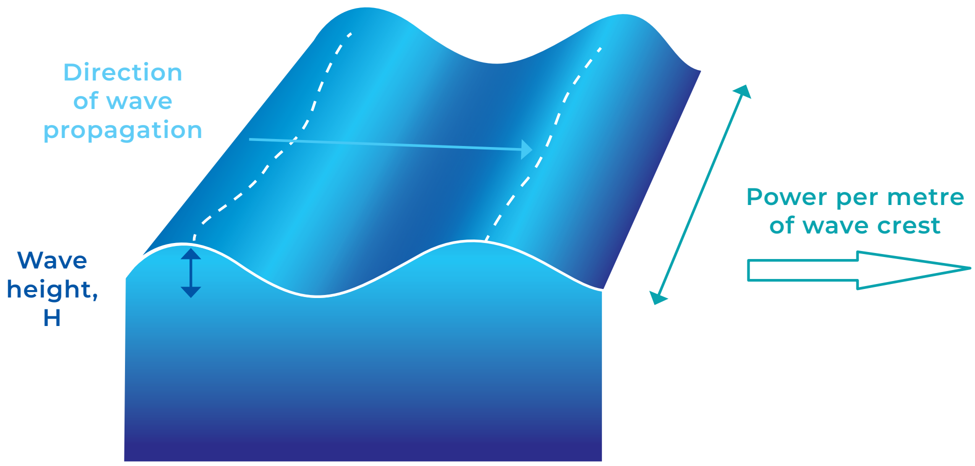
Waves deliver more than ten times Australia's average electricity generation to our coastline. Moreover, because wind energy from many ocean regions has accumulated in the swell, the swell varies much less than the wind varies in any particular region.

Figure 1.1. Ocean waves are generated by winds. Source: Pecher and Kofoed (2016).



Waves are characterised by their height, which is the distance between the lowest (trough) and highest (crest) parts of the wave, and by their period, which is the time between crests if measured at a stationary point. Waves carry immense energy, proportional to the square of the wave height and its period. Given that water is 800 times denser than air, waves are more energy-dense and spatially concentrated than wind. For example, waves arriving at the southern coast of Australia contain sufficient power in each metre of coastline for the average consumption of 20-60 homes.

Figure 1.2. Ocean wave fundamentals.



Wave energy converters (WECs) are machines that convert ocean wave energy into electrical energy or other useful forms of energy. People have always observed the immense energy in waves and sought for over two centuries to harness it. Two fundamental features of wave energy must be understood as a precursor to success; lack of understanding of, and difficulty addressing, these features have slowed the development of the wave energy industry.

There are very many small companies developing competing WEC technologies. This arises from the need to address a fundamental feature of wave energy: as waves pass, they cause the water to move forwards on the wave crest but backwards on the trough, upwards as the crest approaches but downwards as it passes.

Image courtesy of University of Western Australia

This constantly-reversing motion is fundamentally different to the movement of water flowing down-river or the movement of air created by wind, which are essentially movements in one direction. To efficiently extract energy from water or air moving in one direction requires only a single moving part: the turbine. Various forms of turbines have been utilised for centuries as wind- and water-mills, and now in electricity generation. For wave motion, however, there is no obvious equivalent to the turbine. This complexity has inspired hundreds of inventions, creating as many companies. Some are very efficient but mechanically complex, expensive and fragile; others are less efficient but mechanically simple, cheap and robust. Some of the best inventions have been developed and ocean-tested by Australian companies. Individual WECs have operated on a trial basis for short periods both in Australia and overseas for decades. A diversity of inventions normally leads to beneficial competition and eventually technology convergence. However, this has not occurred in wave energy, because of the second feature.

The second feature is that WEC designs must be either physically enormous and simple, or smaller and rather complex, machines which are challenging for small companies to develop. The fundamental reason is that the majority of WEC designs exploit the physical principle called resonance.

Machines are designed to be mechanical oscillators: pendulums, floats on springs and so on, they naturally swing, rock, bob or pulse with an innate number of beats per minute. Once this natural frequency matches the frequency of ocean swell, their motion becomes very large, many times the motion of the surrounding water, thus extracting maximum power from the waves. Therefore, engineers design WECs, rather like musical instruments, to be 'tuned' to the 'note' of the prevailing swell where they are to be installed. The greatest power is carried by ocean swell with the lowest frequency, and frequencies may be very low: a wave crest might arrive once every 10 to 15 seconds on the southern coast of Australia. Just like a musical instrument, the lowest notes are produced by the largest versions of each instrument, or for WECs by a smaller version with sophisticated mechanics and control to 'trick' a smaller machine into mimicking a large one.

To match Southern Ocean swell, a simple un-tuned heaving buoy WEC needs to be the height of an eight-storey building. A smaller WEC can do the same job if it has advanced mechanics and control. Building such giant and/or sophisticated machines and installing them in the ocean is resource-intensive for small companies, which have faced additional challenges from inconsistent funding and incentives for wave energy development and limited knowledge sharing.

While new wave energy companies emerge regularly, many have in the past struggled to survive financially due to these technical and economic barriers.

Details of inventions definitely matter, but may be more relevant to the longevity of the machines or to their capital cost than the gross power delivered. The choice of WEC technology, and of the company developing it, may come down to the geography in which WECs are to be deployed, how the WEC may be integrated with other local maritime needs, the financial model for the development, the market application for which it is designed, the current energy system model within that market and the cost of energy within that market.

In summary, wave energy conversion is much more mature than many policy-makers and investors believe. There is now substantial knowledge on the features of wave energy, and a recognition of the importance of knowledge sharing and collaboration, sustained strategic support and focus on the right markets and price points. Acknowledgement of the two features noted above should lead to a more rational approach to WEC developments, in which the excellent work completed by technology developers to date can be utilised by Government and corporate stakeholders that are informed decision-makers, rather than passive facilitators.

CHAPTER 2

INTERNATIONAL TRENDS AND DEVELOPMENTS

OCEAN WAVE ENERGY IN AUSTRALIA

Contents

2. International Trends and Developments 26

2.1. Wave Energy History and Status 26

2.2. International Funding and Jurisdictional Target Landscape 34

2.3. Climate Change Context 48

2.4. Synergies with Offshore Wind 53

2.5. Conclusion 55

References 203

Tables

Table 2.1. Examples of hybrid wind-wave energy platforms. 55

Image courtesy of Corpower.

Figures

Figure 2.1. Salter Duck, courtesy of the Edinburgh Wave Power Project archive. **27**

Figure 2.2. A wave energy converter (WEC) in open ocean can absorb energy from a wave front approximately one-sixth of a wavelength wide if it oscillates vertically, twice that if it oscillates horizontally, and thrice as much if it oscillates in both directions. **27**

Figure 2.3. Australia's wave energy resource compared to other selected countries, based on data from Gunn and Stock-Williams (2012). **32**

Figure 2.4. Wave Swell Energy's UniWave200. Figure courtesy of Wave Swell Energy. **33**

Figure 2.5. The mutually reinforcing cycles of technology development and market deployment drive down technology costs (from Mitchell et al., 2011). **35**

Figure 2.6. EU's offshore wind and ocean energy capacity, including targets outlined in its Strategy on Offshore Renewable Energy (European Commission, 2020b). The updated target (European Commission, 2023a) aims to achieve 111 GW of total offshore renewables by 2030. **37**

Figure 2.7. Mocean's Blue X wave energy device, courtesy of Mocean Energy. **40**

Figure 2.8. Installed capacity of renewable energy per year, from 2015 to 2023: China vs. the rest of the world, based on data from IRENA (2024). **43**

Figure 2.9. ARENA funding for ocean energy projects in Australia, based on data from ARENA (2022). **46**

Figure 2.10. Three key actions required in the Net Zero Emissions by 2050 (NZE) Scenario, from IEA. **48**

Figure 2.11. Australia's CO_2 emissions per capita compared to other selected countries, based on data from IEA. **50**

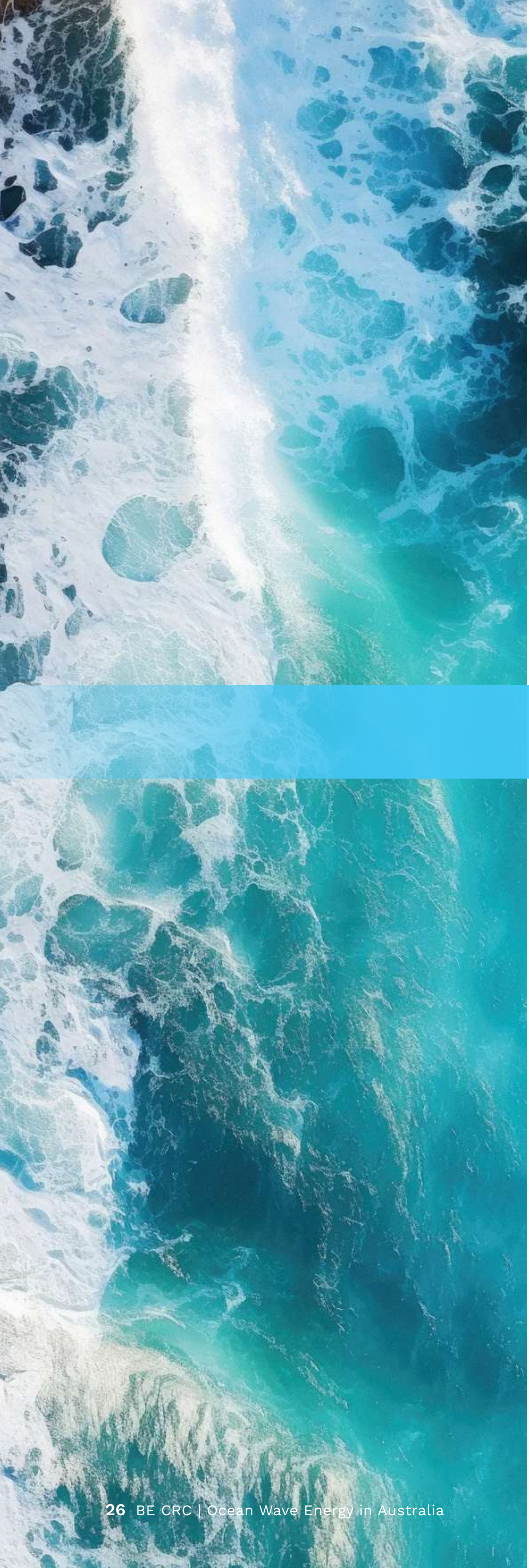
Figure 2.12. Australia's annual electricity consumption per capita compared to other selected countries, based on data from IEA. **50**

Figure 2.13. Australia's electricity generation by source, compared to other selected countries and the world, based on data from IEA. **51**

Figure 2.14. Australia's renewables share of electricity generation, compared to other selected countries, based on data from IEA. **51**

Figure 2.15. Global distribution of annual mean wave energy flux, from Cornett (2008). **52**

Figure 2.16. Global distribution of wave power temporal variability, from Cornett (2008). High coefficient of variation (COV) means high variability. **53**



2. International Trends and Developments

Wave energy is no longer a distant possibility but a burgeoning global industry. Around the world, countries are seizing the opportunity to harness this vast, untapped resource, investing in research, technology development, and market integration.

This chapter explores key historical developments and highlights the significant international advancements already shaping the wave energy sector. It also provides a comparative analysis, illustrating that wave energy is far from an immature concept, and more critically, why Australia must adopt a strategic approach if it is to avoid falling behind, as it once did with solar and wind energy.

2.1. Wave Energy History and Status

2.1.1. History

The beginning of modern wave energy research can be traced back to the oil crisis of 1973, which ignited a global search for alternative energy sources, bringing wave energy to the forefront. During this period, numerous pivotal discoveries were made (Evans, 1981).

Although wave energy had been considered long before the 1970s, its history is relatively brief compared to other renewable energy sources. The first patent for wave energy was filed in 1799 (Girard, 1799), during a time when windmills were common and solar energy had long been used for drying and other applications.

Girard's patent described a float attached to a lever, driven by the rise and fall of the waves. Between 1856 and 1973, over 340 British patents on wave energy were filed (Leishman and Scobie, 1976), yet significant progress did not occur until the 1970s. One of the most notable early inventors was Yoshio Masuda, whose wave-powered navigation buoys were commercialised by the Japanese company Ryokuseisha as early as 1965 (Falcão and Henriques, 2016).

In 1974, Stephen Salter of the University of Edinburgh demonstrated a method to absorb over 80% of incoming wave energy in a wave tank experiment using his Salter Duck, a teardrop-shaped wave energy converter (WEC) that nods with the waves. Its rounded back minimises downstream wave generation, making it highly efficient (Figure 2.1). It is now understood that any shape can achieve perfect absorption in a (theoretical) tank experiment if it oscillates in more than one direction.

For open ocean applications, a significant discovery was the antenna effect, where a small oscillating WEC can absorb much more energy than its physical size suggests. A WEC can absorb energy from a wave front equal to one-sixth of the wavelength if it oscillates vertically, double that amount if it oscillates horizontally, and triple if it oscillates in both directions (Figure 2.2). These results hold regardless of the WEC's size, meaning that, in theory, WECs can absorb more energy than the amount incident on their physical surface.

By the early 1980s, several WEC concepts were nearing deployment (Grove Palmer, 1982). However, falling oil prices led to reduced funding and stalled progress. Despite this, a few prototypes were constructed and installed in the late 1980s (Falnes, 1993). Interest in wave energy revived in the late 1990s, amid growing concerns over the environmental impact of fossil fuels.

Figure 2.1. Salter Duck, courtesy of the Edinburgh Wave Power Project archive.

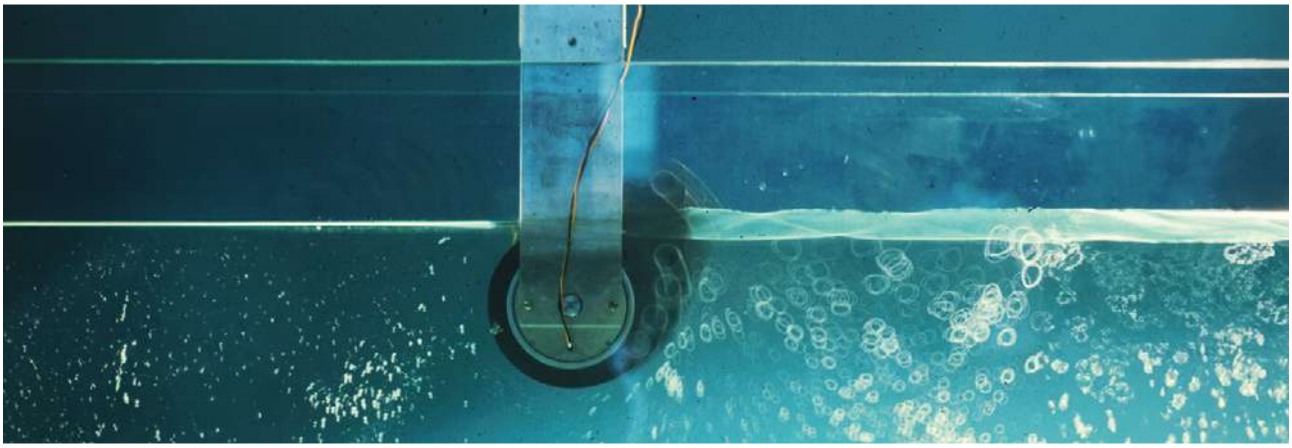
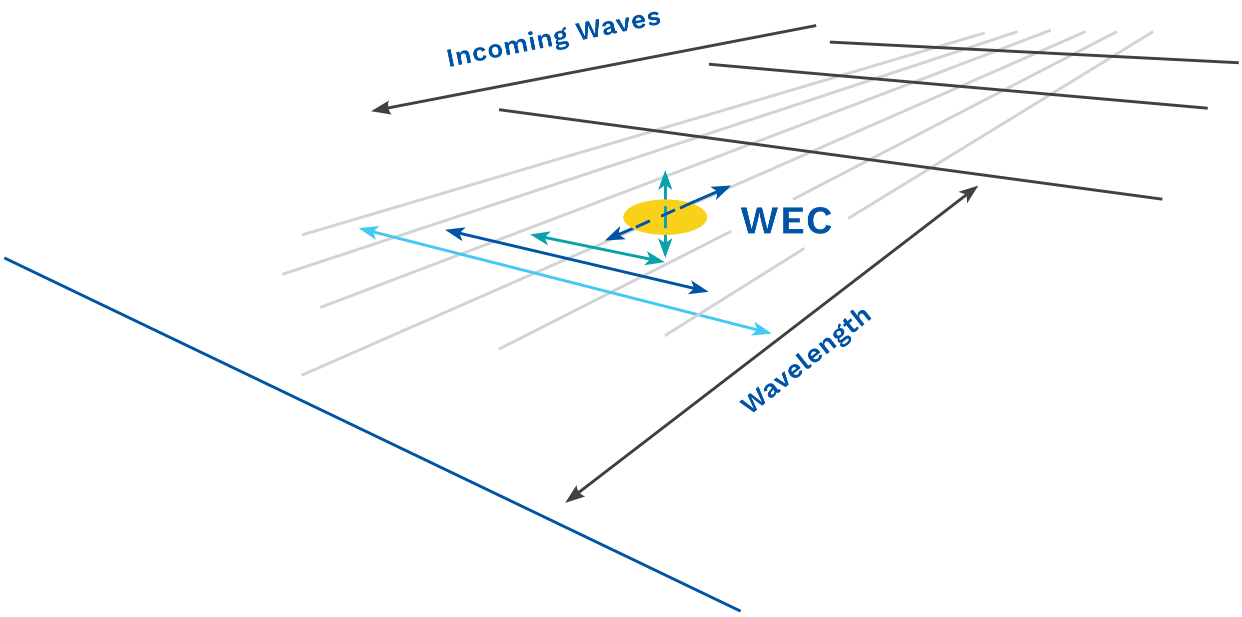


Figure 2.2. A wave energy converter (WEC) in open ocean can absorb energy from a wave front approximately one-sixth of a wavelength wide if it oscillates vertically, twice that if it oscillates horizontally, and thrice as much if it oscillates in both directions.



The Historical Timeline below illustrates the peaks and troughs of wave energy development: a period of limited activity before the 1970s, a surge of innovation around 1975, a sharp decline after 1980, and a revitalised momentum in the years following 2000.

Historical Timeline

1799	French engineer Girard and his son patented a device for harnessing wave power to drive machinery.
1910	Bochaux-Praceique constructed one of the first known wave power devices, powering his home in Royan, France.
1945	Japanese naval officer Yoshio Masuda began experimenting with wave energy devices (Masuda, 1986), influencing future developments in the field.
1965	Japanese company Ryokuseisha started manufacturing wave-powered navigation buoys.
1973	The oil crisis exposed the vulnerability of industrialised nations to oil dependency, driving interest in alternative energy sources.
1974	∆ The International Energy Agency (IEA) was established to promote energy security. ∆ Stephen Salter from the University of Edinburgh published a landmark paper Wave Power (Salter, 1974), introducing the influential 'Salter Duck' wave energy converter. ∆ The UK Wave Energy Programme initiated significant research and development in wave energy technologies (Grove Palmer, 1982).
1975	Key discoveries in point absorber capture width limits were made independently by researchers from Norway, the UK, and the USA.
1976	Allan Wells patented the Wells turbine for use in oscillating water columns (OWCs).
1978	Latching control for wave energy devices was proposed by Budal and Falnes, with various phase control strategies explored thereafter.
1979	The first International Symposium on Wave Energy Utilisation was held in Gothenburg, Sweden.
1985	Two full-scale shoreline prototypes (350 kW and 500 kW) were installed near Bergen, Norway.
1991	∆ The Islay OWC (75 kW) was commissioned in Scotland (Whittaker et al., 1993). ∆ OWC prototypes were also constructed in Japan (60 kW at Sakata) (Ohneda et al., 1991) and India (125 kW at Trivandrum) (Ravindran and Koola, 1991). ∆ The European Commission included wave energy in its renewable energy R&D program (Falcão. 2010; Senior, 1991).
1993	The first European Wave and Tidal Energy Conference was held in Edinburgh, UK.
1996	Construction began on the 400-kW Pico OWC in the Azores, Portugal, which operated for 20 years.
1997	The Kyoto Protocol was signed, coming into effect in 2005.
2001	∆ The 250 kW LIMPET OWC was commissioned. The plant was in continuous operation until 2012. ∆ Ocean Energy Systems (OES), a Technology Collaboration Programme under IEA, was founded.
2003	∆ The European Marine Energy Centre (EMEC), the world's first open-sea facility for testing wave and tidal energy converters, was established in Orkney, Scotland. ∆ The Wave Dragon was tested in Denmark. It achieved more than 20,000 hours supply to the grid

2004
The Pelamis was deployed off the coast of Scotland, marking the first full-scale prototype deployed at EMEC.

2006
The first International Conference on Ocean Energy was held in Bremerhaven, Germany.

2007
The International Electrotechnical Commission (IEC) established TC 114 to develop marine energy standards.

2008
The Aguçadoura Wave Farm, the world's first wave farm, began operation in Portugal using Pelamis devices.

2009
- Wave Star Energy installed a test section of a 600-kW prototype in Denmark.
- The Oyster wave energy converter by Aquamarine Power was deployed at EMEC.

2010
- **Oceanlinx MK3 floating OWC was installed at Port Kembla, New South Wales.**
- A residential discussion meeting on wave energy was held by the Royal Society and attended by leading experts of wave energy, covering theory, practical problems, and some of the most promising devices.

2011
The Mutriku breakwater-integrated OWC was commissioned in Spain.

2014
- Wave Energy Scotland (WES) was established to maintain Scotland's leading role in marine energy development.
- The FloWave circular wave tank opened at the University of Edinburgh.

2015
- The US Department of Energy initiated the Wave Energy Prize.
- Ocean Power Technologies commercialised its PowerBuoy wave energy converter.

2016
- The Paris Agreement was signed and came into effect the same year.
- **Carnegie Wave Energy's CETO 5 system completed testing off Western Australia.**
- Eco Wave Power operated a proof-of-concept array in Gibraltar.

2019
AW-Energy's 350-kW WaveRoller unit was deployed off Portugal.

2020
Standards Australia established EL-066 committee on marine energy, part of TC 114.

2021
- EuropeWave was established to drive a competitive Pre-Commercial Procurement (PCP) program for wave energy.
- **Wave Swell Energy deployed the unidirectional UniWave 200, an OWC device, at King Island.**

2023
- CorPower Ocean deployed its 300 kW C4 wave energy converter at the Aguçadoura site in Portugal.
- OES published an international roadmap to develop 300GW of ocean energy by 2050.

2024
- Ocean Energy deployed the 1 MW-rated OE35 OWC device in Hawaii.
- C-Power deployed the SeaRAY device in Hawaii, demonstrating its ability to power subsea sensors and vehicles.
- **Carnegie deployed the MoorPower scaled demonstrator in Western Australia.**

2.1.2. Status

Europe has established itself as a global leader in wave energy research and development. Historically, the UK, Norway, Denmark, Sweden, Portugal, Ireland, Spain, France, and Italy have played pivotal roles. In Asia, Japan and India have long-standing research initiatives, while China has recently intensified their efforts. The USA is emerging as a significant player in wave energy.

Numerous technology developers are active in the wave energy sector. Prominent names include:

- **Europe:** CorPower Ocean, Mocean Energy, Eco Wave Power, AW-Energy, OceanEnergy, Seabased, Bombora Wave Power, Wavepiston, IDOM, Waves4Power, Crestwing, Symphony Wave Power, NoviOcean, Ocean Harvesting Technologies, Checkmate Seaenergy, Wave for Energy, GEPS Techno
- **USA:** Ocean Power Technologies, Oscilla Power, CalWave Power Technologies, AquaHarmonics, Atargis Energy, Atmocean, C-Power, Panthalassa
- **Australia:** Carnegie Clean Energy, Wave Swell Energy, AMOG
- **Canada:** Oneka Technologies
- **Asia:** INGINE

The wave energy sector stands apart for its diverse range of technology concepts, reflecting its inherent complexity—especially when compared to wind and solar. This diversity stems not only from the varied environmental conditions at deployment sites but also from gaps in the sector's historical development, which have disrupted the continuity of earlier lessons.

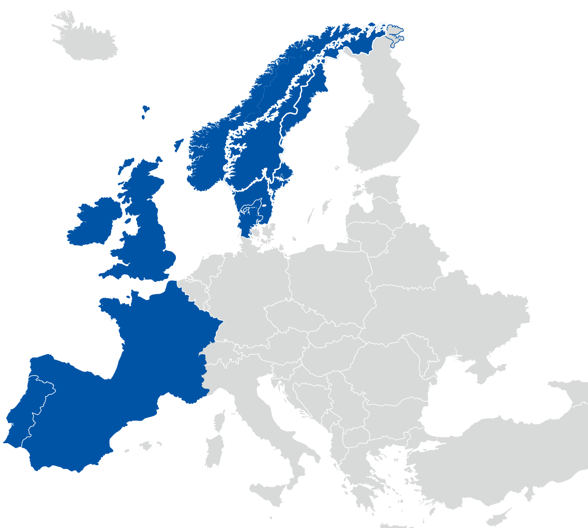
Today, initiatives like Wave Energy Scotland's structured innovation approach are driving efforts to achieve design consensus and foster technological convergence. The growing emphasis on performance metrics and staged evaluations is seen as crucial for driving innovation, reducing risks, and building confidence in the sector (Supergen ORE Hub, 2022).

Grid-connected Test Centres

Numerous grid-connected test centres have been established globally. These centres enable developers to trial their technologies under open-sea conditions.

Key European test sites include:

- **UK:** European Marine Energy Centre (EMEC)
- **Denmark:** DanWEC
- **France:** SEM-REV
- **Spain:** BiMEP and PLOCAN
- **Ireland:** SmartBay and Atlantic Marine Energy Test Site (AMETS)
- **Norway:** Runde
- **Sweden:** Lysekil
- **Portugal:** Aguçadoura



In the USA, the U.S. Navy Wave Energy Test Site (WETS) in Hawaii and PacWave South, set to open in 2025 off the coast of Oregon, serve as primary test centres. China has established a test centre on Wanshan Island, Guangdong, and is currently developing the National Ocean Integrated Test Site (NOITS) in Weihai, Shandong, along with another two test centres (Fang et al., 2022).

International Wave Energy Standards

In 2007, the International Electrotechnical Commission (IEC) Technical Committee 114 (TC114) on Marine Energy – wave, tidal, and other water current converters was established. This body develops international, consensus-based standards for the marine energy industry to support the development and implementation of marine energy technologies and facilitate progress towards commercial-scale projects. TC114 is comprised of over 200 experts from 30 countries, organised into project committees and working groups.

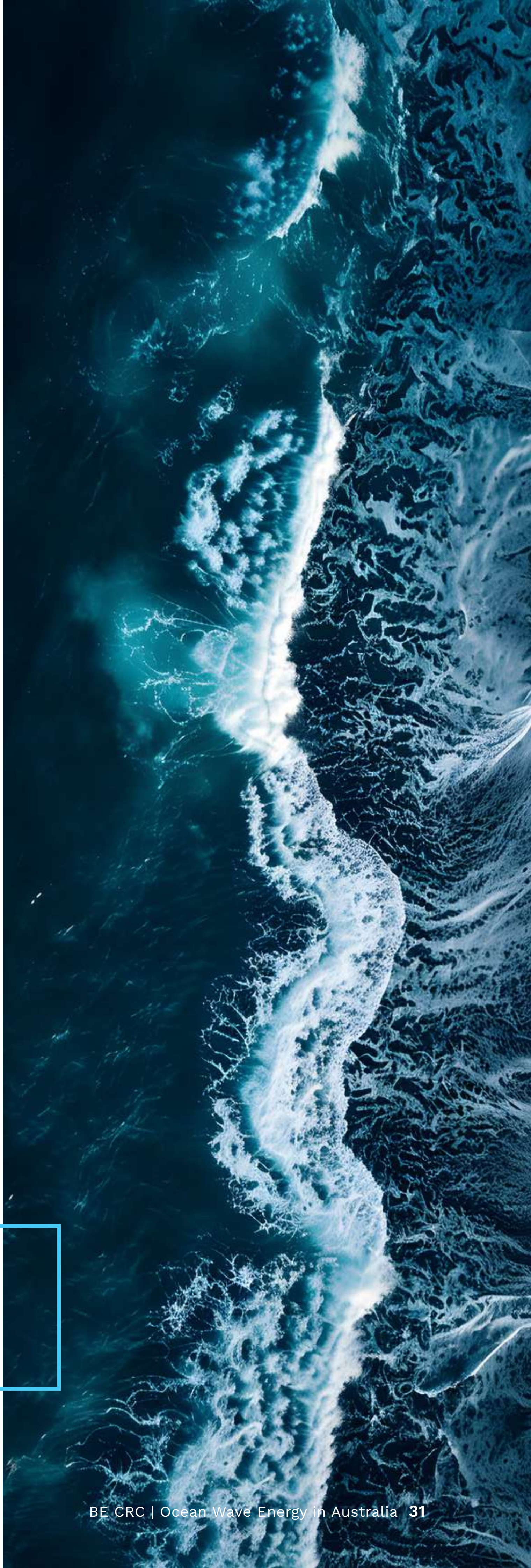
To date, TC114 has published 18 technical specifications for marine renewable energy, covering design, resource characterisation, acoustics, moorings, and power performance. These standards ensure the reliability, efficiency, and safety of marine energy technologies, facilitating their development and deployment globally.

Opportunities

The wave energy sector is accelerating rapidly. In Europe alone, the next 5 years will see as much capacity added as the past 11 years (Dupont, 2024). In November 2023, the International Energy Agency Technology Collaboration Programme on Ocean Energy Systems (IEA-OES) published an international roadmap to develop 300 GW of ocean energy by 2050 (IEA-OES, 2023). This roadmap addresses the challenges and opportunities in the wave and tidal energy sector.

The IEA-OES roadmap projects a global installed capacity of 300 GW of ocean energy by 2050, which is expected to create 680,000 jobs, and generate USD 340 billion in gross value added.

This roadmap also predicts prevention of over 500 million tonnes of carbon emissions.



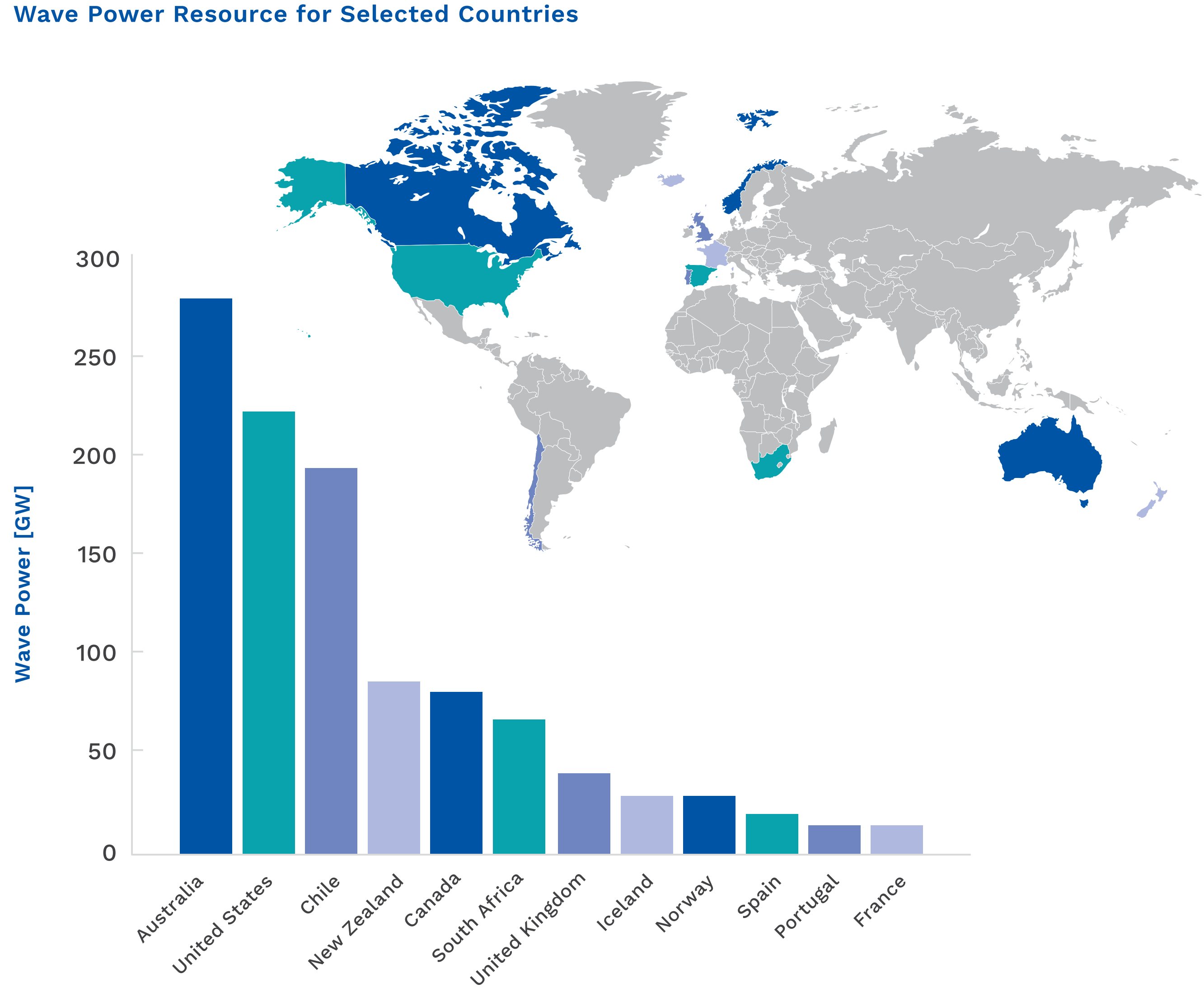
The potential of wave energy is substantial, and the knowledge base has significantly expanded over the years. Synergies with offshore wind, digitalisation, advances in robotics, sensing, and autonomous systems, along with the identification of niche markets, are opening new opportunities for wave energy.

While politically driven funding environments have historically created gaps and slowed progress, there is growing recognition that the initial focus should be on achieving predicted output and ensuring device survival, despite high initial costs, rather than forcing premature competition with more established renewable technologies. As costs are expected to decrease with larger installed capacity, sustained policy support and long-term, coordinated funding for both technology and market development (technology push and market pull) will be essential to foster continuous innovation in the wave energy sector.

2.1.3. Australian Context

Although Australia entered the wave energy sector relatively late, it has developed a strong foundation in wave energy research and development, with several notable projects and ongoing initiatives, as highlighted by Manasseh et al. (2017). As discussed in Chapter 3 of this report, studies quantifying Australia's wave energy potential show that the country has the highest wave energy potential globally (Figure 2.3), particularly along its southern and western coasts.

Figure 2.3. Australia's wave energy resource compared to other selected countries, based on data from Gunn and Stock-Williams (2012).



Key Projects

- One of Australia's most prominent wave energy technologies is Carnegie Clean Energy's CETO system. The CETO operates underwater, harnessing wave energy through submerged buoys. The Perth Wave Energy Project deployed three CETO 5 devices off Garden Island, Western Australia, in late 2014. Carnegie, through its subsidiary CETO Wave Energy Ireland, is now progressing with the deployment of the CETO 6 system at BiMEP in Spain, funded by the EuropeWave PCP Programme, Spain's RENMARINAS DEMOS Program, and the Basque Energy Agency. Carnegie's wave-powered barge concept, MoorPower™, harnesses wave energy for operations like aquaculture, which currently relies heavily on diesel. A demonstrator has been deployed in Fremantle, WA.
- Wave Swell Energy developed the UniWave200, a wave energy converter that utilises a unidirectional oscillating water column (OWC) design, where waves force air through a turbine to generate electricity. Deployed off King Island in 2021 (Figure 2.4) for a two-year period, the UniWave200 demonstrated an independently verified wave-to-grid energy conversion efficiency of nearly 50% for waves above 1 metre in height. The energy produced complemented Hydro Tasmania's existing hybrid grid, demonstrating the potential for integrating wave energy into hybrid autonomous microgrids, including those used by remote island communities.
- Engineering consultancy AMOG has developed its own wave energy converter, the Sea-Saw, a floating vessel with a damped pendulum. It has undergone extensive testing at the Australian Maritime College's (AMC) wave basin and Edinburgh's FloWave. The Sea-Saw was one of the five projects that advanced to the final phase of EuropeWave's PCP programme.
- At the time of writing, the Albany M4 demonstration project is on the verge of deploying a reduced-scale M4 device at King George Sound, Albany, Western Australia.

Figure 2.4. Wave Swell Energy's UniWave200. (Right).

Figure courtesy of Wave Swell Energy.

Research and Development

Australia is home to several institutions active in wave energy research and development, including the Australian Maritime College (AMC), Commonwealth Scientific and Industrial Research Organisation (CSIRO), The University of Western Australia (UWA), The University of Adelaide, Swinburne University of Technology, University of New South Wales (UNSW), and The University of Queensland (UQ). Significant capabilities exist within these institutions to support the wave energy sector, as reviewed by Hemer et al. (2018) and discussed again in Chapter 5.

The Australian Renewable Energy Agency (ARENA) has played a notable role in funding successful wave energy projects, including Carnegie's Garden Island project and Wave Swell Energy's King Island deployment. The Clean Energy Finance Corporation (CEFC) also offers financial support to renewable energy projects, including those in wave energy. Established in 2019 under the Australian Government's Cooperative Research Centre (CRC) Program, the Blue Economy CRC brings together the aquaculture, offshore engineering, and renewable energy sectors to address the challenges of offshore food and energy production.

Australia still lacks national grid-connected test centres for wave energy, with only several laboratory-scale facilities currently available.

Australian Wave and Tidal Energy Technical Committee: EL-066 Marine energy - Wave, tidal and other water current converters

In June 2020, Australian members convened the inaugural Standards Australia EL-066 mirror committee meeting as part of the broader TC114. The formation of EL-066 and Australia's entry into TC114 as a Participating Country marked the country's formal involvement in the international marine energy standards community.

The committee's goal is to support the development of wave and tidal energy, aligning with international standards, and ensure that Australian ocean energy technologies meet certification requirements and future customer expectations. The mirror committee, currently comprising 15 experts from Australian research institutions, advisory bodies, and industry, has met 13 times since inception and is reviewing existing standards for local adoption. Members also provide feedback to the International TC114 Committee on future priorities and join international teams to develop and maintain standards.

Australian involvement in the international standardisation committee IEC TC114 and the formation of the national committee EL-066 are encouraging developments since these actions were advocated in 2018 (Hemer et al., 2018).

2.2. International Funding and Jurisdictional Target Landscape

The global push towards clean energy has seen substantial investments from both private and public sectors. Governments worldwide have committed a significant USD 1.34 trillion to clean energy investments since 2020. In the first half of 2023 alone, USD 130 billion was allocated to further these initiatives (IEA, 2023d). Energy security concerns have also escalated, driven by the COVID-19 pandemic, supply chain disruptions, and geopolitical tensions, particularly Russia's invasion of Ukraine.

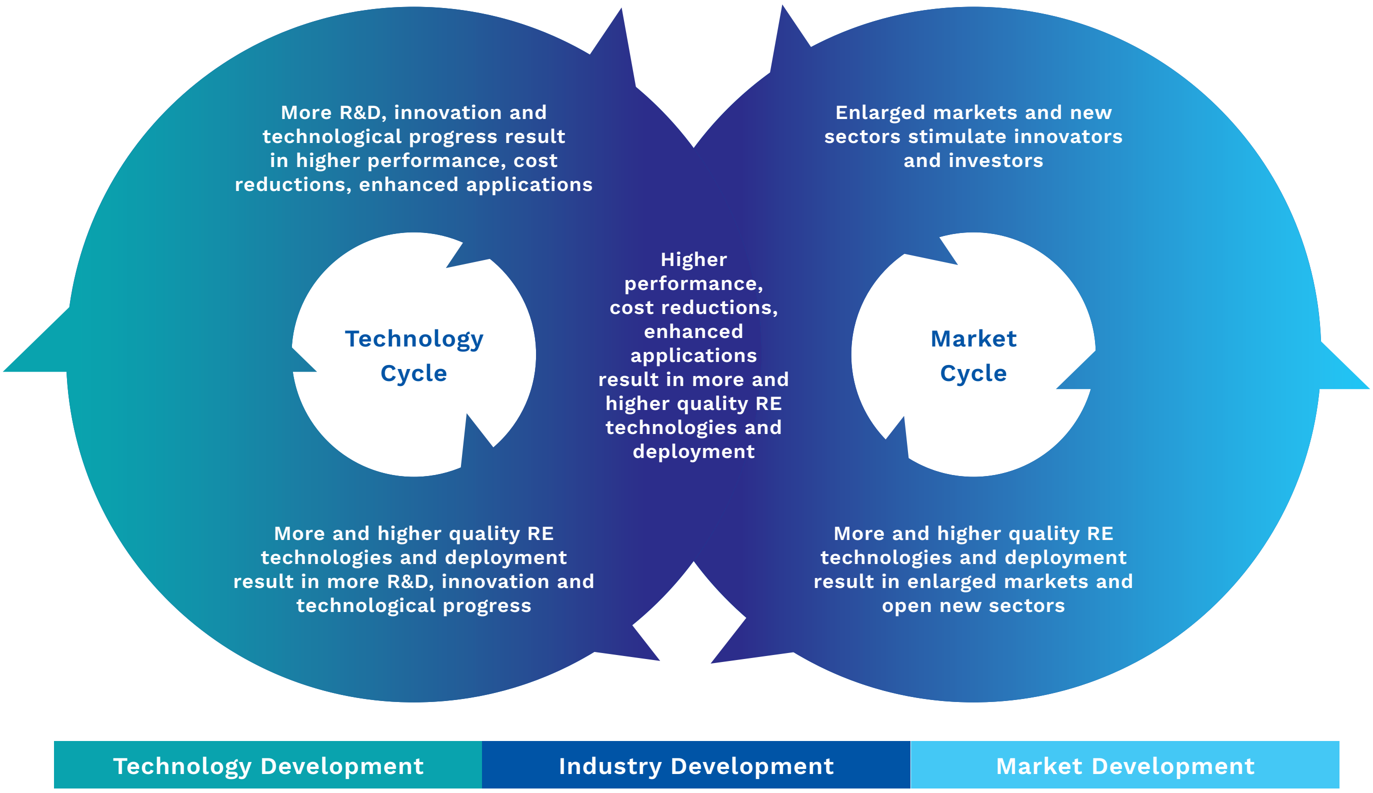
North-western European coastal countries are currently at the forefront of ocean energy technology development, with the North and South American, north-western Pacific and Australasian countries also involved. Governments have introduced various policy initiatives to support the growth of marine energy technologies.

These policies can be categorised into six main areas (Edenhofer et al., 2012):

- Capacity or generation targets;
- Market incentives;
- Capital grants and financial incentives, including prizes;
- Industry development;
- Research and testing facilities and infrastructure; and
- Permitting/space/resource allocation regimes, standards and protocols.

Striking a balance between technology-driven innovation (or technology push) and market demand incentives (market pull) is crucial for advancing the wave energy sector, as demonstrated by the success of wind and solar energy adoption (see Figure 2.5). The recent IEA-OES roadmap emphasises this balance, with sustained long-term market pull mechanisms (such as Feed-in Tariffs and Contracts for Difference) providing a foundation and enabling investor confidence. Meanwhile, technology push mechanisms, including R&D grants or loans are important to accelerate growth, particularly in the short term.

Figure 2.5. The mutually reinforcing cycles of technology development and market deployment drive down technology costs (from Mitchell et al., 2011).



Countries with dedicated ocean energy policies are generally more advanced in terms of technology development and deployment. Given the early stage of the technology, continuous government support is crucial for accelerating the development and commercialisation of these technologies. While most nations offer research and development (R&D) grants for renewable energy technologies, some have specific programs for ocean energy. The United Kingdom, for instance, has had the most extensive and long-standing support programs. The United States Federal Government has also significantly increased its investment in ocean energy since 2008.

2.2.1. The European Union and the United Kingdom

The European Union has faced significant challenges in the energy sector following Russia's invasion of Ukraine. In 2022, the EU spent over USD 300 billion on natural gas imports—a threefold increase compared to the average expenditure over the previous five years. This energy crisis prompted the EU to elevate its clean energy ambitions and prioritise energy security within its transition strategies. The response has been robust, involving substantial legislative measures and national as well as EU-level incentives amounting to nearly USD 500 billion dedicated to clean energy investments (IEA, 2023b).

However, the EU's clean energy transition heavily relies on a significant supply of raw materials, for which it remains highly dependent on imports. To mitigate this dependency and enhance the resilience of energy supply chains, the EU has intensified efforts to promote domestic production, mirroring global trends in response to the supply chain disruptions post-COVID-19 and the ongoing energy crisis.

Key EU initiatives and legislative measures include:

- **European Green Deal:** The EU's comprehensive strategy to achieve climate neutrality by 2050, promote a circular economy, protect biodiversity, and ensure a just and sustainable transition for all sectors and regions.
- **Fit for 55:** The implementation framework for the European Green Deal, aimed at reducing greenhouse gas emissions by at least 55% by 2030.
- **REPowerEU:** This plan outlines strategies to reduce dependence on Russian natural gas through energy savings, diversification of energy sources, and accelerated deployment of renewable energy.
- **Net-Zero Industry Act:** Designed to enhance the EU's manufacturing capabilities for green technologies, this act is the EU's answer to increasing global competition for leadership in clean technology, particularly in response to the U.S. Inflation Reduction Act. Ocean energy is among 19 key technologies, including solar, wind, and batteries, recognised as 'net-zero technologies' of strategic importance to the EU's decarbonisation efforts.

EU Strategy on Offshore Renewable Energy (2020)

The EU's offshore renewable energy strategy sets ambitious targets to expand Europe's offshore wind capacity from 12 GW in 2020 to at least 60 GW by 2030, and to 300 GW by 2050. Additionally, the strategy includes goals for ocean energy and other emerging technologies, such as floating wind and solar.

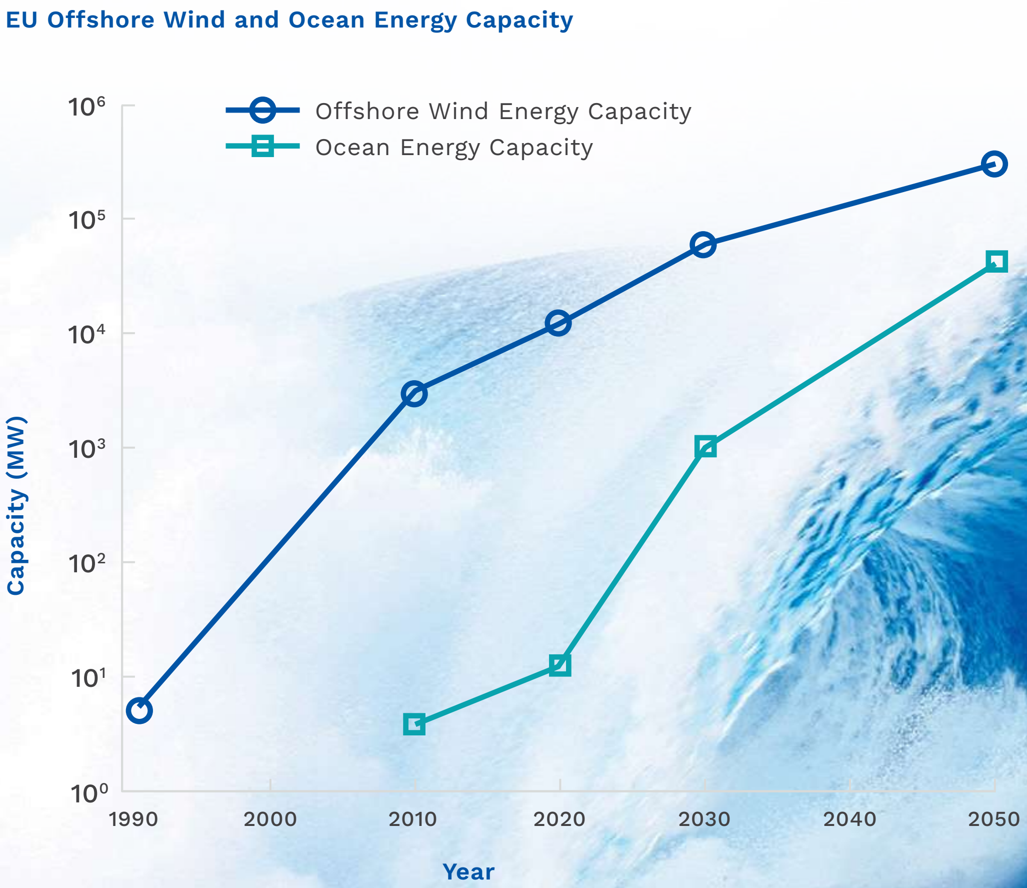
The EU is aiming for at least 100 MW of ocean energy capacity by 2027, 1 GW by 2030, and 40 GW by 2050.

These goals are illustrated in Figure 2.6. Achieving these objectives will require the marine renewables industry to scale up 5 times by 2030 and 25 times by 2050 to support the Green Deal's objectives. An investment of nearly EUR 800 billion will be necessary by 2050 to meet these targets. To support this transformation, the European Commission has committed to establishing a clear and supportive legal framework, mobilising relevant funds to support the sector's development, and strengthening supply chains.

The updated communication from the Commission to the European Parliament (European Commission, 2023a) outlines the goal of achieving 111 GW of total offshore renewables by 2030, nearly double the ambition set in 2020. Key recommendations include:

- Strengthening maritime spatial planning (MSP) to enhance regional cooperation and ensure the sustainable coexistence of offshore renewables with other maritime industries.
- Sustaining research and innovation (R&I) efforts to maintain the EU's technological leadership and develop sustainable solutions that reconcile offshore renewable activities with environmental considerations.
- Supporting EU supply chains to develop their capabilities, remain competitive, and achieve higher installation targets for offshore capacities within the EU and in third countries, facilitated through dedicated trade dialogues involving industry stakeholders.

Figure 2.6. EU's offshore wind and ocean energy capacity, including targets outlined in its Strategy on Offshore Renewable Energy (European Commission, 2020b). The updated target (European Commission, 2023a) aims to achieve 111 GW of total offshore renewables by 2030.



EU Leadership in Wave Energy

EU companies currently hold 44% of global patents in wave energy, underscoring the region's technological leadership. Between 2007 and 2019, EU funding provided EUR 493 million for ocean wave and tidal energy R&D, leveraging EUR 2.9 million in private-sector investment for every EUR 1 million of public funding (European Commission, 2020a).

By 2030, ocean energy is projected to contribute to the European economy up to a cumulative EUR 5.8 billion in Gross Value Added (GVA) (Cagney, 2020). The European Technology & Innovation Platform for Ocean Energy (ETIP Ocean) estimates that ocean energy can create economic activity worth EUR 140 billion and 500,000 direct and indirect jobs in Europe by 2050 (Henry et al., 2022).

Key EU programs supporting wave energy R&D include:

- **EuropeWave (2021-2026):** A EUR 20 million R&D program aimed at advancing wave energy through a competitive Pre-Commercial Procurement (PCP) model. Building on the approach pioneered by Wave Energy Scotland, it supports the design, development, and demonstration of robust, cost-effective WEC systems. The EuropeWave programme recently awarded EUR 13.4 million to three developers, including a subsidiary of Carnegie Clean Energy, to design, build, and test devices in real sea conditions by 2025.
- **PROSPER 2030 (2026-2030):** Set to continue the momentum beyond EuropeWave, this initiative will focus on scaling successful technologies and integrating them into the broader energy mix.
- **Horizon Europe Cluster 5 (2021-2027):** Allocating EUR 15.1 billion in grants, this cluster supports research and innovation across various sectors, including ocean energy.
- **Innovation Fund:** One of the world's largest funding programmes for demonstrating innovative low-carbon technologies. It recently granted EUR 65 million to two wave energy projects, Saoirse and SEAWORTHY.

Recent European Developments and Strategic Partnerships

In 2023, increased market visibility and funding have attracted major energy players, including power utilities and oil and gas companies (Dupont, 2024):

- State-owned Irish utility ESB and leading Irish renewable developer Simply Blue launched a joint venture to deliver a 5-MW wave energy pre-commercial farm off the coast of Ireland, marking a significant step towards commercial-scale deployment.
- Global energy giants Shell, Equinor, and Total Energies have respectively partnered with European wave energy developers Wavepiston, Havkraft, and Mocean Energy to explore wave energy solutions for decarbonising offshore operations.

Recent EU projects include:

- **EU-SCORES (European Scalable Offshore Renewable Energy Sources, https://euscores.eu/):** This EUR 45 million project aims to deliver world-first bankable hybrid offshore marine energy parks.
- **EVOLVE (Economic Value of Ocean Energy, https://evolveenergy.eu/):** This initiative quantifies the system benefits of ocean energy by analysing production, supply and demand profiles. For instance, the installation of 10 GW of wave energy in Great Britain alone could save GBP 1.46 billion annually in power system dispatch costs and cut emissions by up to 1.05 $MtCO_2$ (Pennock, 2023). Further discussions about the findings of the project are covered in Chapter 4 of this report.
- **VALID (Verification through Accelerated testing Leading to Improved wave energy Designs, https://www.validhtp.eu/):** This EUR 5 million project aims to develop a new test rig platform and methodology for accelerated hybrid testing that can be used across the wave energy sector.
- **WEDUSEA (Wave Energy Demonstration at Utility Scale to Enable Arrays, https://wedusea.eu/):** This EUR 19.6 million project, involving 14 industry and academic partners from Ireland, the UK, France, Germany, and Spain, aims to demonstrate a grid-connected 1 MW OE35 floating wave energy converter.

Several strategic roadmaps are guiding ocean energy development at both EU and national levels. Some examples are:

- **European Offshore Renewable Energy Roadmap:** Funded by the EU's FP7 program, ORECCA (Offshore Renewable Energy Conversion platforms - Coordination Action) provides a comprehensive framework for advancing offshore wind, wave energy, and tidal stream technologies (Jeffrey and Sedgwick, 2011).
- **European Ocean Energy Roadmap 2010-2050:** Developed by the European Ocean Energy Association, this roadmap outlines long-term objectives for the sector, emphasising the need for sustained investment and innovation (European Ocean Energy Association, 2010).
- **Ireland's Ocean Energy Roadmap:** This roadmap envisions up to 29 GW of installed capacity by 2050, with 95% from wave energy and 5% from tidal energy, potentially creating 70,000 jobs and generating EUR 120 billion in economic benefits (Sustainable Energy Authority of Ireland, 2015).
- **Offshore Renewable Energy Technology Roadmap:** The domestic rollout of offshore renewable energy is expected to contribute at least EUR 8.8 billion in Gross Value Added to the Irish economy (Sustainable Energy Authority of Ireland, 2024).

Wave Energy in the United Kingdom

Wave energy is a key element of the UK's renewable energy strategy. Achieving the targets set out in the Strategic Energy Technology Plan (European Commission, 2023b)—namely, a Levelised Cost of Energy (LCOE) of EUR 0.20 per kWh by 2025 and EUR 0.15 per kWh by 2030—could see up to 6 GW of wave energy devices installed in the UK by 2050. This would meet approximately 15% of the UK's current electricity demand and contribute to the UK's transition to a low-carbon economy.

The 6 GW deployment is projected to contribute GBP 6-21 billion to the UK economy in GVA (Wong and Jeffrey, 2023) and could save over GBP 0.5 billion annually in dispatch costs. The wave energy sector is poised to create up to 8,100 new jobs by 2040, with a high level of UK content—approximately 80%—in the domestic market (Supergen ORE Hub, 2022).

The UK holds an estimated 35% of Europe's wave energy resource (Jin and Greaves, 2021), positioning it as a critical player in the continent's ocean renewable energy landscape. Recent funding programs have bolstered this position, including:

- GBP 4 million from the EPSRC for Marine Wave Energy;
- GBP 40 million from the Scottish Government for Wave Energy Scotland;
- GBP 16.5 million from the EPSRC for the Supergen ORE Hub; and
- EUR 100 million from European Structural Funds to develop Wales as a world-class centre of marine energy.

Within 2022 to 2025, according to data collated as of June 2023, the UK has provided a total public funding of EUR 63 million into the wave and tidal stream sectors (with EUR 32 million for wave), the highest support in terms of technology push funding among all European countries, contributing to around 12% of total R&I public funding in Europe economy (Wong and Jeffrey, 2023). A relatively large portion of UK funding is focused on early-stage research.

Wave energy technology in the UK is currently at the prototype development stage, with several key projects demonstrating significant progress:

- **Mocean Energy:** Completed sea trials of a 10 kW ½ scale prototype (Figure 2.7) in 2021 and again from March 2023 to April 2024 (EMEC, n.d.), and is now developing a 250 kW pre-commercial prototype under the EuropeWave programme (EuropeWave, n.d.).
- **AWS Ocean Energy:** Completed shakedown test of a 16 kW ½ scale prototype in 2022 (EMEC, n.d.).
- **Bombora Wave Power Europe:** Originally an Australian company, it is currently fabricating a full-scale 1.5 MW prototype in Pembrokeshire (Bombora, n.d.).

Figure 2.7. Mocean's Blue X wave energy device, courtesy of Mocean Energy (left).

The UK Wave Energy Road Map (Supergen ORE Hub, 2022) outlines a pathway to achieving GBP 90/MWh LCOE by 2035 and 22 GW installed capacity by 2050. This vision is supported by the UK's established expertise, infrastructure, and supply chain, bolstered by lessons learned from earlier prototype developments and a strong community of academics and industry. Previously, the Marine Energy Technology Roadmap (ETI and UKERC, 2014) emphasised the importance of establishing an extensive supply chain for building the skills and capacity necessary for the sector's growth.

The UK's universities (e.g., Edinburgh, Plymouth, Exeter, Strathclyde) and companies are well-positioned to provide consultancy and technical support for wave energy technology. The country's mature oil & gas and wind sectors offer robust capabilities in marine operations and infrastructure.

The Supergen Offshore Renewable Energy (ORE) Hub brings together leading researchers, industry stakeholders, and policymakers across the UK to advance offshore renewable energy technologies. Combining the former Supergen Wind and Supergen Marine Hubs, it builds on their work to explore synergies between offshore wind, wave, and tidal technologies. Launched in July 2018 with GBP 5 million from the Engineering and Physical Sciences Research Council (EPSRC), and further supported by an additional GBP 4 million in June 2019 and GBP 7.5 million in 2023, the Hub is part of the Supergen Programme established in 2001 to deliver sustained and coordinated research on Sustainable PowER GENeration and supply. The Supergen ORE Hub's core research activities, set to continue through 2027, are organised into five workstreams: ORE expansion – policy and scenarios, data for ORE design and decision-making, ORE modelling, ORE design methods, and future ORE systems and concepts (Supergen ORE Hub, 2023).

Wave Energy Scotland (WES) was established in 2014 by the Scottish Government, following the collapse of Pelamis and Aquamarine, to ensure that Scotland retained its leadership in wave energy. Since its inception, WES has funded 132 contracts, committed GBP 50 million, and collaborated with 300 organisations across 18 countries. This highlights Scotland's strong dedication to advancing the wave energy sector. The Scottish Energy Strategy (Scottish Government, 2017) outlines Scotland's vision for a sustainable energy future and specifically recognises the wave and tidal energy sector as a significant economic and climate opportunity. The Scottish Programme for Government 2022 to 2023 (Scottish Government, 2022) reaffirmed this commitment, pledging continued support for the development of these sectors.

The UK Offshore Renewables Joint Industry Programme (ORJIP) for Ocean Energy's Forward Look includes a list of strategic research priorities to tackle key consenting issues in the wave and tidal sectors. This effort ensures that research remains focused on priority consenting challenges (Aquatera, 2017).

2.2.2. United States of America

The U.S. has initiated a series of unprecedented government interventions aimed at accelerating the transition to clean energy and mitigating greenhouse gas (GHG) emissions. Central to these efforts are two significant legislative measures: the Bipartisan Infrastructure Investment and Jobs Act of 2021 and the Inflation Reduction Act of 2022.

The Bipartisan Infrastructure Investment and Jobs Act allocates approximately USD 190 billion to clean energy and mass transit infrastructure, forming part of a broader USD 550 billion federal investment package. The Act is designed to modernise the nation's infrastructure, with a focus on enhancing resilience and sustainability. Notably, it sets an ambitious target of achieving 30 GW of offshore wind capacity by 2030, demonstrating the U.S. commitment to expanding renewable energy sources.

The Inflation Reduction Act (IRA) represents a landmark in U.S. climate legislation, providing an estimated USD 370 billion to promote energy security and combat climate change. This Act supports the domestic production of clean technologies through a mix of grants, loans, rebates, and incentives. Significant allocations include USD 27 billion for the Greenhouse Gas Reduction Fund and USD 40 billion in loan authority for innovative clean energy projects. Additionally, USD 2 billion is directed to the Department of Energy's Office of Science and national laboratories to further clean energy research.

The U.S. Department of Energy (DOE) Initiatives

For FY 2024, the DOE has requested a budget of USD 3.8 billion for the Office of Energy Efficiency and Renewable Energy (EERE), as part of a broader USD 10.7 billion allocation across multiple agencies to support clean energy innovation and research (The White House, 2024a). Furthermore, the DOE's funding from the Infrastructure Investment and Jobs Act and the Inflation Reduction Act totals over USD 62 billion, targeting energy infrastructure, grid resilience, and the advancement of renewable energy technologies (The White House, 2024b).

The theoretical annual energy potential of waves off U.S. coasts is estimated at approximately 2,640 TWh, equivalent to 63% of the total utility-scale electricity generation in the United States as of 2023 (EIA, n.d.). The technically recoverable wave power resource, over the U.S. outer continental shelf to the 200-meter depth contour, is estimated at 1,170 TWh per year (Lehmann et al., 2017). A recent grid integration study by the Pacific Northwest National Laboratory (PNNL) has highlighted the benefits of wave energy integration for bulk-scale power systems and market operations (Akdemir et al., 2023).

The U.S. government has substantially increased its funding for ocean energy research, development, and innovation (RD&I). In 2023, the Water Power Technologies Office's (WPTO) Marine Energy Program received a record USD 120 million, marking the third consecutive year of budget increases (Office of Energy Efficiency & Renewable Energy, n.d.).

Since 2019, U.S. RD&I funding for ocean energy has totalled USD 520 million, significantly surpassing European investment in the sector.

State-level support is also intensifying, with California and Oregon enacting laws to further boost ocean energy development (Dupont, 2024). In 2023, the California Legislature passed Senate Bill 605, which requires the California Energy Commission and other state authorities to undertake a feasibility study on the costs and benefits of using wave and tidal energy to help meet the state's clean energy and pollution reduction goals. The bill also mandates collaboration with other stakeholders to identify suitable sea space for offshore wave and tidal energy projects in both state and federal waters (State of California, 2023). The results of these investigations are expected in a report due in February 2025.

The U.S. DOE's WPTO has recently announced plans to allocate another USD 112.5 million to support wave energy technology development (Office of Energy Efficiency & Renewable Energy, n.d.). This opportunity, expected to open in September 2024, focuses on reducing deployment risks, attracting investment, and enabling longer-term demonstrations to advance WEC technology and its potential contribution to the U.S. energy landscape. Additionally, the U.S. DOE has announced a USD 400 million funding program through the Office of Clean Energy Demonstrations for projects that include marine renewables (Office of Clean Energy Demonstrations, 2024).

The Portal and Repository for Information on Marine Renewable Energy (PRIMRE) (OpenEI, n.d.) is a strategic initiative to support the growth and development of the marine energy sector in the United States. PRIMRE provides centralised access to a wide array of essential data and information, including power performance metrics, environmental monitoring reports, device testing guidelines, and software tools. It is designed to meet the needs of researchers, developers, and policymakers involved in marine energy. The platform helps organise vocabularies, retain important early lessons from developers, guide research activities internationally, inform permitting decisions for regulators, and provide authoritative information for the public. PRIMRE plays a vital role in organising and preserving industry knowledge, which is particularly valuable during the early and rapidly evolving stages of the marine energy sector (Whiting et al., 2023).

Another important initiative by the U.S DoE's WPTO is TEAMER: Testing Expertise and Access for Marine Energy Research (TEAMER, n.d.). It aims to advance marine energy technologies by providing access to leading facilities and experts in the field, as well as publicly available project data. The program supports the development and testing of marine renewable energy projects through three annual open funding calls. TEAMER plans to distribute around USD 25 million through competitive Requests for Technical Support (RFTSs) to help refine and commercialise promising marine energy technologies.

2.2.3 Asia

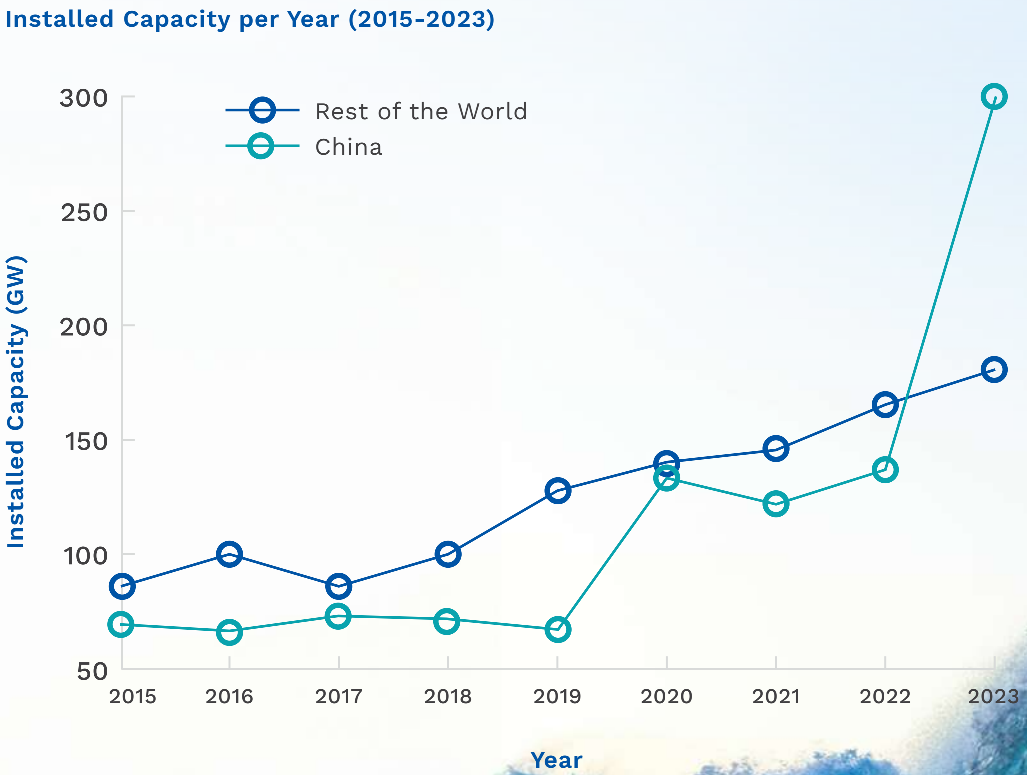
In recent years, China has emerged as a pivotal force in shaping global energy trends, particularly in the clean energy sector. As the world's largest consumer of various clean energy technologies, China has made significant strides in transitioning to renewable energy, positioning itself as a leader in the global energy transition.

According to the International Renewable Energy Agency (IRENA, 2024), China accounted for 63% of global net additions in total renewable capacity in 2023, contributing 298 GW of the 473 GW added globally. Even more striking is China's contribution to year-on-year growth in global renewable capacity, which was 96% in 2023. Excluding China, global net additions in renewable capacity were only 7 GW higher than in 2022, highlighting China's outsized role in global renewable energy growth (Figure 2.8).

As of 2023, China's installed capacity of renewable energy exceeded 1,450 GW, representing more than 50% of the country's total installed power generation capacity. Renewable energy sources, such as wind and solar, now account for over 15% of China's total electricity consumption. In 2023 alone, China's solar capacity more than doubled, and wind power capacity increased by 66% compared to the previous year.

Made in China 2025 (MIC 2025) is a comprehensive initiative aimed at transforming China's manufacturing sector from one dominated by heavy industry to a more advanced, value-added, and innovation-driven economy. Aligned with the goals of MIC 2025, China's 14th Five-Year Plan for Renewables sets ambitious targets to bolster the country's clean energy capacity. The plan aims to generate 3,300 TWh of renewable energy by 2025, effectively doubling solar and wind energy production. By 2030, China is targeting at least 1,200 GW of installed solar and wind capacity. The plan also sets a goal for over 50% of incremental electricity consumption to be met by renewables by 2025.

Figure 2.8. Installed capacity of renewable energy per year, from 2015 to 2023: China vs. the rest of the world, based on data from IRENA (2024).



China is also making significant strides in the development of ocean energy. The country's wave energy potential is estimated to be 7.7 GW, and research and development in this area have been ongoing since 1980 (You et al., 2012). Notable progress includes sea trials of wave energy devices by institutions such as the Guangzhou Institute of Energy Conversion (GIEC) and the National Ocean Technology Center (NOTC). GIEC's 100 kW rated Sharp Eagle was tested near Wanshan Island in 2015, and NOTC tested a 100 kW bottom-hinged Wave Energy Converter (WEC) near Daguan Island, Shandong, in 2012 (Liu et al., 2017). The 1-MW rated Nankun was deployed in Zhuhai in 2023. A national ocean energy road map is under development.

The Chinese government has enshrined the "large-scale deployment of ocean energy" in its five-year plans, with specific targets for deploying pilot farm fleets. In August 2023, China issued the Plan for Green and Low-carbon Advanced Technology Demonstration Projects to support demonstration projects including wave energy (IEA-OES, 2024). Given China's history of surpassing its renewable energy targets, this pledge signals a serious commitment to advancing ocean energy as part of its broader renewable energy strategy (Dupont, 2024).

Japan and South Korea are also significantly accelerating their efforts. Japan's Green Growth Strategy aims to stimulate USD 100 billion in private investment over the next decade (Ministry of Economy, Trade and Industry, 2021). South Korea's New Deal, unveiled in 2020, includes a substantial commitment of USD 60 billion towards the energy transition. By 2025, the country plans to invest USD 25 billion to generate 387,000 new jobs (IEA, 2021). In addition, South Korea has set ambitious renewable energy generation targets: 12.7 GW by 2020, 26.3 GW by 2022, and 42.7 GW by 2025 (Ministry of Economy and Finance, 2020).

2.2.4. Australia

Australia is at a critical juncture in its energy transition. According to the latest 2023 Energy Policy Review by the International Energy Agency (IEA, 2023a; IEA 2023c), under current trajectories, Australia will struggle to meet its 2030 emissions reduction targets and align with the goal of achieving Net Zero by 2050 without stronger efforts to improve energy efficiency and boost clean energy investment.

Australia's energy transition is complicated by a combination of global and domestic challenges. In 2022, Australia faced significant disruptions in its domestic gas and electricity markets, resulting in supply shortages and rising energy costs. These issues, along with the country's vulnerability to extreme weather events such as storms, flooding, wildfires, and heatwaves, underscore the critical need for resilient and sustainable energy infrastructure.

The Australian Government has set an ambitious goal to generate 82% of the nation's electricity from renewable sources by 2030, a significant increase from 27% in 2021. Current installed renewable energy capacity stands at 26 GW (2020), with the IEA forecasting this to grow to 40 GW by 2030. However, achieving this target will require not only an increase in renewable energy investments but also a strategic focus on diversifying the renewable energy portfolio.

To align Australia's energy transition with its climate targets, the IEA recommends the following actions:

- **Increase Investment in Diverse Renewable Technologies:** Australia should set dedicated targets for renewable gases, offshore wind, and energy storage to boost the overall decarbonisation of the economy.
- **Develop a Renewable Energy Industrial Strategy:** Aligning with Australia's ambition to become a green energy superpower, a comprehensive industrial strategy is needed. This strategy should focus on enhancing resilience in supply chains, developing skills, upgrading port infrastructure, and strengthening cybersecurity.
- **Strengthen Public Funding for Energy RD&D:** Compared to international standards, Australia's public funding for energy research, development, and demonstration (RD&D) is insufficient, representing only 0.019% of GDP in 2020, half of the IEA average.

Strategic Plans

The Australian Government's Powering Australia plan (DCCEEW, 2024a) is a AUD 23 billion strategic framework aimed at creating jobs, reducing energy costs, and lowering emissions through the expansion of renewable energy sources. The plan emphasises the development of key technologies such as solar, wind, energy storage, and hydrogen.

The vision for Australia to become a global leader in renewable energy is further articulated in the Future Made in Australia policy (Treasury, 2024). This strategy is underpinned by the recognition of Australia's vast renewable energy resources and the need to capitalise on these to support economic growth and energy independence.

The Australian Energy Market Operator (AEMO) 2024 Integrated System Plan (AEMO, 2024) reinforces this vision, projecting the need for a significant increase in grid-scale renewable energy. The plan outlines a requirement to triple the current capacity of variable renewable energy by 2030 and increase it six-fold by 2050. This expansion will involve adding approximately 6 GW of new capacity each year, with a projected total grid-scale solar capacity of 58 GW and wind capacity of 69 GW by 2050. The integration of 75 GW of firm dispatchable capacity, including battery storage, pumped hydro, and gas-fired generation, will be critical to ensuring reliability (see Chapter 4, where this concept is further explained).

Additionally, the plan highlights the need for 10,000 km of new transmission infrastructure by 2050, with an estimated upfront capital investment of AUD 142 billion. The demand for skilled workers in the energy sector is expected to peak at over 60,000 by 2050, highlighting the scale of the transition.

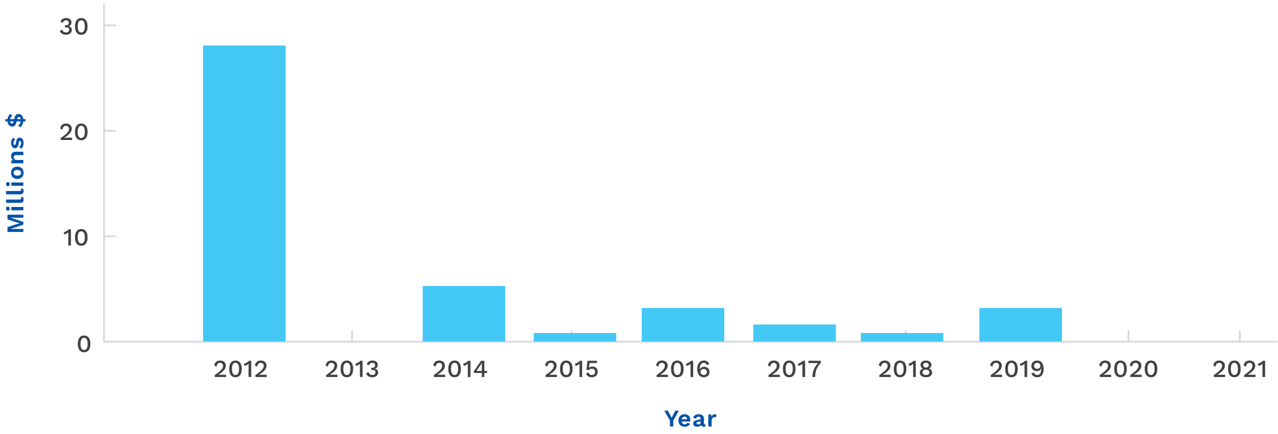
Australia's pathway to a 100% renewable energy future is based on four key pillars:

- **Low-Cost Renewable Energy:** Expansion of wind, solar, and hydroelectric power;
- **Firming Technologies:** Development of pumped hydro, batteries, and gas generation to ensure grid stability;
- **New Transmission and Distribution Networks:** Upgrading and expanding infrastructure to support increased renewable generation; and,
- **Renewable Power Systems:** Establishing systems capable of operating entirely on renewable energy.

Figure 2.9. ARENA funding for ocean energy projects in Australia, based on data from ARENA (2022).

ARENA Funding for Ocean Energy Projects

Government Funding



Funding and Support for Wave Energy

The Australian Renewable Energy Agency (ARENA) has played a pivotal role in advancing renewable energy technologies across the country. Since its inception in 2012, ARENA has invested AUD 2.25 billion in grant funding, supporting 663 projects. Of this, approximately AUD 44 million has been allocated to ocean energy projects (ARENA, 2022) (Figure 2.9).

The breakdown of ARENA's funding for ocean energy projects illustrates a diverse range of initiatives, including feasibility studies, technology development, and pilot projects.

Notable examples include:

- UniWave200 King Island Project (2019): Total project cost of AUD 12.3 million, with AUD 4.03 million from ARENA;
- Australian Wave Energy Atlas (2014): Total project cost of AUD 3.28 million, with AUD 1.32 million from ARENA;
- Perth Wave Energy Project (2012): Total project cost of AUD 39.87 million, with AUD 13.09 million from ARENA.

In total, ARENA's ocean energy projects have a combined cost of AUD 111.16 million, with AUD 43.58 million funded by ARENA. This indicates a significant but relatively modest commitment to ocean energy, with funding accounting for approximately 1.94% of ARENA's total grant funding. Notably, there has been no active ARENA engagement in ocean energy in recent years.

Australia's blue economy generates more than AUD 118 billion each year and supports 462,000 jobs across various sectors, including offshore energy, fisheries and aquaculture, shipping, marine recreation, and tourism. The Department of Climate Change, Energy, the Environment and Water is currently drafting a national Sustainable Ocean Plan (DCCEEW, 2024b) to guide Australia's future ocean management by uniting governments, industry, research, conservation, and communities to ensure a sustainable ocean economy, healthy and resilient coasts, and equitable resource use.

Offshore Renewable Energy Systems is one of five Research Programs managed by the Blue Economy Cooperative Research Centre (CRC), which operates under the Australian Government's CRC Program. Established in 2019 with a 10-year term and total funding exceeding AUD 300 million, the Blue Economy CRC is one of the largest funded cooperative research initiatives. Despite the size of the CRC overall, wave energy forms only a small fraction of its activity. Wave energy projects that have received partial funding from the Blue Economy CRC include Carnegie Clean Energy's MoorPower project and the M4 wave energy demonstration project in Albany, Western Australia.

The Offshore Electricity Infrastructure Act 2021 provides a licensing scheme to enable the construction, operation and decommissioning of offshore renewable energy and offshore electricity infrastructure projects, including wave energy. This Act is further discussed in Chapter 6.

Despite these investments, ocean energy remains a relatively small component of Australia's renewable energy strategy.

There are currently no dedicated roadmaps or funding schemes for ocean energy, including wave energy, within the country's broader energy planning frameworks.

Furthermore, ocean energy is not included in the latest Integrated System Plan (ISP), which outlines the future direction for Australia's energy infrastructure.

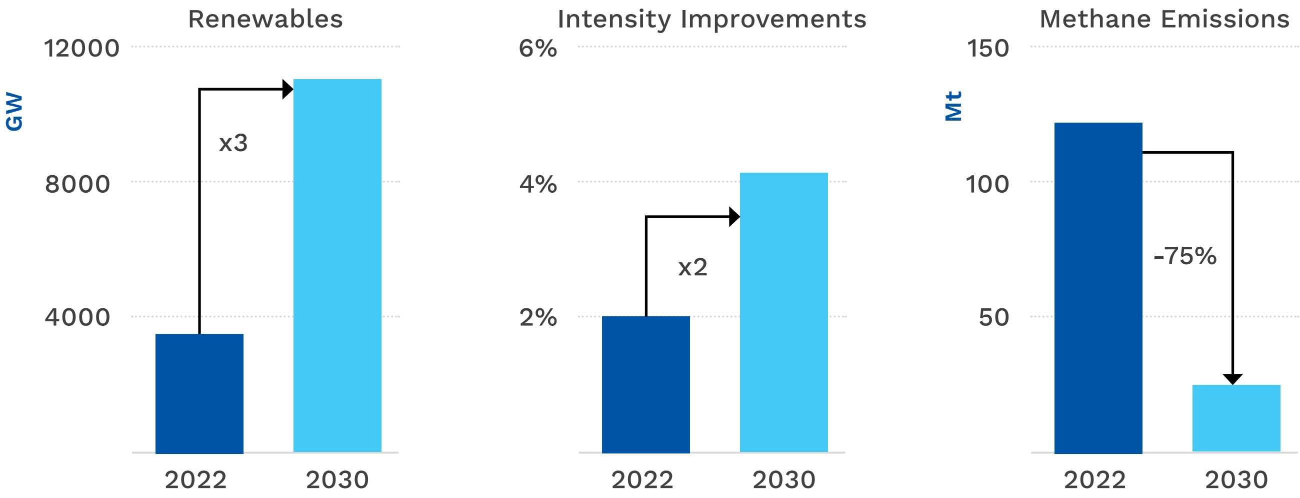
Given Australia's significant potential for ocean renewable energy, with wave energy alone potentially capable of contributing up to 10% of the country's renewable energy needs by 2030 (Behrens et al., 2012), failure to capitalise on this potential, as highlighted by Hemer et al. (2018), would be missing significant opportunities for Australia to diversify its renewable energy portfolio and grow its blue economy.

2.3. Climate Change Context

2.3.1. Global Emission Reduction Goals

The International Energy Agency's (IEA) World Energy Outlook 2023 (IEA, 2023b) emphasizes the urgent need to bend the emissions curve sharply downward by 2030 to stay on the pathway to limiting global warming to 1.5°C. The key actions required in the Net Zero Emissions by 2050 (NZE) Scenario are tripling the installed capacity of renewables, doubling the rate of energy intensity improvements, and significantly cutting methane emissions (Figure 2.10).

Figure 2.10. Three key actions required in the Net Zero Emissions by 2050 (NZE) Scenario, from IEA.



IEA. CC. BY 4.0

The concerted efforts of major economies are crucial for meeting the global targets. The following outlines specific commitments from key regions and countries:

USA

- Target a 50-52% reduction in GHG emissions by 2030, relative to 2005 levels;
- Achieve net zero GHG emissions by 2050;
- Attain 100% carbon-free electricity generation by 2035.

EU

- Achieve net zero emissions by 2050;
- Specific member state targets for carbon neutrality include: Finland by 2035; Austria by 2040; Germany, Portugal and Sweden by 2045.
- Ensure a 42.5% share of renewables in gross final energy consumption by 2030.

UK

- Achieve net zero emissions by 2050.

Other European nations

- Climate neutrality: Iceland by 2040; Switzerland and Norway by 2050.

China

- Reduce CO_2 intensity of the economy by 18% from 2021 to 2025;
- Reduce energy intensity by 13.5% from 2021 to 2025;
- Achieve a 20% share of non-fossil energy in the energy mix by 2025, and 25% by 2030;
- Peak CO_2 emissions before 2030;
- Lower CO_2 emissions per unit of GDP by over 65% from 2005 levels by 2030;
- Achieve carbon neutrality by 2060.

Australia's Climate Commitments

Central to Australia's climate strategy is the commitment to achieve net zero emissions by 2050. The Net Zero 2050 plan encompasses a broad range of policies aimed at decarbonising the economy while ensuring economic growth and energy security. The Powering Australia plan is a cornerstone of the government's strategy, aiming to create jobs, lower energy costs, and significantly reduce emissions through the expansion of renewable energy. This comprehensive plan leverages Australia's natural resources to position the nation as a renewable energy superpower. To encourage emissions reduction across various sectors, the Australian Government has implemented several incentive programs: Emissions Reduction Fund (ERF), Climate Active, and Renewable Energy Target (RET), as well as regulatory frameworks: National Greenhouse and Energy Reporting (NGER) Scheme and Safeguard Mechanism.

Australia's climate strategy is supported by a network of agencies and partnerships that drive research, finance, and regulation:

- Australian Renewable Energy Agency (ARENA) finances innovative low-emissions technologies.
- Clean Energy Finance Corporation (CEFC) provides investment in clean energy projects.
- Commonwealth Scientific Industrial Research Organisation (CSIRO) conducts climate research and projections.
- Clean Energy Regulator oversees the implementation of the NGER, ERF, and RET schemes.
- Climate Change Authority advises the government on policy development and future emissions targets.
- Australian Climate Service enhances climate data and analysis for better planning and preparedness.

As Australia prepares to submit its next Nationally Determined Contribution (NDC) under the Paris Agreement in 2025, the Climate Change Authority is tasked with developing advice on the nation's 2035 emissions reduction targets (Climate Change Authority, 2024). This guidance, requested by the Minister for Climate Change and Energy, is critical to shaping Australia's long-term climate strategy and ensuring that the country meets its international obligations.

Australia's current NDC, as outlined in the Climate Change Act 2022, includes three key emissions reduction targets:

- A commitment to reduce greenhouse gas emissions to 43% below 2005 levels by 2030, implemented as a single-year point target.
- A multi-year emissions budget for the period 2021 to 2030, with an indicative value of 4381 million tonnes CO_2-equivalent, corresponding to the 43% target.
- Achieving net zero emissions by 2050.

However, Australia's CO_2 intensity per GDP in 2021 was 0.302 kg CO_2/USD, notably higher than the IEA average of 0.186 kg CO_2/USD. Despite a slight reduction from 2000 to 2022, Australia remains one of the highest CO_2 emitters per capita in the world (Figure 2.11). By 2022, its per capita emissions exceeded those of the United States, United Kingdom, and China. In 2020, energy-related greenhouse gas (GHG) emissions accounted for 79% of Australia's total emissions, with coal being the dominant source, contributing nearly 50%. These figures highlight the pressing need to decarbonise the energy sector, particularly in electricity and heat generation. Compounding the issue, Australia's annual electricity consumption per capita is high, averaging around 10 MWh per capita throughout 2000-2022 (Figure 2.12).

Figure 2.11. Australia's CO_2 emissions per capita compared to other selected countries, based on data from IEA.

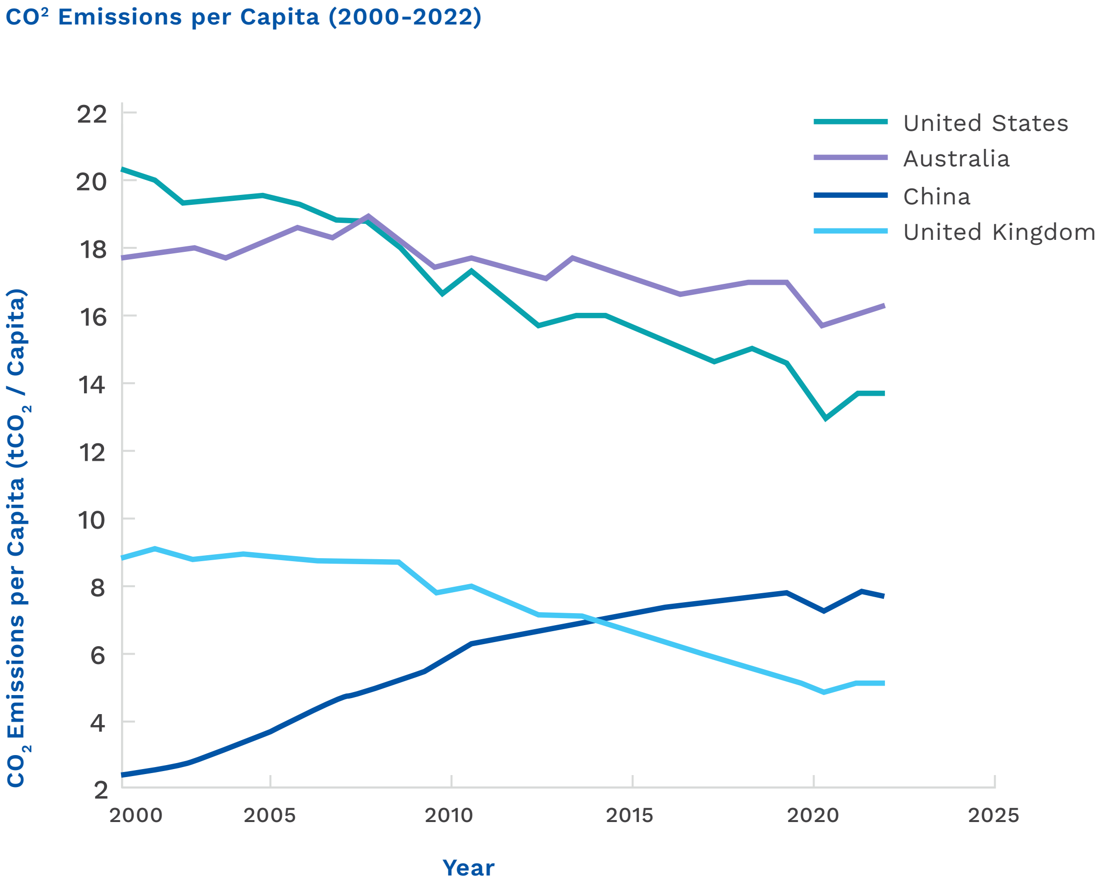
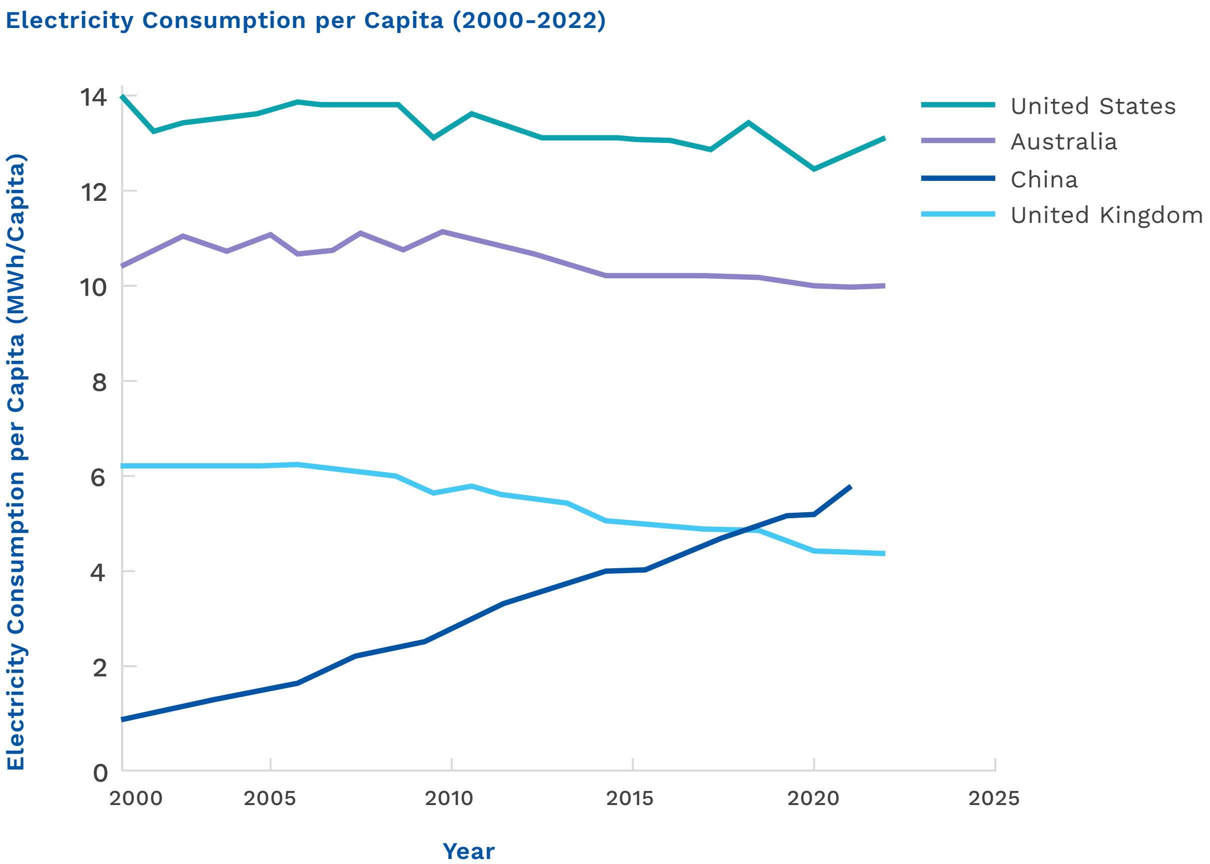


Figure 2.12. Australia's annual electricity consumption per capita compared to other selected countries, based on data from IEA.



Historical data of electricity generation shows a gradual but significant shift towards renewable energy sources across various nations, particularly in the last two decades, although progress varies across countries (Figure 2.13). Australia has consistently relied heavily on fossil fuels for electricity generation. In recent years, there has been a noticeable increase in the contribution of renewable energy sources (Figure 2.14).

Compared to countries like Denmark or Germany, where the shift from fossil fuels to renewables is more pronounced, Australia's transition appears slower. The heavy reliance on coal and other fossil fuels has only started to decline more visibly in the past decade.

Figure 2.13. Australia's electricity generation by source, compared to other selected countries and the world, based on data from IEA.

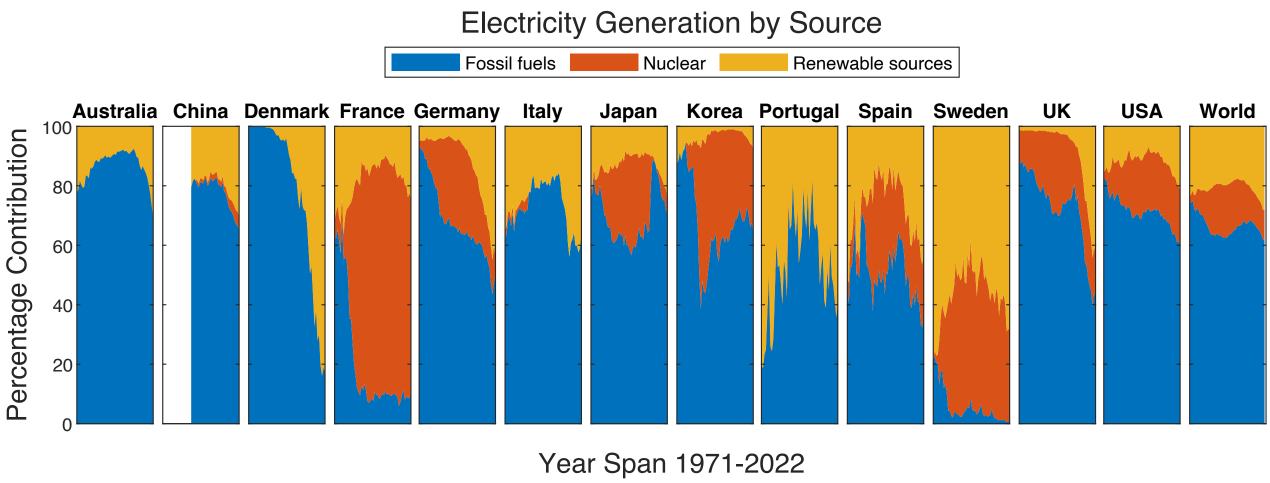
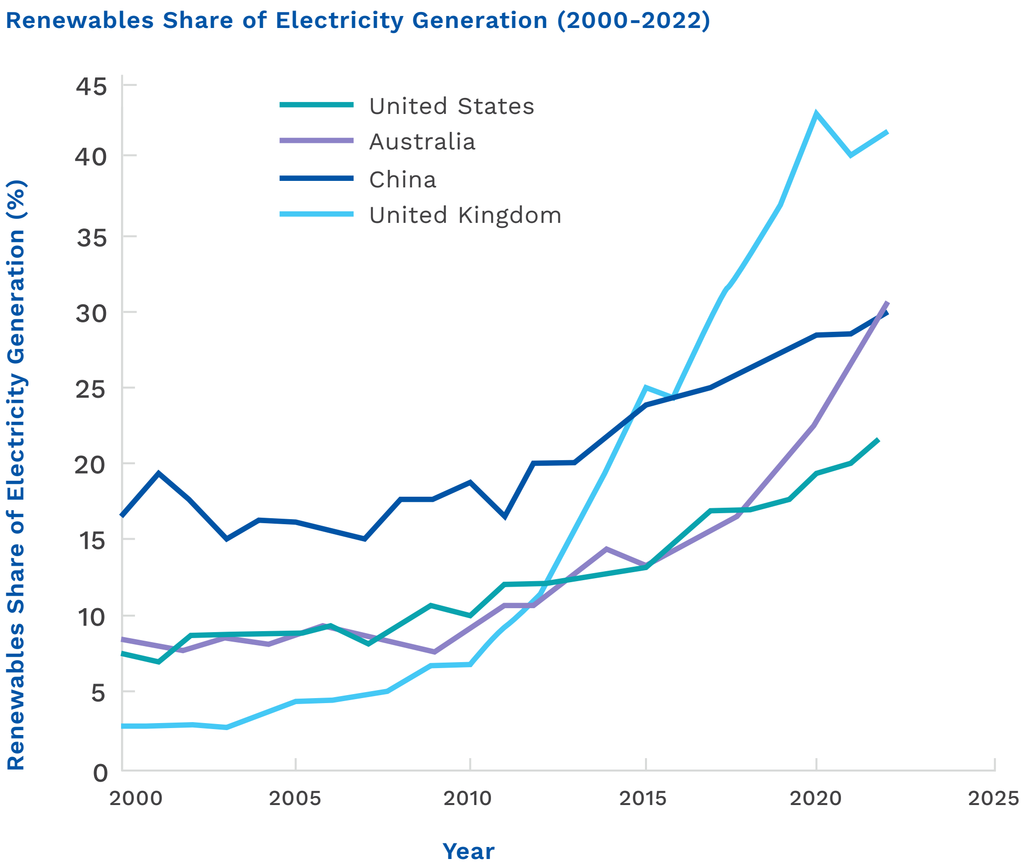


Figure 2.14. Australia's renewables share of electricity generation, compared to other selected countries, based on data from IEA.



2.3.2. Size of Opportunity: Global Wave Energy Resource

The potential for harnessing wave energy on a global scale is substantial. The total global wave power resource is estimated to be 2.11 terawatts (Gunn and Stock-Williams, 2012), approximately 10% of the global energy consumption (Ritchie et al., 2024), and two-thirds of the global electricity production (Ritchie and Rosado, 2024).

Wave power is most abundant in higher latitudes of the Southern Hemisphere, as well as in the North Atlantic and North Pacific (Figure 2.15). In the Northern Hemisphere, the strongest wave energy levels are found off the western coastlines of the British Isles, Iceland, and Greenland, with slightly lower levels along the western coasts of the United States and Canada. The Southern Hemisphere has the highest coastal energy levels overall, particularly off southern Chile, South Africa, and the southern and southwestern shores of Australia and New Zealand. In mid-latitudes, Western Australia stands out, with California also having a relatively high wave energy potential for its latitude (Barstow et al., 2009). Detailed analysis of the Australian wave resource is provided in Chapter 3.

Temporal variability in wave energy is a crucial factor, as the ratio of extreme to average energy levels impacts costs, making locations with lower variability more attractive. A significant difference exists between the hemispheres in terms of wave energy stability. In the Northern Hemisphere, wave energy levels show significant seasonal variation between summer and winter, unlike the Southern Hemisphere where energy levels remain relatively more stable (Figure 2.15). Australia stands out as one of the regions with the highest wave power levels and the least variability.

Figure 2.15. Global distribution of annual mean wave energy flux, from Cornett (2008).

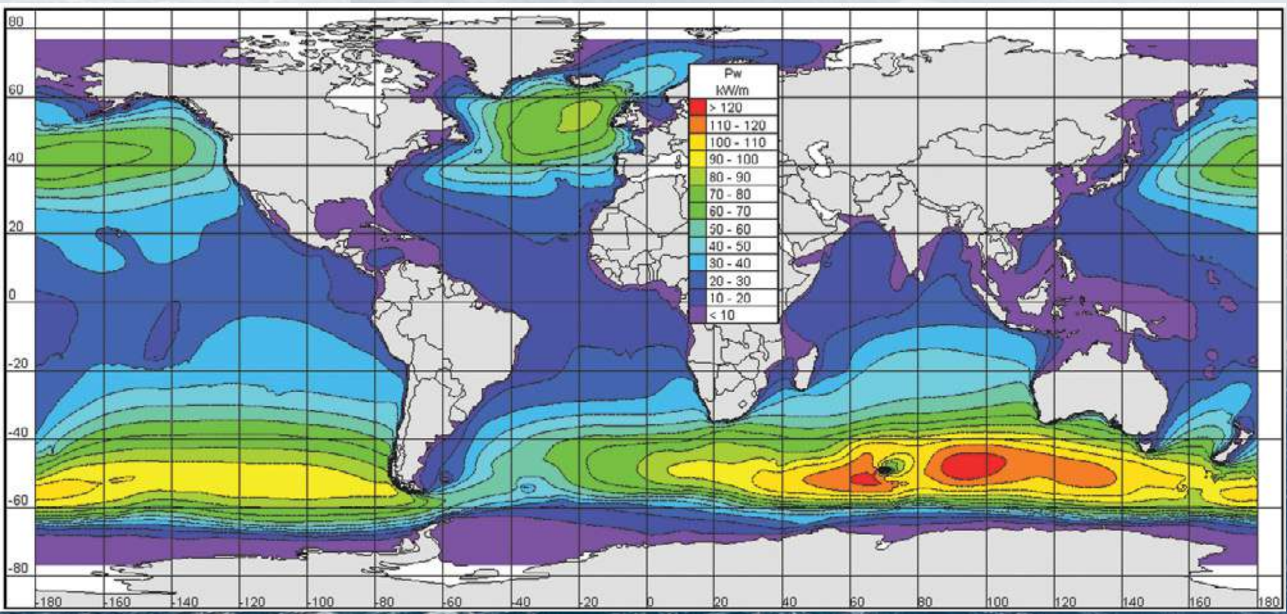
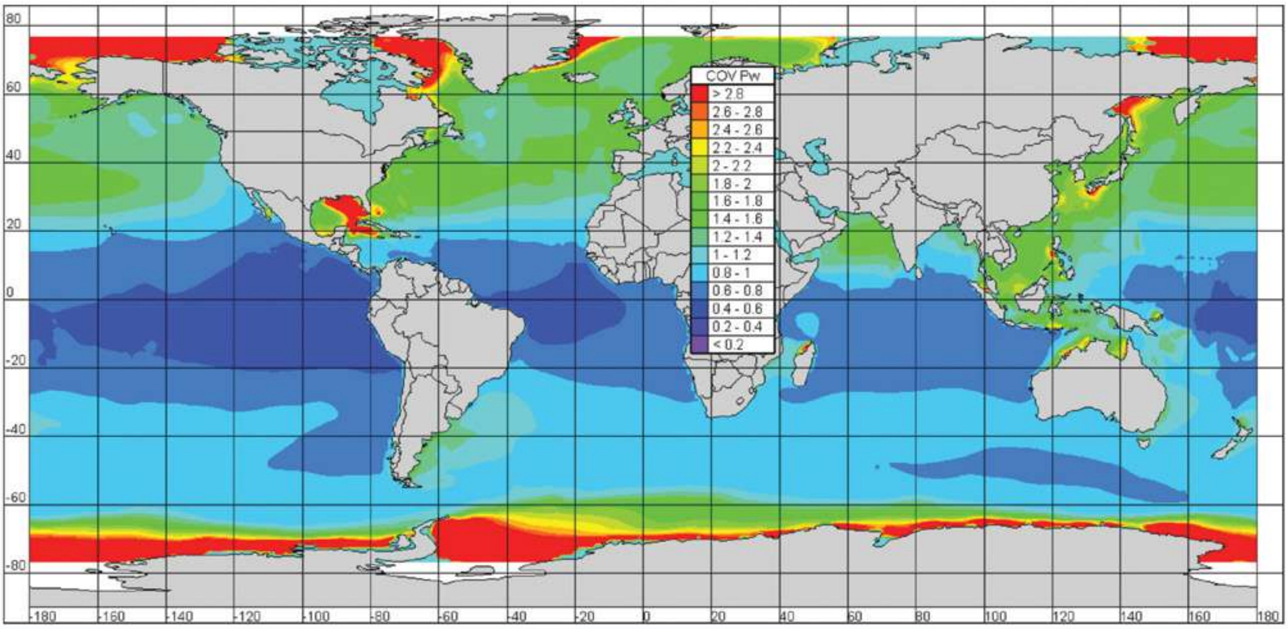


Figure 2.16. Global distribution of wave power temporal variability, from Cornett (2008). High coefficient of variation (COV) means high variability.



2.4. Synergies with Offshore Wind

Synergies with offshore wind are opening new opportunities for wave energy. Some wave energy and offshore wind technologies, including bottom-fixed and floating solutions, are designed to operate in coastal or offshore waters with the potential to occupy the same dedicated area while also sharing infrastructure and different stages of technology development and operation.

2.4.1. Complementarity of Wave and Wind

The combined use of wave energy converters and offshore wind turbines benefits both systems by influencing their performance and exploiting opportunities common for offshore industries and renewable energy plants.

Combined performance impacts include:

Decreased variability in the power output, and smoother electricity production. Despite the fact that ocean waves are generated by strong winds blowing over the water surface, wind and wave resources at a particular site usually have a low temporal correlation. This is mainly explained by the fact that the wave climate is dominated by swell waves that propagate from afar (10,000 km), while the wind climate depends on local winds. A low temporal correlation of two renewable energy sources leads to a more predictable, less variable, and smoother power output of the combined wave-wind energy system (Gideon and Bou-Zeid, 2021).

Reduced structural loads and costs for wind turbine foundations (bottom-fixed and floating). Wave energy converters generate electricity by removing energy from ocean waves, resulting in a reduction in wave height downstream of the wave energy farm. Thus, offshore wind farms installed closer to the shore in the wake of the wave energy converters are better protected from the harmful effects of ocean waves and experience reduced structural loads as compared to a stand-alone wind farm (Gubesch et al., 2023). This reduction of loads on the wind turbine substructure could potentially extend the lifetime of turbines and farms (Meyers et al., 2022), leading to lower costs for offshore wind power.

Increased stability of the floating wind turbine platform. Floating offshore wind turbines are subjected to significant motions from turbulent wind and ocean waves, which results in increased loads on their components and degrades aerodynamic efficiency. Certain types of wave energy converters installed on the same platform can act as damping devices that suppress its motion, improving the wind turbine performance and reducing the loads on the rotor and tower (Meng et al., 2023; da Silva et al., 2022).

In addition to the potential performance benefits of combining wind and wave energy systems, there are also **synergies associated with the technology development, deployment, and operation stages,** which include:

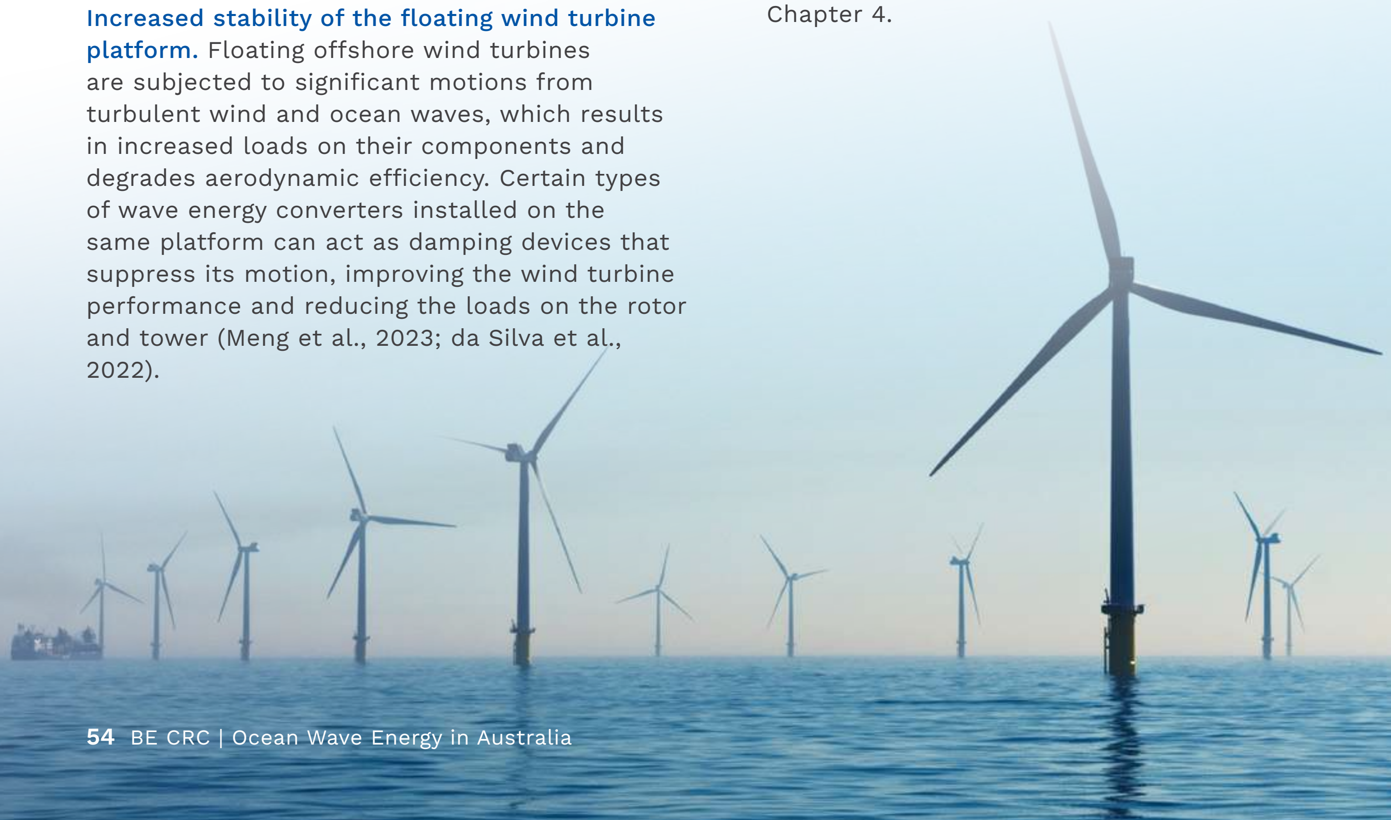
Site licensing. The use of a single deployment site for both systems allows for shared offshore site leasing and investigations including bathymetry and detailed seabed mapping; soil and sediment sampling; current, wave and wind speeds assessments; and environmental surveys.

Installation, operation, and maintenance can be shared by scheduling joint activities that involve access to port services and personnel, optimised vessel usage with subsequent reduction in downtime.

Supply chain can be shared by supplying raw materials (iron, steel, concrete), utilising existing or establishing new manufacturing facilities, providing mooring and anchor solutions, and electrical and machinery equipment, including cables, electric generators, and offshore substations.

Transmission infrastructure (inter-array cables, export cables, offshore and onshore substations) can potentially be shared to transport generated electricity onshore, but subject to regulatory and grid integration requirements.

Some of these benefits are further quantified in Chapter 4.



Combined wind-wave types and international examples

Combined wind-wave energy systems can be approximately divided into two main categories: co-located wind and wave farms that share the same location and infrastructure (different scenarios of asset and activity sharing can be considered), and hybrid systems where the wind turbines and wave energy converters are installed on the same fixed or floating platform. Several examples of hybrid wind-wave platforms are shown in Table 2.1.

Table 2.1. Examples of hybrid wind-wave energy platforms.

Pelagic Power (Norway)

W2Power hybrid wind-wave energy system is a semi-submersible platform, combining two wind turbines and multiple oscillating body WECs. Image source: McTiernan & Thiagarajan Sharman (2020).

Floating Power Plant (Denmark)

Poseidon 37 (P37) is equipped with ten 3-kW oscillating body and oscillating water column WECs and three 11-kW wind turbines. The system was tested in Denmark. Image source: McTiernan & Thiagarajan Sharman (2020).

Floating Power Plant (Denmark)

P80 hybrid wind-wave platform hosts a single wind turbine with capacity around 2.3–5 MW and four WEC units rated at approximately 400–650 kW each. Image source: Watson et al. (2019).

2.5. Conclusion

Wave energy has made substantial progress since its initial rise in the 1970s. The global wave energy sector is rapidly advancing, with countries across Europe, North America, and Asia taking concrete steps toward capturing this emerging market. Their investments in technology, policy frameworks, and infrastructure demonstrate a strategic vision that positions them to capitalise on the potential of wave energy. The sector's growth potential is reinforced by the synergy between wave energy and offshore wind, offering new possibilities for integrated renewable energy systems. For Australia, the stakes are high. Despite having the world's most abundant wave energy resource, Australia's wave energy sector remains underfunded and lacks a dedicated strategy to fully harness this potential. This chapter has shown that wave energy is not an immature industry—it is evolving, gaining momentum, and attracting international attention. To remain competitive and realise the benefits of this clean, renewable energy source, Australia must develop a coherent strategy that aligns with global efforts and capitalises on its natural advantages.

CHAPTER 3
AUSTRALIAN OCEAN WAVE RESOURCE

OCEAN WAVE ENERGY IN AUSTRALIA

Contents

3. Australian ocean wave resource **59**

3.1. Resource assessment **59**

3.2. Case study: Albany, south-west Western Australia **71**

3.3. Case study: south-west Victoria **73**

3.4. Summary of Australian offshore wave resource **75**

References **208**

Tables

Table 3.1. Annual mean integrated wave energy flux across 25 m and 50 m depth contours adjacent to each Australian state and territory (TWh/yr) together with current electricity generation (TWh/yr). Source [DCCEEW, 2023; Hemer et al., 2017a; Hemer et al., 2017b]. **63**

Table 3.2. Mean wave energy flux (kW/m) in the Offshore Renewable Energy Infrastructure Regions. *Source [AMSIS, 2024; AWavEA, 2017; DCCEEW, 2024].* **64**

Table 3.3. Mean and modal wave energy flux (in kW/m) in Albany, together with probability of occurrence of sea-states with wave energy flux above various thresholds. Mean energy flux refers to the average hourly value across the whole 38 years of historical wave data, while modal refers to the most commonly occurring hourly energy flux level. Wave data for analysis from [Cuttler et al., 2020]. **72**

Figures

Figure 3.1. Map of mean wave energy flux (kW/m) in Australian waters. *Source [AWavEA, 2017; Hemer et al., 2017a; Hemer et al., 2017b].* 61

Figure 3.2. Map of declared and proposed Offshore Renewable Energy Infrastructure Regions for offshore wind and other ocean renewable developments, as of August 2024. *Source [AMSIS, 2024; DCCEEW, 2024].* 63

Figure 3.3. Map of mean wave energy period (left) and mean wave direction from which waves approach (right) in Australian waters. *Source [AWavEA, 2017].* 64

Figure 3.4. Summer and winter mean wave energy flux (kW/m) represented by January (left) and July (right) monthly values. *Source [AWavEA, 2017].* 65

Figure 3.5. Map of the ratio between 10-year return period significant wave height and average significant wave height. *Source [AWavEA, 2017; Hemer et al., 2017a; Hemer et al., 2017b].* 68

Figure 3.6. Comparison of input wave power (left) and power per WEC in the array (right) for the southern coast of Victoria based on the wave climate in August. *Source [Manasseh et al., 2018].* 69

Figure 3.7: Map of Albany in south-west Western Australia. 71

Figure 3.8: Probability plot of hourly wave conditions at Albany (in 60 m water depth, approximately 15 km offshore). The plot is generated from 38 years of historical simulated wave data [Cuttler et al., 2020], with each hourly condition, referred to as a sea-state, characterised by significant wave height Hs and wave energy period Te. The plot shows the distribution of wave conditions, with the most frequently occurring conditions shown in yellow, the least common conditions shown in blue, while the white area demarks conditions not present in the dataset. 72

Figure 3.9: Map of south-west Victoria. 73

Figure 3.10: Probability plot of hourly wave conditions at Cape Bridgewater (in 67 m water depth, approximately 8 km offshore). The plot is generated from approximately 2 years of historical wave buoy data, with each hourly condition, referred to as a sea-state, characterised by significant wave height Hs and wave energy period Te. The plot shows the distribution of wave conditions, with the most frequently occurring conditions shown in yellow, the least common conditions shown in blue, while the white area demarks conditions not present in the dataset. Wave data was provided by the Victorian Coastal Monitoring Program with funding through Department of Environment, Land, Water and Planning, University of Melbourne and Deakin University. Data was sourced from Australia's Integrated Marine Observing System (IMOS) – IMOS is enabled by the National Collaborative Research Infrastructure Strategy (NCRIS). 74

Figure 3.11: The wave hindcast output points available from the global resolution grid at 10° increments and from the higher resolution grid around the Australian coast at 0.5° increments (left) and the bathymetry used in the model, including 25 m, 50 m and 200 m depth contours (right). Source [Hemer et al., 2017a; Hemer et al., 2017b]. 227

Figure 3.12: Comparison of modelled significant wave height (Hs in units of m, top panels) and wave energy flux (CgE in units of kW/m, bottom panels) relative to observations from altimeters. Legend in the far-right panels shows the goodness of fit by means of number of co-locations (N), correlation coefficient (R), root-mean-square error (RMSE), bias (B), scatter index (SI) and least-square fit through origin (fit0). Source [Hemer et al., 2017a; Hemer et al., 2017b]. 228

3. Australian ocean wave resource

Australia has the largest ocean wave resource of any country in the world, thanks to its extensive coastline exposed to the energetic Southern Ocean.

The total energy delivered by ocean waves to the Australian continent, over a year, is estimated to be ten times greater than the current annual national electricity generation. This chapter also highlights other favourable characteristics of the Australian wave climate, which make it particularly well-suited for energy harnessing. Along the southern coast, waves are virtually ever-present, guaranteeing continuity of supply. The wave power levels throughout the year are fairly consistent, pointing to low seasonal variability. Extreme wave conditions, which correlate with high capital and operational costs, are considerably milder compared to other global wave energy hot-spots, suggesting the Australian southern margin could boast low levelized cost of wave energy.

The south-west, south and south-east coasts are prime locations for development of a wave energy industry, while the wave climate along the sparsely populated north is not suitable for ocean wave energy harnessing.

3.1. Resource assessment

A first step, when considering a new renewable energy source, is to determine the resource potential.

To this end, the Australian Wave Energy Atlas (AWavEA) project, funded by the Australian Renewable Energy Agency (ARENA) and led by CSIRO, delivered a comprehensive national wave energy resource assessment [Hemer et al., 2017a] [Hemer et al., 2018]. The wave resource data is openly accessible and available at https://nationalmap.gov.au/renewables.

In the AWavEA wave resource assessment, a multi-decadal (1979-2010) wave model hindcast was used. A wave hindcast is a wave model simulation over a historic time period that has been forced by atmospheric winds to provide a spatially and temporally continuous depiction of the wave condition over past decades. Such a long-term and validated dataset is then used to characterise the wave climate, in terms of its average (i.e. mean) properties such as mean wave heights or mean wave power density levels, as well as seasonal variations or intermittency attributes, for example. Further details of the AWavEA model are provided in Appendix A.

In addition to the national overview from the AWavEA, numerous studies for locations along the Australian coast have also assessed the wave energy resource in terms of the power output that can be potentially generated by different Wave Energy Converter (WEC) designs which depend on their specific wave power conversion characteristics. These studies use input wave fields from the AWavEA or nearshore higher resolution wave model simulations that downscale the AWavEA wave data. This chapter provides a summary of the works undertaken on the Australian ocean wave resource.

Wave energy resource is typically expressed as wave power density, or wave energy flux in units of kW/m of wave crest. It is also typical to assess wave energy crossing a particular depth contour, representing a line around the coast. This is different to wind energy assessment, which is typically undertaken over an area.

3.1.1. National wave resource overview

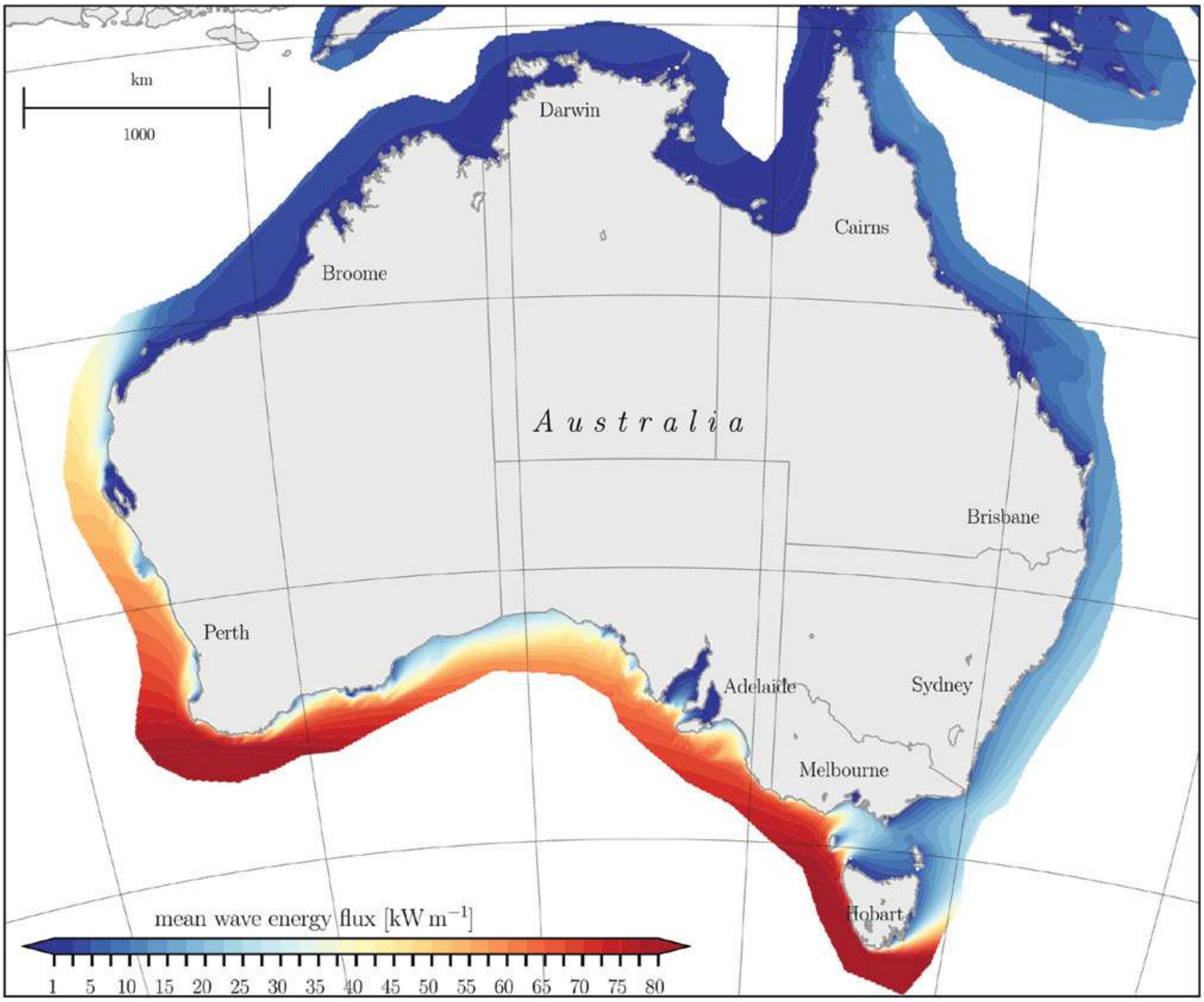
Australia's wave energy resource is around ten times larger than Australia's total electricity generation. Most of this energy is concentrated along the southern coastline.

The southern margin of Australia has the most energetic wave resource, as seen in Figure 3.1. The mean wave power density levels reach 60 kW/m, or more, in many locations.

With an average household electricity consumption rate of around 1 kW ([Frontier Economics, 2020; Wang et al., 2020]), this means that the wave energy flux through a span of a single meter along these coastlines is equivalent to the demand of 60 households. Converting even a small fraction of this energy-dense resource represents a significant opportunity towards delivering on the national Net Zero target. The south-east coast of Australia possesses a more modest, yet still abundant and exploitable, wave resource. The Northern Territory, northern Western Australia and northern Queensland would not be suitable for wave energy harnessing due to the mild average resource.

Wave power levels of 20 - 60 kW/m are common along the south coast. On average, a single meter of wavefront receives the equivalent energy to electricity consumption of 20 - 60 households.

Figure 3.1. Map of mean wave energy flux (kW/m) in Australian waters. Source [AWavEA, 2017; Hemer et al., 2017a; Hemer et al., 2017b].



Integrating the flux across the 200 m depth contour representing the perimeter of the outer continental shelf yields a total wave energy resource of approximately 2730 TWh/yr. This figure is higher than the total wave energy resource for the US continental shelf edge of 2640 TWh/yr [EPRI, 2011] and is an order of magnitude larger than Australia's total electricity generation, which in 2022 amounted to 273 TWh/yr [DCCEEW, 2023]. For reference, Australia's potential offshore wind energy has been assessed as being 9396 TWh/yr when constrained to seas of depth less than 1000 m and distance to infrastructure of less than 100 km [Briggs et al., 2021].

However, it should be noted that this value cannot be directly compared to the wave energy resource since wind energy is calculated over an area while wave energy is assessed along a line that is represented by a depth contour.

Nevertheless, we note the enormity of both of these renewable energy resources. Wave Energy Converters (WECs) are typically deployed in waters less than 30 m deep [Hemer et al., 2017a]. At these depths, the available energy is generally less than observed offshore due to wave energy loss from frictional processes, wave breaking and coastal sheltering. Estimates of wave energy at the 50 m and 25 m depth contours show that the power available at these depths is 96% and 65% of that available at the 200 m contour, respectively. Even with wave energy dissipation across the continental shelf, the Australian nearshore, more accessible wave resource is nonetheless immense. Moreover, the practical extractable wave resource in the nearshore zone has been found to be comparable to that of deeper offshore waters [Folley and Whittaker, 2009]. This is due to depth-limited wave breaking whereby the wave resource in nearshore areas is effectively filtered of harsher, more extreme conditions, which would be beyond the operational windows for wave energy harnessing.

For all Australian states and territories, the available nearshore wave energy resource is greater than the current state-wide electricity production.

The Western Australia (WA) coast has the richest wave energy resource in the country, as per Table 3.1. South Australia, Victoria and Tasmania also have ample wave energy incoming to their shores, especially when compared to their current electricity generation.

Two case studies at the end of this Chapter, from south-west WA and south-west Victoria, provide more detail on the respective local wave climates. The wave conditions from these two locations, more than 2000 km apart, are found to exhibit very similar characteristics. This suggests that the wave resource potential along much of the south coast is comparable, though with a notable reduction of wave energy across the wide continental shelf offshore of the Nullarbor Plain.

(Image courtesy of University of Western Australia.)

Table 3.1. Annual mean integrated wave energy flux across 25 m and 50 m depth contours adjacent to each Australian state and territory (TWh/yr) together with current electricity generation (TWh/yr). Source [DCCEEW, 2023; Hemer et al., 2017a; Hemer et al., 2017b].

Region	25 m contour	50 m contour	Electricity generation in 2022
Western Australia	754	1156	44.8
South Australia	385	631	14.8
Victoria	158	184	54.5
Tasmania	272	333	10.9
New South Wales	79	79	73.2
Queensland	140	237	69.6
Northern Territory	17	18	5.3
Annual total (TWh/yr)	1796	2652	273

Since the passage of the Offshore Electricity Infrastructure Act 2021, 5 priority areas have been declared, and a further 1 has been proposed (Figure 3.2), for development of offshore wind and other offshore renewable energy projects. The regions are summarised in Table 3.2. The declared areas in the Southern Ocean off Victoria and the Indian Ocean off Western Australia possess highly energetic wave climates, while the other areas are more sheltered from the Southern Ocean swells. Deploying wave energy converters within or adjacent to offshore wind farms is explored in Chapter 4, where it is found that addition of wave energy brings down costs. A complementary study was carried out by [Gao et al., 2022].

The wave energy resource in the Offshore Renewable Energy Infrastructure Regions is considerable, suggesting combined wind-wave harnessing potential.

Figure 3.2: Map of declared and proposed Offshore Renewable Energy Infrastructure Regions for offshore wind and other ocean renewable developments, as of August 2024. Source [AMSIS, 2024; DCCEEW, 2024].

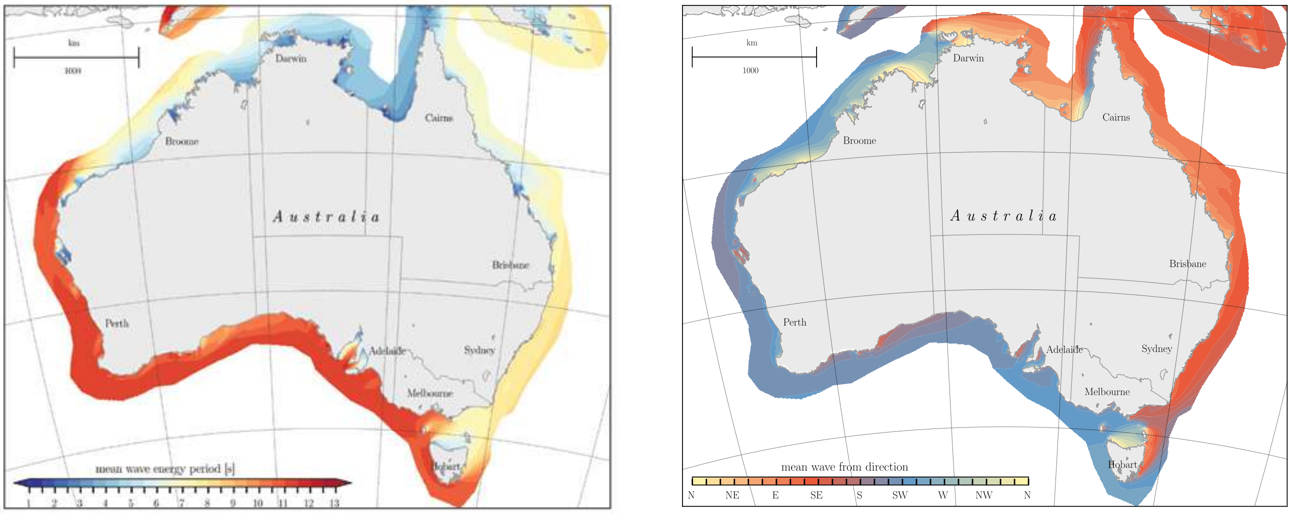
Table 3.2. Mean wave energy flux (kW/m) in the Offshore Renewable Energy Infrastructure Regions. Source [AMSIS, 2024; AWavEA, 2017; DCCEEW, 2024].

Region	Status as of 08/2024	Area (km²)	Water depth (m)	Wave energy flux (kW/m)
Gippsland, Vic	Declared	15,000	20 - 100	2 – 22
Hunter, NSW	Declared	1,854	135 - 950	15 – 17
Southern Ocean, Vic	Declared	1,030	50 - 100	50 – 65
Illawarra, NSW	Declared	1,022	130 - 800	11 – 14
Indian Ocean off Bunbury, WA	Declared	3,995	30 – 1,000	20 – 70
Bass Strait, Tas	Proposed	10,136	45 – 80	4 – 16

Since Wave Energy Converters are designed to operate in resonance with the incoming waves, characterising the wave periods at a potential wave energy site is critical. Figure 3.3 (left panel) shows the mean wave energy period along the Australian coastline. The southern coast is typified by wave periods of 11 s, while the waves incident on the south-east coast tend to be considerably shorter with mean wave energy periods of around 7 - 8 s. In the north, the waves are even shorter.

Depending on their origin and subsequent evolution, waves can approach the coastline from different directions. The mean wave direction, derived from the hindcast model outputs, is displayed in Figure 3.3 on the right. Along the south coast of Australia, the waves approach from the Southern Ocean predominantly from the south-west and west-south-west directions. The south-east coast is, however, somewhat sheltered and therefore exhibits a different wave climate, with less energetic waves coming from the south-east.

Figure 3.3. Map of mean wave energy period (left) and mean wave direction from which waves approach (right) in Australian waters. Source [AWavEA, 2017].



3.1.2. Wave energy consistency – seasonal variability, highs and lows, and extremes

In the above section, the averaged wave resource and its spatial distribution along the Australian coastline were discussed. At any given offshore location, the wave conditions vary in time, throughout a day and across seasons for example, giving rise to temporal variation of the available wave energy resource. It is worth noting that, in general, wave energy does not follow a repeatable daily pattern, like renewable energy derived from solar and tidal resources.

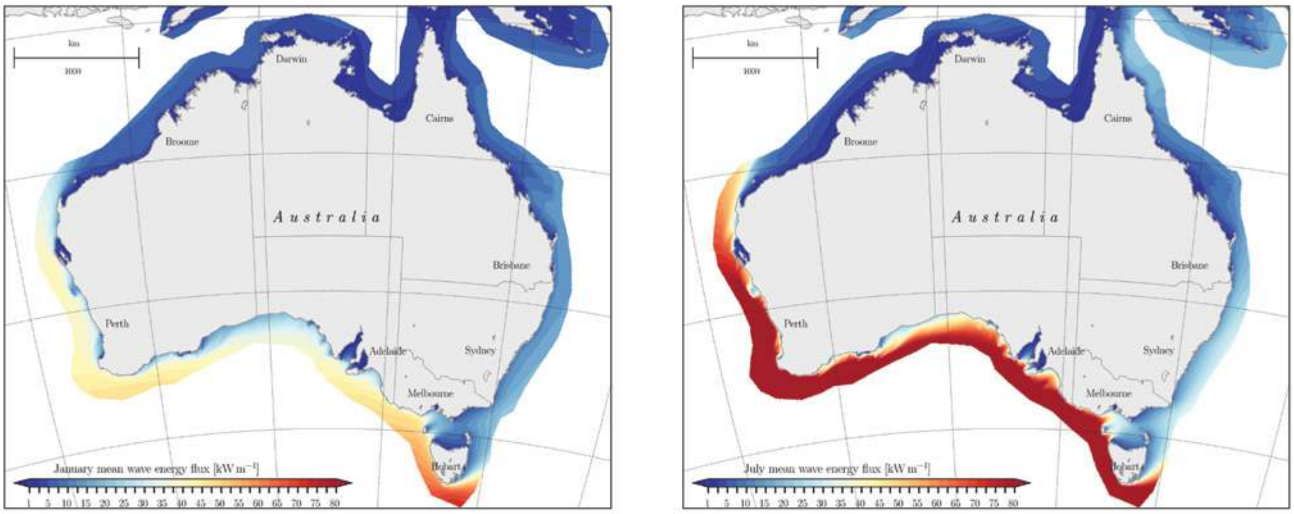
This is because ocean waves at a particular location can be generated by local weather systems (referred to as wind seas) as well as arrive from remote weather systems, that had occurred earlier in time, having propagated vast distances over the ocean (referred to as swell). Wave energy varies across several time scales from individual waves and wave groups in seconds and minutes, through swells and storms in hours and days, to seasons and longer-term changes.

The southern coastline has high consistency of wave energy throughout the year while the north has longer periods of low wave energy and occasional high waves due to tropical cyclones.

Wave climate variability is important for assessing the suitability of a location for wave energy extraction. The southern coast of Australia has a marked seasonal cycle due to the northward shift in the Southern Ocean storm belt during the winter months leading to larger waves occurring along Australia's southern coast during this time (Figure 3.4). This seasonal cycle, with winter highs and summer lows, is opposite to the trend in available solar energy, suggesting an advantageous complementarity when harnessing both renewable resources (more details in Chapter 4).

Overall, the monthly variations in wave energy are relatively small compared with the mean wave energy flux, leading to relatively consistent conditions throughout the year. The lowest relative variability is along the south-east coast, which is largely sheltered from the Southern Ocean storms (detailed analysis in [Morim et al., 2016]). By comparison, the highest relative variability is observed in the north where tropical cyclones can cause episodes of high wave energy compared with the mean wave energy flux, which is generally very benign.

Figure 3.4: Summer and winter mean wave energy flux (kW/m) represented by January (left) and July (right) monthly values. Source [AWavEA, 2017].



Two important considerations for the deployment of WECs are their operability (power production) and their survivability during extreme conditions. Therefore, assessing normal operational as well as very low and extremely high conditions matters.

Occurrences of low wave events, during which a WEC provides little to no energy, are important to understand from continuity-of-supply perspective. Along the southern margin, wave heights of less than 1 m occur very rarely and only for short duration at a time (there are typically more than 100 days between such low wave events). In contrast, northern coastal waters exhibit low wave events lasting months (>100 days). The south-east coast shows a relatively consistent resource, with low wave events occurring weekly but being very short-lived.

Low wave energy occurrences along the south coast are brief and rare, highlighting the superb persistence of the resource.

The typical duration of high wave energy events is of relevance for WEC design and energy yield estimates, as well as for maintenance weather windows, for example.

In the south, wave events with significant wave height exceeding 4 m typically last 1-2 days and occur every 1-2 weeks. In comparison, storm wave events exceeding 4 m in the tropical north typically do not occur within 100 days of each other, owing to the relative infrequency of tropical cyclones.

Many WEC designs are envisaged to operate up to significant wave heights of 7 m [Morim et al., 2019a], beyond which they enter survivability mode, during which they do not generate power. This is akin to operation of wind turbines which are switched off under extreme wind speeds.

Extreme waves can reduce the life span of wave energy converters and complicate commissioning and maintenance. Along the southern margin of Australia, the ratio of extreme to average wave heights is low, making it an attractive location for wave energy harnessing.

Extreme wave conditions can reduce the lifespan of wave energy converters and complicate commissioning and maintenance, adding to operational costs. The ratio of the 10-year return period wave height to the average wave height is a useful metric for assessing the suitability of wave energy extraction (Figure 3.5).

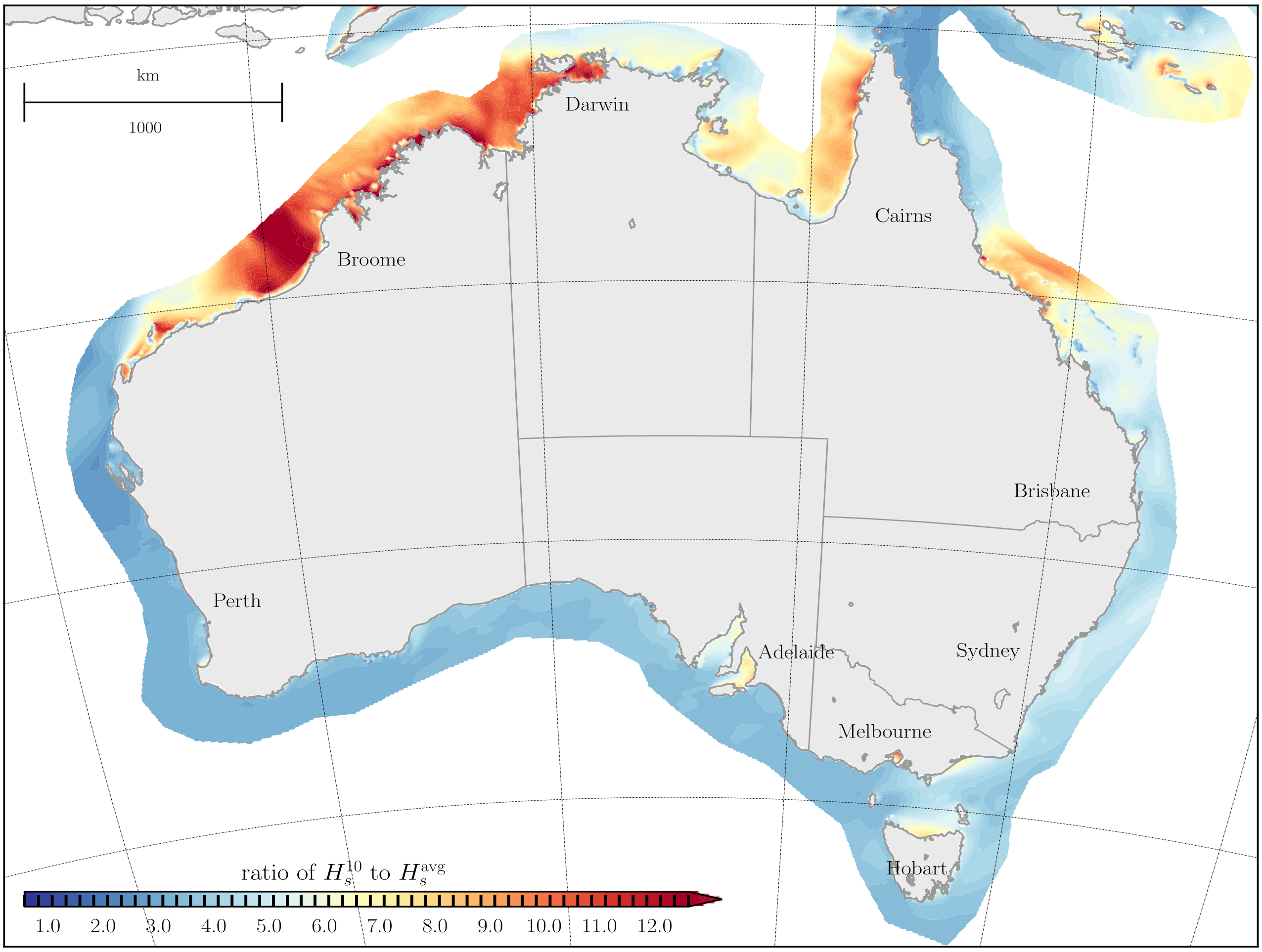
A smaller ratio indicates a more uniform wave climate, which is more desirable for wave energy extraction. From a national perspective, this ratio is fairly consistent over much of the southern Australian continental shelf but is considerably larger in the northern regions.

This is due to the irregular occurrence of extreme wave-generating tropical cyclones.

For WEC design, 50-year return period wave conditions are recommended (International Electrotechnical Commission Technical Specification IEC TS 62600-2). However, defining these design wave conditions is not straightforward. Most wave buoy measurement datasets are not long enough to reliably extrapolate to these rare conditions [Greenslade et al., 2018] [Liu et al., 2022], while numerical hindcast models may struggle to simulate historical extremes [Hemer et al., 2017a]. These design wave conditions are also needed by the offshore wind industry.

Image courtesy of CorPower Ocean.

Figure 3.5: Map of the ratio between 10-year return period significant wave height and average significant wave height. Source [AWavEA, 2017; Hemer et al., 2017a; Hemer et al., 2017b].



3.1.3. Wave direction considerations

Nearshore wave refraction leading to more consistent wave direction may increase wave energy yields in some locations along the coast.

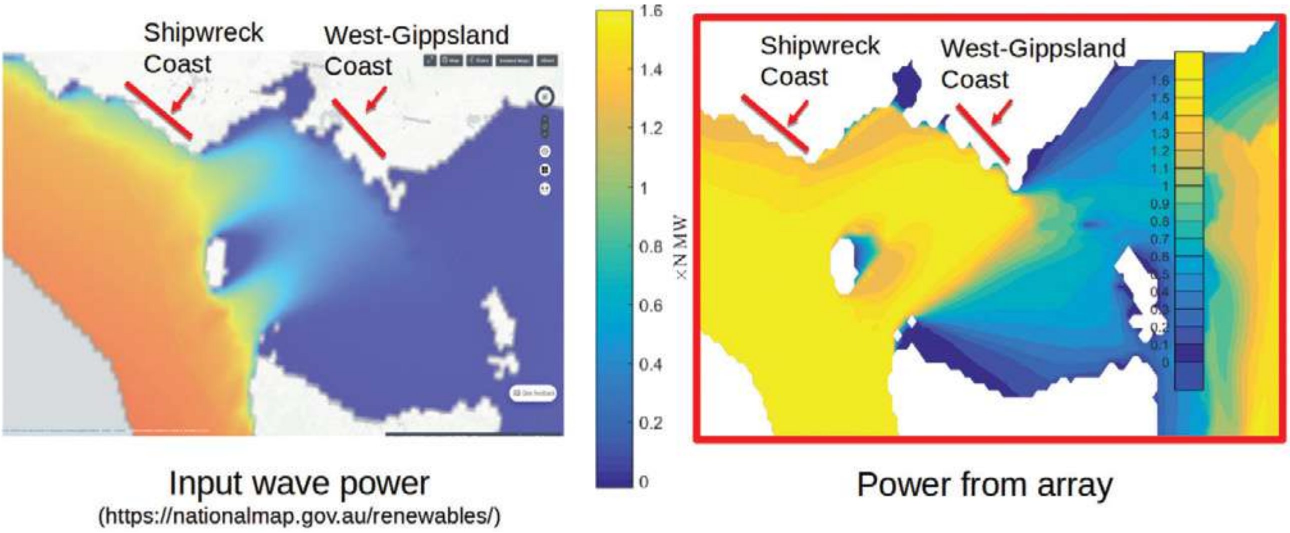
Consistency of wave direction is another important factor in the operability of wave energy converters (WECs).

An assessment of the extractible wave power from WEC archetypes arranged in various array configurations was undertaken by [Manasseh et al., 2018] using computer modelling. In the simulations, each machine was assumed to be tuned to the peak wave frequency at each location, to ensure they were always resonating and had a maximum power output of 2 MW, to enable comparability between regions. A key finding of the analysis conducted is that the derived power from an array of resonating WECs in regions of lower incident wave energy resource could be similar to regions of higher incident wave energy resource. The main reason is that although the shallower continental shelf acts to dissipate wave energy, it also causes waves to refract, which aligns the waves to a more consistent direction. This enables consistent extraction of wave power. Figure 3.6 shows two sections of coastline in Bass Strait, referred to as the Shipwreck Coast and the West Gippsland Coast, respectively. The incident wave power shown in the left subplot is largest on the Shipwreck Coast compared with the West Gippsland Coast.

This is because the Shipwreck Coast receives high incident wave power directly from the Southern Ocean whereas the West Gippsland Coast is in a wave shadow due to the presence of King Island, and because the waves reaching this coastline have travelled 250 km over the shallower Bass Strait, losing energy to bottom friction.

However, the right subplot in Figure 3.6 shows that the power that can be extracted from one of the considered WEC arrays on the West Gippsland Coast is one third greater despite the input wave power being only one half the value of that on the Shipwreck Coast. As the waves travel across Bass Strait, they undergo refraction, which aligns the wave direction of approach at right angles to the coast and this in turn reduces the directional variability of waves. In the study, other Australian locations where an optimally oriented WEC array could potentially extract more wave power than indicated by the input wave resource were identified.

Figure 3.6: Comparison of input wave power (left) and power per WEC in the array (right) for the southern coast of Victoria based on the wave climate in August. Source [Manasseh et al., 2018].



3.1.4. Inter-annual variability and long-term change

Understanding the inter-annual and long-term trends in wave energy is an important consideration in assessing wave energy deployments.

In addition to weather-induced variability that characterises the wave climate, variability on longer scales is also important to consider in feasibility assessments of wave energy. The wave climate can undergo significant oscillations due to seasonal and inter-annual variations. Several modes of inter-annual climate variability affect the Australian coastline and therefore have the potential to affect wave energy generation. Long-term trends in wave climate variables due to climate change may also occur in some locations.

The El Niño Southern Oscillation (ENSO) is a climate phenomenon that manifests in variations in atmospheric pressure and winds as well as ocean temperatures and sea levels across the Pacific. The El Niño phase of the oscillation is characterised by higher pressure over Australia, weaker trade winds, lower rainfall and fewer tropical cyclones while the opposite phase, the La Niña, is characterised by stronger trade winds, greater rainfall, higher sea levels, particularly in the north of the country and greater tropical storm frequency.

ENSO variations have been shown to influence eastern Australian wave climate due to changes in storm frequency and wind and wave direction [Ranasinghe et al., 2004] [Harley et al., 2011]. A correlation between ENSO and wave direction was found at Albany whereby more southerly waves occur during La Niña conditions [Cuttler et al., 2020].

The Southern Annular Mode (SAM) is an oscillation in the position of the Southern Ocean storm belt, with a southward shift representing the positive phase and a northward shift representing the negative phase of the oscillation. The positive phase of SAM causes a decrease in wave heights along the southern Australian coastline and a counter-clockwise rotation of waves so they become more southerly [Hemer et al., 2010] [Marshall et al., 2018]. An increase in the Southern Ocean wave climate has been observed in satellite data over the past decades [Young and Ribal, 2019] and is consistent with a positive trend in SAM over this time [Thompson and Solomon, 2002] [Cuttler et al., 2020] [Bosserelle et al., 2012].

Changes in wave climate have also been observed for the southern mainland coast in Bass Strait, where the western coastline is dominated by swell from the Southern Ocean, with the significant wave height and the wave energy flux undergoing increases of 5% and 14% respectively over the 1988-2013 period. In the eastern Bass Strait, where there is less exposure to the Southern Ocean swell, the changes were slightly negative to zero [Ghanavati et al., 2024]. The observed trends of increase in Southern Ocean wave climate are expected to continue into the future as a result of climate change [Morim et al., 2019b] leading to an increase in wave period along the southern coastline and an anti-clockwise rotation of waves to propagate from a more southerly direction.

The southern hemisphere subtropical ridge (STR) is a large-scale climate feature separating the easterly trade winds in the north and the westerly storm belt in the south. Its annual movement from approximately 30°S in the winter to 40°S during summer causes seasonal variations in the wave climate in the Australian mid-latitudes. On the east coast, the monthly-averaged wave power is highest from March to August and lowest from September to February [Morim et al., 2019a]. A southerly shift in the STR increases the winter wave energy flux along the central NSW coast and rotates the wave power from the south towards the east and south-east [Mortlock and Goodwin, 2015]. The entire STR feature is projected to shift south as a result of ongoing climate change [Yang et al., 2020].

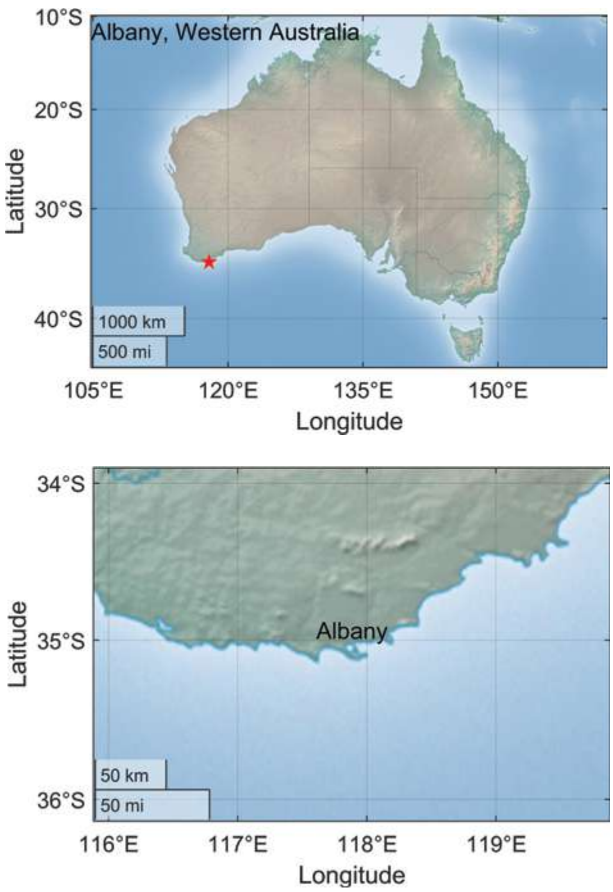
3.2. Case study: Albany, south-west Western Australia

Albany is a coastal town in the Great Southern region of Western Australia (Figure 3.7), with a population of around 35,000 people.

The municipality is connected to the South West Interconnected System (SWIS), with a large proportion of its electricity generated locally at the Albany and Grasmere wind farms.

The local economy is linked to the surrounding Southern Ocean - historically through whaling in the 1950-70's and presently through tourism and recreation thanks to abundant marine life and spectacular coastal scenery, the Port of Albany and local aquaculture.

Figure 3.7: Map of Albany in south-west Western Australia.



The south coast of Western Australia boasts highly energetic and consistent wave climate. While most of the severe swells arrive in the winter months, the summer periods are also subject to abundant waves.

The seasonal variability at Albany was found to be considerably lower, when compared against ten wave energy hotspots along the European Atlantic Ocean coast [Cuttler et al., 2020]. This year-round consistency makes it an attractive site for wave energy harnessing.

In Albany, it is extremely rare for the wave heights to drop below 1 m (Figure 3.8). The most common, known as the modal, wave conditions at Albany are wave heights of 2.2 m and wave periods of 11 s (Figure 3.8). The mean wave energy flux, the average rate at which energy is carried by waves and delivered towards the coastline, is approximately 64 kW per meter of wave crest. This is an enormous untapped energy source – the raw wave power in a mere kilometre of such a wave front is greater than Albany's average residential electricity demand. As seen in Table 3.3, the consistency of the wave climate is unparalleled – more than 90% of the time, across day and night and throughout all seasons, the hourly wave energy flux is greater than 20 kW/m.

The power level of 10 kW/m (on an hourly basis) is guaranteed virtually at all times making 'wave droughts', periods with no incident wave power, extremely rare. In Chapter 4 the benefits of the exceptional persistence of the wave resource are explored for renewable electricity grids.

Waves along the south-west Western Australia coast are ever-present. Periods of no incident wave power are extremely rare. This continuity is highly desirable for energy harnessing.

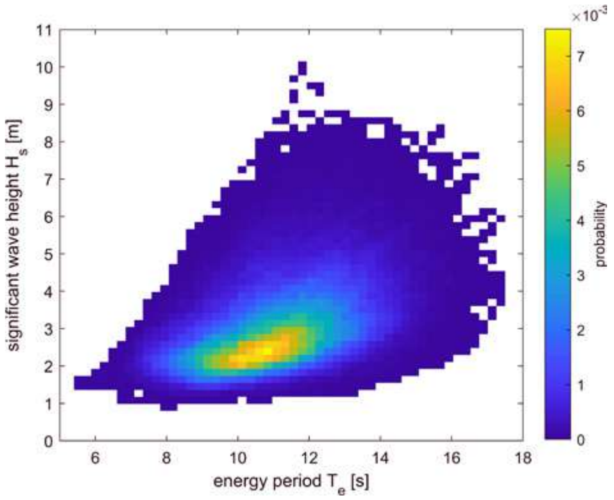


Figure 3.8: Probability plot of hourly wave conditions at Albany (in 60 m water depth, approximately 15 km offshore). The plot is generated from 38 years of historical simulated wave data [Cuttler et al., 2020], with each hourly condition, referred to as a sea-state, characterised by significant wave height Hs and wave energy period Te. The plot shows the distribution of wave conditions, with the most frequently occurring conditions shown in yellow, the least common conditions shown in blue, while the white area demarks conditions not present in the dataset.

Table 3.3: Mean and modal wave energy flux (in kW/m) in Albany, together with probability of occurrence of sea-states with wave energy flux above various thresholds. Mean energy flux refers to the average hourly value across the whole 38 years of historical wave data, while modal refers to the most commonly occurring hourly energy flux level. Wave data for analysis from [Cuttler et al., 2020].

Mean Wave Energy Flux	64 kW m^{-1}
Modal wave energy flux	26 kW m^{-1}
Proportion of time with wave energy flux > 64 kW m-1	35 %
Proportion of time with wave energy flux > 26 kW m-1	80 %
Proportion of time with wave energy flux > 20 kW m-1	90 %
Proportion of time with wave energy flux > 10 kW m-1	99 %

In addition to the commonly occurring conditions, it is informative to consider rare extreme events. The estimated 1 in 100 years wave conditions for Albany are significant wave height of 9.4 m (according to analysis [Santo et al., 2020]).

The ratio of the extreme and modal conditions is a simple metric that can characterize suitability of a given site for wave energy harnessing. In a very simplified manner, for wave energy converters, we can think of operational conditions as income (as these correspond to energy, and thus revenue, generation) and extreme conditions as cost (as these correlate to capital and operation expenditure related to survival and damage prevention during these events). For Albany this extreme-to-modal wave height ratio is 4.7 while for the European Marine Energy Centre on the Orkney Islands, a well-known ocean energy test site, this ratio is 14.7 (from [Santo et al., 2020] and [Orszaghova et al., 2022]).

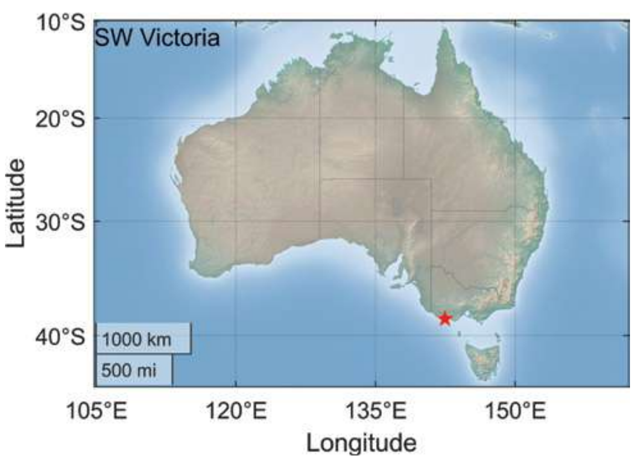
The combination of stable wave power levels with minimal 'wave droughts' together with low extremes highlights the potential of wave energy harnessing in south-west Western Australia.

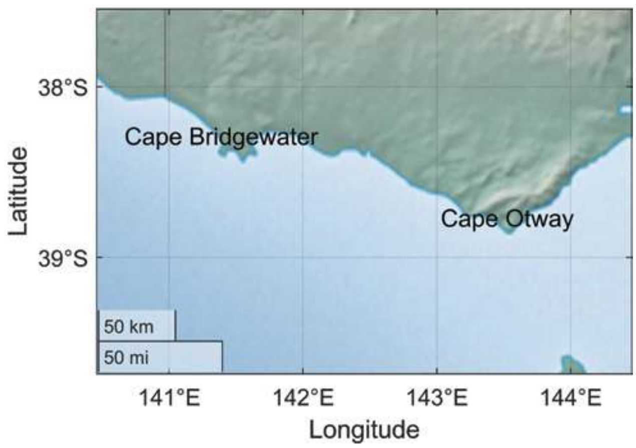
3.3. Case study: south-west Victoria

South-west Victoria (Figure 3.9) might be considered in oceanographic terms to extend from Cape Bridgewater, near the South Australian border, to Cape Otway.

This coastline is covered by the local-government Shires of Glenelg, Moyne, Corangamite and Colac-Otway, and the City of Warrnambool (Administratively, the SW Victorian region is usually considered to include the Surf Coast Shire, which is to the east of Cape Otway). South-west Victoria is one of Australia's most important wave-energy regions, owing to two natural factors and several economic factors.

Figure 3.9: Map of south-west Victoria.





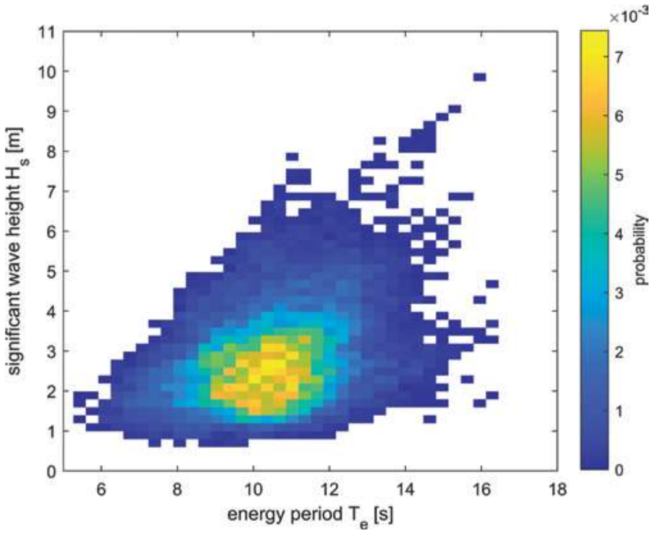
Wave energy in south-west Victoria would have the second-lowest levelised cost of wave-generated electricity in Australia.

The south-west Victorian coast is directly exposed to Southern Ocean swell, which is driven by westerly 'Roaring Forties' winds that encircle the globe. Due west of Cape Otway there is no land until the eastern shore of Patagonia in South America. Thus, some of the most powerful ocean swell on Earth, which has been growing unimpeded by land for thousands of kilometres, impacts this coast. It is exceeded in power only by the swell impacting the west coast of Tasmania, the South Island of New Zealand, and the southern coast of Chile. South-west Victoria also has a narrow continental shelf: the seabed falls to abyssal depths only 50 km off Portland.

Thus, ocean swell arrives at the coast having lost minimal energy from interactions with the seabed. Wave buoys continuously measure the conditions at Cape Bridgewater, Portland, and Port Fairy. Most common significant wave heights range from 1.5 m to 3.5 m at Cape Bridgewater, with a mean value around 3 m; the waves are also long, with typical wave periods of 9 - 12 s (Figure 3.10).

The long-term mean wave power level at this location is about 60 kW per metre of wave crest, similar to Albany, Western Australia (see Table 3.3). Hence, a single kilometre of coastline in SW Victoria on average receives 60 MW of wave power; and 50 km of coastline receives 3 GW, equal to the combined output of Victoria's remaining coal-fired power stations, Loy Yang A and B. The straight-line distance from Cape Bridgewater to Cape Otway is 190 km. It has been estimated that of all the wave-energy regions in Australia, SW Victoria would have the second-lowest levelised cost of electricity (LCOE) [Behrens et al., 2012]; the west coast of Tasmania would have the lowest. Moreover, south-west Victoria also offers excellent economic opportunities, as discussed in Chapter 6.

Figure 3.10: Probability plot of hourly wave conditions at Cape Bridgewater (in 67 m water depth, approximately 8 km offshore). The plot is generated from approximately 2 years of historical wave buoy data, with each hourly condition, referred to as a sea-state, characterised by significant wave height Hs and wave energy period Te. The plot shows the distribution of wave conditions, with the most frequently occurring conditions shown in yellow, the least common conditions shown in blue, while the white area demarks conditions not present in the dataset. Wave data was provided by the Victorian Coastal Monitoring Program with funding through Department of Environment, Land, Water and Planning, University of Melbourne and Deakin University. Data was sourced from Australia's Integrated Marine Observing System (IMOS) – IMOS is enabled by the National Collaborative Research Infrastructure Strategy (NCRIS).



3.4. Summary of Australian offshore wave resource

Australia's offshore wave energy resource potential has been assessed at 2730 TWh/yr along the 200 m depth contour along the outer continental shelf of Australia making it the largest wave energy resource of any country in the world and ten times greater than Australia's total electricity generation in 2022 of 273 TWh/yr.

Wave Energy Converters (WECs) are typically designed for deployment in shallower water depths. Even with some wave energy dissipation across the continental shelf, the Australian nearshore wave resource is nonetheless immense, and is also more accessible and practically exploitable.

The overall size of the wave resource, as well as its consistency over time are important. High average wave power levels with low variability are desirable for wave energy extraction.

- The south and south-west mainland coastline and the south-west coast of Tasmania experience the highest wave energy owing to these coastlines facing the energetic wave swell from the Southern Ocean. The wave climate also exhibits low values of the ratio of 10-year wave heights to mean wave heights. Periods of low wave energy, which would correspond to zero or very low electricity production, are also infrequent and short-lived.

The south and south-west coastlines are promising locations for wave energy harnessing, thanks to the enormity of the resource and its minimal intermittency.

- The south-east coastline exhibits the lowest seasonal variability due to being largely sheltered from the Southern Ocean swells, which, however, also limits the overall wave resource in this area.

The south-east coast possesses more modest resource but offers superb year-round consistency.

- The northern coastline is on average subjected to low levels of wave energy with infrequent but potentially large extreme wave events during the occurrence of tropical cyclones. Periods of very calm conditions are also frequent and long-lived in the north. Overall, the north coast is not well suited for wave energy exploitation.
- The wave resource in the Offshore Renewable Energy Infrastructure Regions, earmarked for offshore wind development, is considerable. The potential for co-location of wave and offshore wind energy should be investigated.

Comparisons to other global wave energy hot-spots suggest Australian waters are a favourable setting for ocean wave energy harnessing, both in terms of the raw wave resource as well as the potential energy yield from different WEC designs.

CHAPTER 4

MARKET OPPORTUNITIES, APPLICATIONS AND INTEGRATION

CONTENTS

Contents

4. Market opportunities, applications and integration 82

4.1. The value of dispatchable wave energy 82

4.2. Coastal Protection 110

4.3. Co-location 125

4.4. Summary 136

References 210

Tables

Table 4.1. Statistics of hourly wind and wave power computed from observations throughout the year at several sites from 1998 to 2005 (Hemer et al., 2012). 92

Table 4.2. Wave characteristics at Carpenter Rocks wave energy converter study site. 105

Table 4.3. Single WEC wave power generation at Carpenter Rocks wave energy converter study site. 105

Table 4.4. Loss of load probabilities for hypothetical renewable energy configurations at Carpenter Rocks. 106

Table 4.5. Carpenter Rocks community: 70% dispatchable power. 107

Table 4.6. Surrounding region communities: 70% dispatchable power. 108

Figures

Figure 4.1. Study region and drought likelihoods. Climate influence on compound solar and wind droughts in Australia (Richardson et al., 2022, with permission – detailed caption quoted below). 84

Figure 4.2. Aggregated rooftop solar, utility solar and wind energy generation for January to September 2024 in South Australia. Note the potential for wave energy to complement wind and solar during the winter period. 84

Figure 4.3. An example of daily spot price and demand (5th September 2024) (AEMO 2024a). 88

Figure 4.4. Quarterly average electricity spot price probability distribution (2019 to 2025). Derived from AEMO data (AEMO, 2024a). 88

Figure 4.5. Using energy storage with wave, wind, and solar power to raise dispatchability threshold to 50%. 90

Figure 4.6. Australia's high-energy wave buoy sites (Hemer et al., 2012). 92

Figure 4.7: Cumulative probability distribution function of wave and wind power (normalised by their respective mean values shown in the legend) at Cape Sorell (Hemer et al., 2012). 93

Figure 4.8: Capital costs under the Global NZE by 2050 Scenario 3. Derived from GenCost data (Graham et al., 2024). 95

Figure 4.9: Battery capacities for standalone renewable energy resources to achieve from 0.1 to 1 dispatchability. 97

Figure 4.10: CAPEX estimates per MW average power for standalone renewable energy resources to achieve from 0 to 0.7 dispatchability. (A version of this figure in terms of rated power appears in Appendix A). 97

Figure 4.11: Battery capacities for a range of hybrid renewable energy resources to achieve from 0 to 0.8 dispatchability. Location Carpenter Rocks. **98**

Figure 4.12: CAPEX 2050 estimates per MW average power, for a range of hybrid renewable energy resources to achieve from 0.1 to 0.7 dispatchability. Location Carpenter Rocks. The CapEx for dispatchabilities of zero reflect the cost of the generators rather than energy storage, except for solar arrays where some energy storage is included to allow for the diurnal average. (A version of this figure in terms of rated power appears in Appendix B). **98**

Figure 4.13: Inverse seasonal correlation between wave energy converter and solar PV power at Carpenter Rocks. **99**

Figure 4.14: NEM Average and Dispatchable power Projected to 2050. © Australian Electricity Market Operator (AEMO), Source: Integrated System Plan 2024 (AEMO, 2024b). Reproduced with the permission of AEMO. **103**

Figure 4.15: Projected North American electricity generation under the Achievable scenario 3. **104**

Figure 4.16: Impact of wave energy on generated power probability distribution for single and combined renewable energy resources. **106**

Figure 4.17: Impact of wave energy on generated power probability distribution for combined renewable energy resources. **106**

Figure 4.18: The low impact of the power cut out setting on required battery capacity. **107**

Figure 4.19: 2050 cost of renewable energy power generators with 70% dispatchability. Costs are given per megawatt average power. **109**

Figure 4.20: Sign on the sheltered side of the breakwater protecting the harbour at Warrnambool, Victoria. The concrete structure was completed in 1890. Despite being about 8 m high, it can be overtopped by large waves. Photograph by Richard Manasseh. **110**

Figure 4.21: Main Beach at Noosa Heads, Queensland, was almost eliminated during storms in the winter of 2019, revealing the underlying rubble defences built in 1969 to protect what is now some of Australia's most expensive real estate. At this location, natural wave-driven processes can gradually cause the beach to build up again. As in previous such episodes, the approximately 1.3 km long beach was restored by sand pumping and other mechanical measures, estimated to cost AUD 500k-750k per annum (Noosa Council, 2018). Photograph by Richard Manasseh. **111**

Figure 4.22: The world's only continuously operating grid-connected wave-power plant at Mutriku, Basque Country, Spain, is the longest-lived in the world and the one with the most hours of operation. (Image courtesy of www.bimep.eus). **112**

Figure 4.23: Rapidly-eroding dunes in Geraldton, Western Australia, July 2024, showing a toppled fence-post. Between 2021 and 2024, the beach eroded approximately 70 m inland, requiring the demolition in June 2024 of a marine-rescue building. However, in 1942, the sea was actually 50 m further inland than in 2024. Land advanced from 1965 to 1988, retreated to 1997, and advanced to 2007. (City of Greater Geraldton, 2024). Photograph by Richard Manasseh, with thanks to Wade Greenaway, Mid-West Ports Authority. **113**

Figure 4.24: Wave buoys operated by Deakin University. Photograph by Richard Manasseh, with thanks to Daniel Ierodiaconnou, Deakin University. **114**

Figure 4.25: Comparison of the change in volume of sand on the beach with the movement of the shoreline (Net Shoreline Movement; NSM), estimated from aerial photographs taken from the 1970s through to modern drone mapping techniques. Left-hand panel shows how these two measures are related at various distances along the coast; right-hand panel demonstrates self-consistency. From Carvalho et al (2021). Reprinted with permission. **114**

Figure 4.26: Layouts of 16 WECs intended to: (a)-(b) minimise wave height; (c)-(d) minimise longshore gradients in wave 'radiation stress', usually associated with sand transport. In (a) and (c), waves travel from left to right, WEC locations are white dots, wave amplitudes relative to the original state (amplitude 1.0) are in colour scale. In (b) and (d), amplitudes of waves arriving at the right-hand boundary model effect at shoreline. Calculated using methods detailed in Cui et al. (2024) Distances are at a laboratory scale. **117**

Figure 4.27: Simulation of East Beach, Port Fairy, Victoria, showing reduction in wave height from an array of non-interacting wave-energy converters modelled as energy absorbing 'reefs'. Colours: significant wave height; arrows: wave direction. Adapted from Flocard and Hoeke (2017). **120**

Figure 4.28: A wave-energy dissipation structure (wall made of large stacked boulders) has prevented over 10 m of dune erosion at this location in SW Victoria. Buried in the dunes behind the wall is a 19th- and early-20th-century waste dump, the contents of which should not be released into the ocean. Image: Google Maps, ©Airbus, CNES / Airbus,Maxar Technologies, Map data 2024. **121**

Figure 4.29: Erosion of unprotected dunes (foreground) compared to a housing zone protected by a rock revetment (middle ground). The unprotected shoreline has eroded about 8 m. Photograph by Richard Manasseh. **121**

Figure 4.30: Nesting sites of the hooded plover (Charadrius cucullatus) are threatened by dune erosion. Photograph by Richard Manasseh. **122**

Figure 4.31: Examples of co-located wind and wave asset-sharing scenarios. **126**

Figure 4.32: Methodology for scoring co-located wind and wave scenarios. **126**

Figure 4.33: Locations chosen for detailed techno-economic assessment of co-located wind-wave energy system. **127**

Figure 4.34: LCOE value of offshore wind and wave energy farms in eight Australian sites from 2017 to 2021. **128**

Figure 4.35: Carnegie's MoorPower wave converter system. **130**

Figure 4.36: Southern Ocean Mariculture historical (black) and projected (green) emissions with addition of a 200 kW wave energy system (navy) and a 400 kW wave energy system (light blue). Source: AOEG (2024) **131**

Figure 4.37: Adapted from: Map of Australia - discrete Indigenous communities and the Australian standard geographical classification remoteness structure. © Commonwealth of Australia 2007, Source: Australian Bureau of Statistics, Community Housing, and Infrastructure Needs Survey 2006. Reproduced with permission of the Australian Bureau of Statistics. **132**

Figure 4.38: Off-grid power generation in Australia Source: AECOM, based on Geoscience Australia 2006 and 2012 power generation database. **133**

Figure 4.39: Annual number of days with rainfall greater than 1 mm. © Copyright Commonwealth of Australia 2007, Bureau of Meteorology. Source: http://www.bom.gov.au/climate/map/raindays/1mm.shtml. Reproduced with permission of the Bureau of Meteorology. **134**

4. Market opportunities, applications and integration

Wave energy technologies span a range of scales and approaches, and the range of possible markets and applications for these technologies is correspondingly large. This chapter considers important examples of such applications.

In the last decade, wave energy research has focused on its reliability and high energy density, creating diverse opportunities. WECs at different scales have the potential to provide dispatchable electricity for renewable energy networks from utility-scale to microgrids, protect coastlines from erosion without impacting their recreational and environmental values, and supply electricity, oxygen, and hydrogen to support remote communities and offshore industries such as aquaculture and wind farms.

The value of these opportunities is immense in financial, social and ecological terms. For example, wave energy reliability could reduce the cost of utility-scale energy storage by several million dollars per megawatt of generated power by 2050 (Osman et al., 2022). The European industrial research consortium EVOLVE (2023), estimates that introducing 10 GW of wave energy into the UK grid would produce annual cost savings of up to AUD2.76 billion by 2040. Wave energy converters can be set up to produce electricity and at the same time protect coastlines by reducing damaging wave activity. Coastal assets in Australia were valued at AUD226 billion in 2011, and a high risk has recently been assigned to coastal property due to climate change impacts, to a value of AUD25 billion (Ellis et al., 2023). Wave energy converters may also have an enabling role in the future of offshore industries, such as fuel production for the shipping fleets servicing offshore industries (Charalambides et al., 2024), and aquaculture, for which the gross value of production in 2021-2022 was AUD1.9 billion nationally and growing significantly year-on-year (Tuynman et al., 2023). The next three sections will describe each of these opportunities in more detail.

4.1. The value of dispatchable wave energy

As the share of electricity generated from wind and solar photovoltaic (solar PV) power increases in Australian electricity grids, the need to cope with climate change-driven power losses becomes more critical. (Australian Energy Market Commission [AEMC], 2018).

Despite these challenges, renewable energy resources have a remarkable capacity to complement each other, so they are less susceptible to intermittent or variable power losses when supplied from a diverse mix of renewable energy resources rather than relying on a single type. This section describes how wave energy can cost-effectively support solar and wind energy resources to improve power supply reliability.

4.1.1. Variability and Intermittency

Variability refers to cyclic and predictable changes in generated power, such as diurnal and seasonal solar variability. In contrast, intermittency refers to changes that require statistical analysis (Pommeret & Schubert, 2021), such as infrastructure failures, wind energy droughts, or days of cloud and rainfall that reduce solar power.

As an example, wind and solar exposure droughts may last as long as three or four days in any year in Australia. Consecutive days of regional solar or wind drought are key drivers of the energy storage required to manage intermittency. Richardson (2023) has mapped the probabilities of solar and wind droughts occurring in renewable energy-producing regions of Australia (Figure 4.1). The number of consecutive days of wind and solar drought can then be determined from wind farm data (Figure 4.2 – AEMO 2024a; OpenNEM 2024) and climate data (Bureau of Meteorology [BoM], 2024).

Figure 4.1. Study region and drought likelihoods. Climate influence on compound solar and wind droughts in Australia (Richardson et al., 2022, with permission – detailed caption quoted below).

"(a) Renewable Energy Zones (REZs) coloured according to the energy type they produce: solar (seven REZs), wind (10) or both (19). Major cities are shown in red. (b–d) Empirical probability (per centage of days) of a solar radiation, wind speed or compound (solar and wind) drought occurring on any day in the year. Only REZs that produce the relevant energy type are shown. White shading indicates that a solar or wind drought occurs at the same frequency as the all-REZ average (25%). In (d), white shading indicates that compound droughts occur at the frequency expected by chance if wind and solar were independent (0.252 = 6.25%). (e) Probability density function (PDF) of the number of REZs, nREZ, that are simultaneously affected by any drought, with compound droughts counted as single (green) or double (pink). f–h PDFs of the number of REZs that are simultaneously affected by either a solar, a wind or a compound drought during winter, summer or autumn. Results for spring are omitted as they are similar to those for summer. Vertical dashed lines indicate the 95th per centile of the number of REZs in drought per day, which is the threshold used to define widespread droughts."

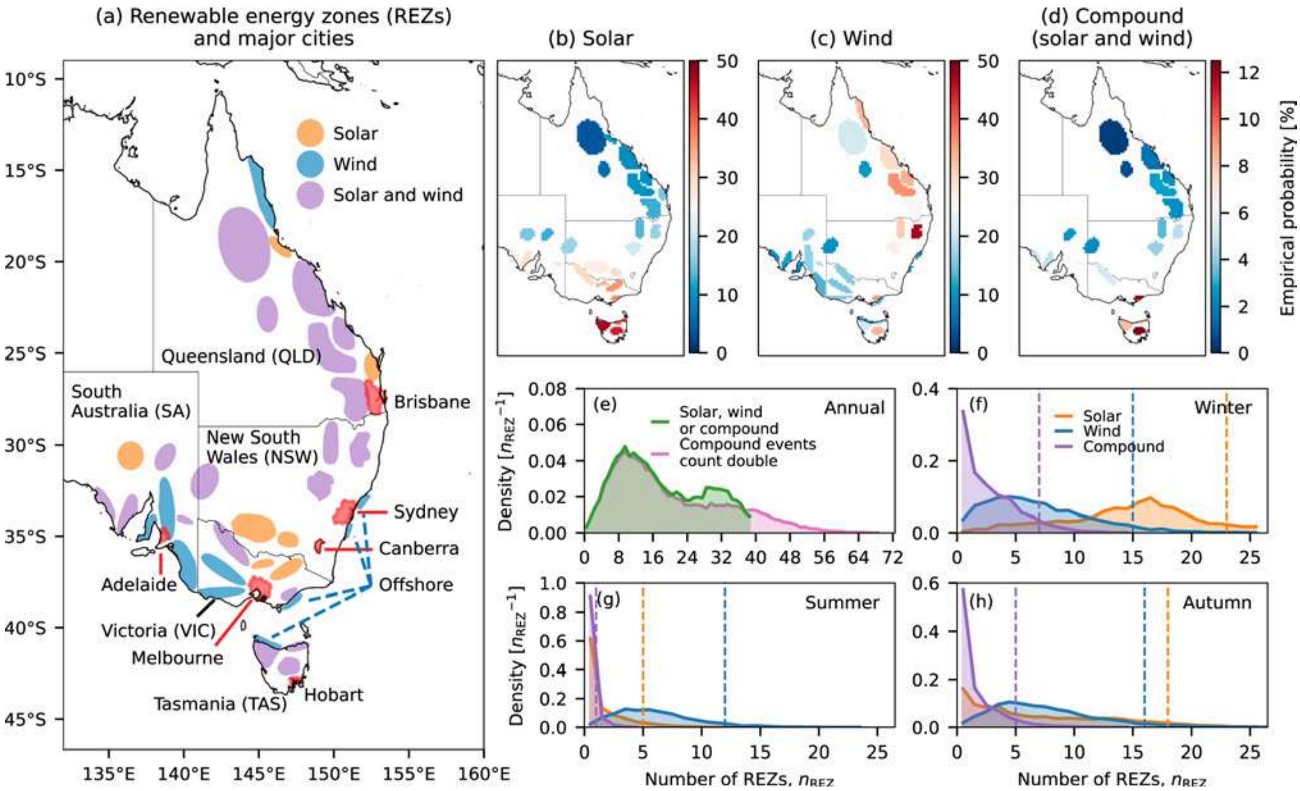
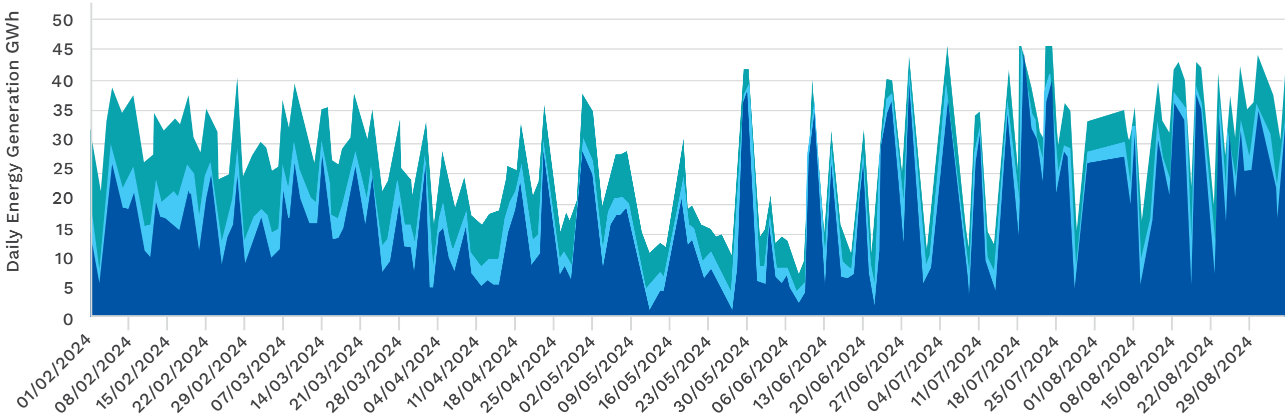


Figure 4.2. Aggregated rooftop solar, utility solar and wind energy generation for January to September 2024 in South Australia. Note the potential for wave energy to complement wind and solar during the winter period.



The management strategies for variability and intermittency tend to be different. Variability is managed by forecasting, scheduling generator capacity, and controlling loads such as off-peak power supplies. Intermittency is managed using the energy stored in utility-scale batteries, pumped hydroelectric storage, coordinating distributed energy storage, or by switching on rapid response power generators such as gas turbines. These strategies drive the production of dispatchable power.

Energy storage is expensive, and the amount of energy storage required can be substantially reduced where the renewable energy supply is from a group of generators using different types of energy resource, or from multiple generators distributed across a region.

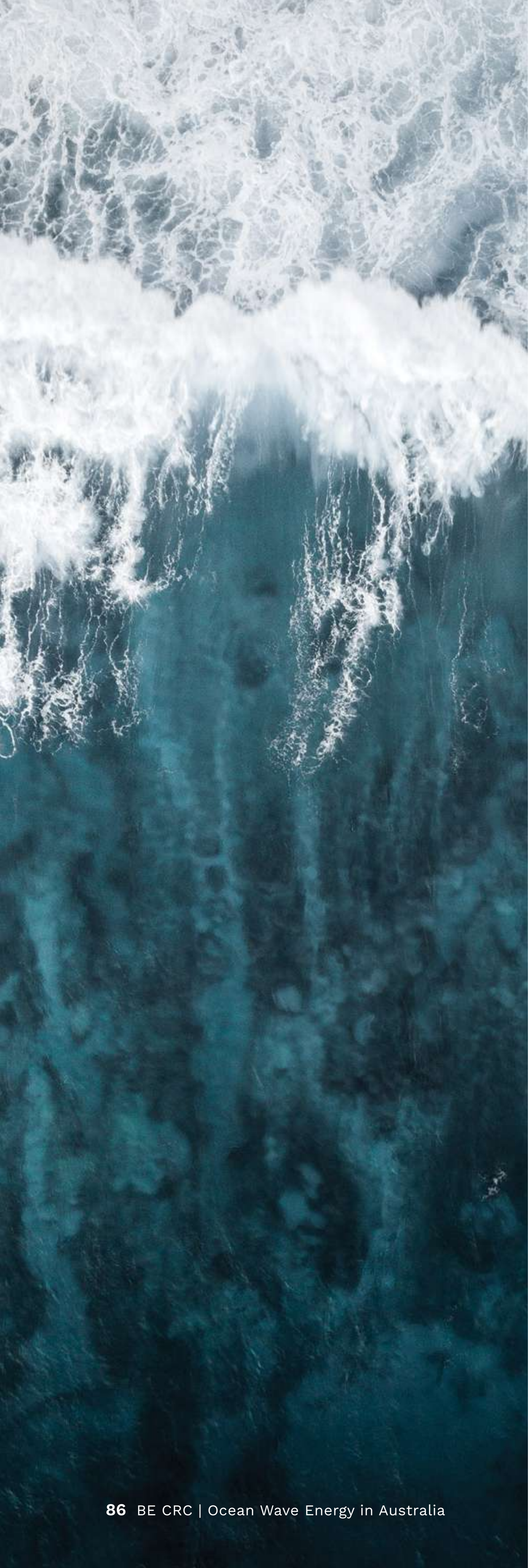
The question addressed here is whether a commercial value can be ascribed to the reliability of a system of multiple renewable energy resources and whether this value can be improved by including wave energy. For this assessment, it is necessary to clarify the terms dispatchability, dispatchability threshold, rated power, and loss of load probability.

4.1.2. Dispatchability - terminology and definitions

Dispatchability is a loosely defined term widely used in the electricity supply industry that refers to the reliability of an electricity supply.

Rai and Nunn (2022) describe it as follows: "While the term "dispatchability" does not have a universal meaning, it is commonly considered as the extent to which the resource (i.e. demand or supply resource) can be relied on to 'follow a target' in relation to its load or generation".

In other words: Dispatchability is the ability to supply power whenever needed up to a power demand limit set by the electricity purchaser or a power generation limit set by the electricity supplier.



Fossil fuel and hydroelectric generators, which can be switched on or off to meet fluctuating electricity demand, are considered highly dispatchable. Conversely, power generated by small wind farms or solar PV arrays cannot be guaranteed. The power they generate is intermittent and variable and would be regarded as having a very low dispatchability.

Renewable energy generators such as wind turbines and solar PV arrays can be adapted to produce dispatchable power by storing surplus energy to be used when the wind is not blowing, or the sun is not shining. Their dispatchability can then match that of fossil fuel generators, provided the energy storage has sufficient capacity to cover the electricity demand for the longest predicted period of power loss.

Dispatchability threshold

In this analysis, the dispatchability threshold is quantified as the maximum power that can be guaranteed divided by the average power generated, and this threshold can range from zero to one. A threshold of zero means no power is guaranteed; while a threshold of one means the guaranteed power is equal to the average power generated. Dispatchable power can be generated at any level required, between zero and the dispatchability threshold (Osman et al., 2022).

The dispatchability threshold does not have to be constant in time. It can be set to vary according to the needs of the electricity supplier or the electricity purchaser. For example, the dispatchability threshold might be adjusted to accommodate daily or seasonal variations in supply or demand.

The primary use of the dispatchability threshold is to determine the minimum energy storage required to guarantee an upper limit of power from intermittent resources that might typically include wind, wave, solar power and surplus power from an electricity grid. The power levels and time constraints on this guarantee can be adjusted, for example to match diurnal or seasonal changes in energy resource or demand. Its utility is closely linked to the Australian Energy Market Operator's (AEMO) definition of 'Plant Availability', which is used to describe the power output in megawatts of scheduled and semi scheduled generators changing transiently over periods of a few minutes. This is briefly outlined in Appendix D, which also indicates how wave energy's dispatchability value could be incorporated into AEMO formalism.

Rated power

The term “rated power” has a different meaning when describing generators powered by solar, wind or wave resources than when describing power generated from non-renewable resources. For renewables, the rated power describes the maximum power that might be generated from the solar, wind, or wave resources in the best conditions, and the average power and dispatchable power are significantly less than the rated power. In the case of non-renewable resources, it describes the constant power that can be generated reliably, and this is close in value to the average and dispatchable power supplies (disregarding downtime due to maintenance), so that the dispatchability is typically close to one. This is well illustrated for the years 2008-09 in the AEMO integrated System Plan (Figure 4.14).

While the rated power for a solar PV array, wind turbine or wave energy converter is useful when estimating the capital cost (CapEx) of a machine, it is not appropriate for determining a value for energy delivery that can be guaranteed. Therefore, the work described here focuses on average and dispatchable power rather than rated power.

Loss of Load Probability

In the electricity supply industry, the probability of intermittent power loss from a generator is sometimes called the Loss of Load Probability (LoLP) (AEMC 2018). In this report, the LoLP is specified as a failure in capacity to supply the electricity required to meet demand within the power range from zero to the dispatchability threshold. The LoLP is a key determinant of the energy storage capacity needed for dispatchability, and the algorithms used in this section allow the LoLP to be estimated for a range of dispatchability thresholds and energy storage capacities (Osman et al., 2022).

4.1.3. Valuing dispatchability

The commercial value of using wave energy to help guarantee power delivery is twofold. The first and most significant is its ability to reduce the number of random or seasonal power loss events so that less energy storage is required to ensure a secure electricity supply. For example, power generators in remote locations usually have a critical need to be able to provide a reliable supply of electricity, and they are susceptible to increasing fuel costs and the need to reduce fossil fuel consumption.

If wave energy is available, its potential for reducing the energy storage and generator fuel required for energy security could be increasingly important for reducing the cost of supplying reliable electricity.

The second commercial value is to ensure a reliable power supply so that power can be offered to the electricity spot market when power from renewable energy resources is scarce. In this case, there are cost savings from reducing the energy storage or fuel needed for a reliable power supply, and it becomes possible to sell electricity at a premium price.

For instance, there may be an abundance of power generated by solar PV arrays during the day, but a limited number of power users, so suppliers may face low or even negative prices for their power. In the early evening or on cloudy days, there may be little or no solar power available, and power could then be sold at a much higher price. Achieving this requires energy storage, such as a utility-scale battery, which may be too costly an investment. Wave energy can increase the reliability of an electricity supply, reducing the amount of energy storage and its cost. The reduced expense may allow renewable energy companies to store or sell their power cost-effectively, depending on the price offered.

The National Electricity Market (NEM) is an example of how this might operate. The electricity spot market is a series of automated negotiations offering electricity prices every five minutes (AEMO, 2017). Figure 4.3 shows an example of the five minute spot price and demand variation throughout one day, and Figure 4.4 shows the probability distribution for the quarterly average weighted prices over the last 25 years.

Figure 4.3. An example of daily spot price and demand (5th September 2024) (AEMO 2024a).

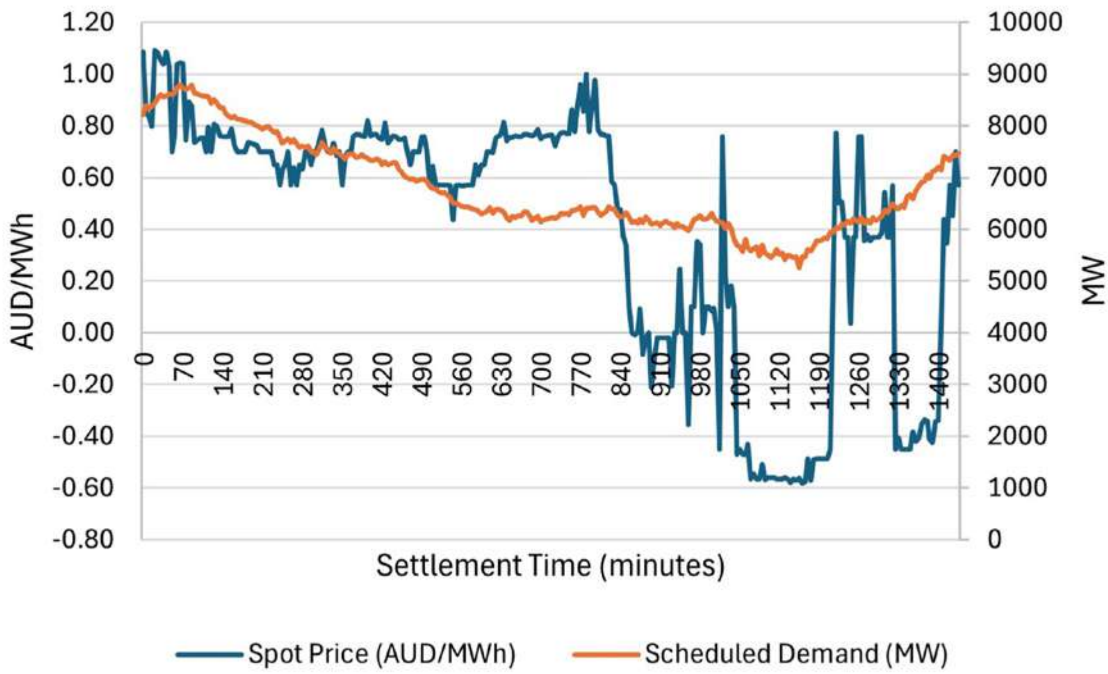
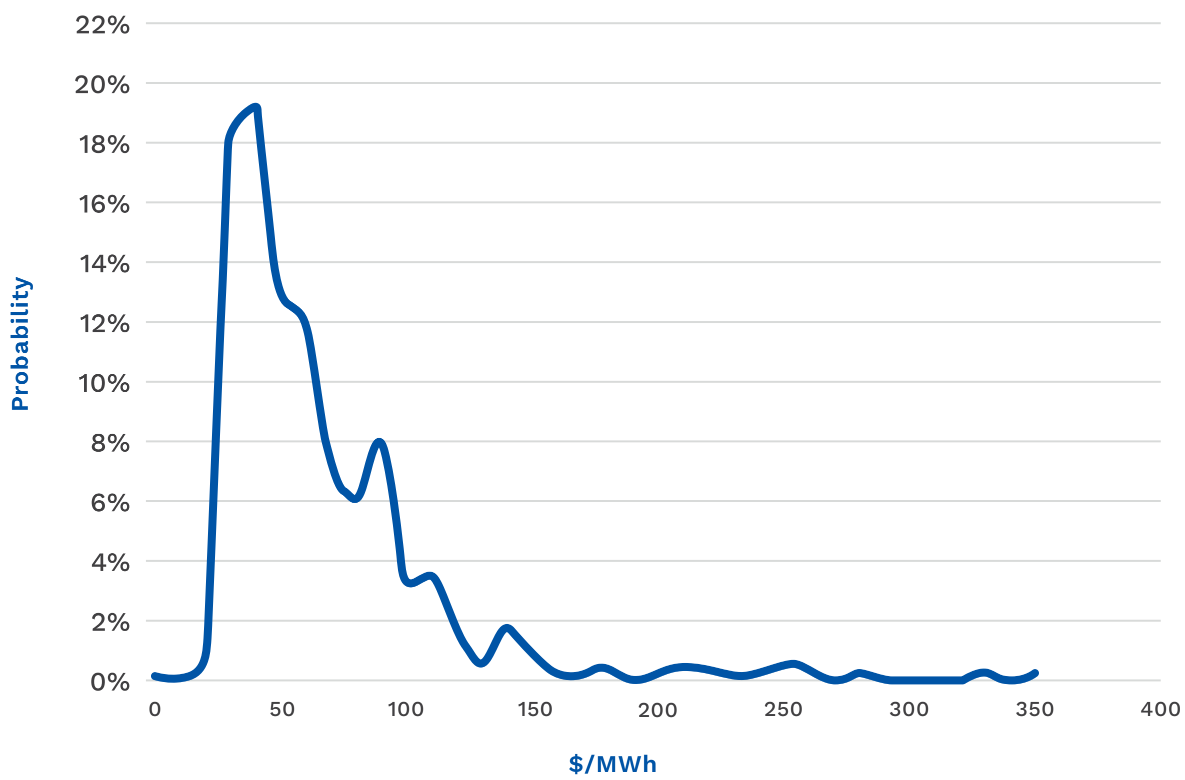


Figure 4.4. Quarterly average electricity spot price probability distribution (2019 to 2025). Derived from AEMO data (AEMO, 2024a).



Rai and Nunn (2020) describe the NEM's valuation of dispatchable power as "the difference between the dispatch-weighted prices received by non-dispatchable and dispatchable generators". This refers to the difference in market price offered to power stations depending on whether the power they generate is dispatchable. Two key factors in this difference are i) the flexibility dispatchable power sellers have for selling when the price is high ii) the potential for dispatchable power suppliers to enter alternative contracts more suitable for dispatchable power.

4.1.4. Renewable energy complementarity for managing intermittency and variability

Energetic complementarity is the ability of multiple energy resources to operate together and increase the reliability of power supply (Kahn, 1978; Jurasz et al., 2019). When the wind does not blow, the sun may be shining, and when neither is available, waves generated by distant storms may power wave energy converters, or tidal currents may flow past a turbine. And if all else fails energy storage devices can provide backup. As more complementary resources are used, energy security improves, and the need for costly energy storage reduces.

Complementarity can be evaluated for time intervals (temporal complementary) or in a region (spatial complementary) (Jurasz et al., 2019). The term spatial complementarity describes the ability of some renewable energy generators to guarantee power when the renewable energy generators are distributed across large areas, regions, or States.

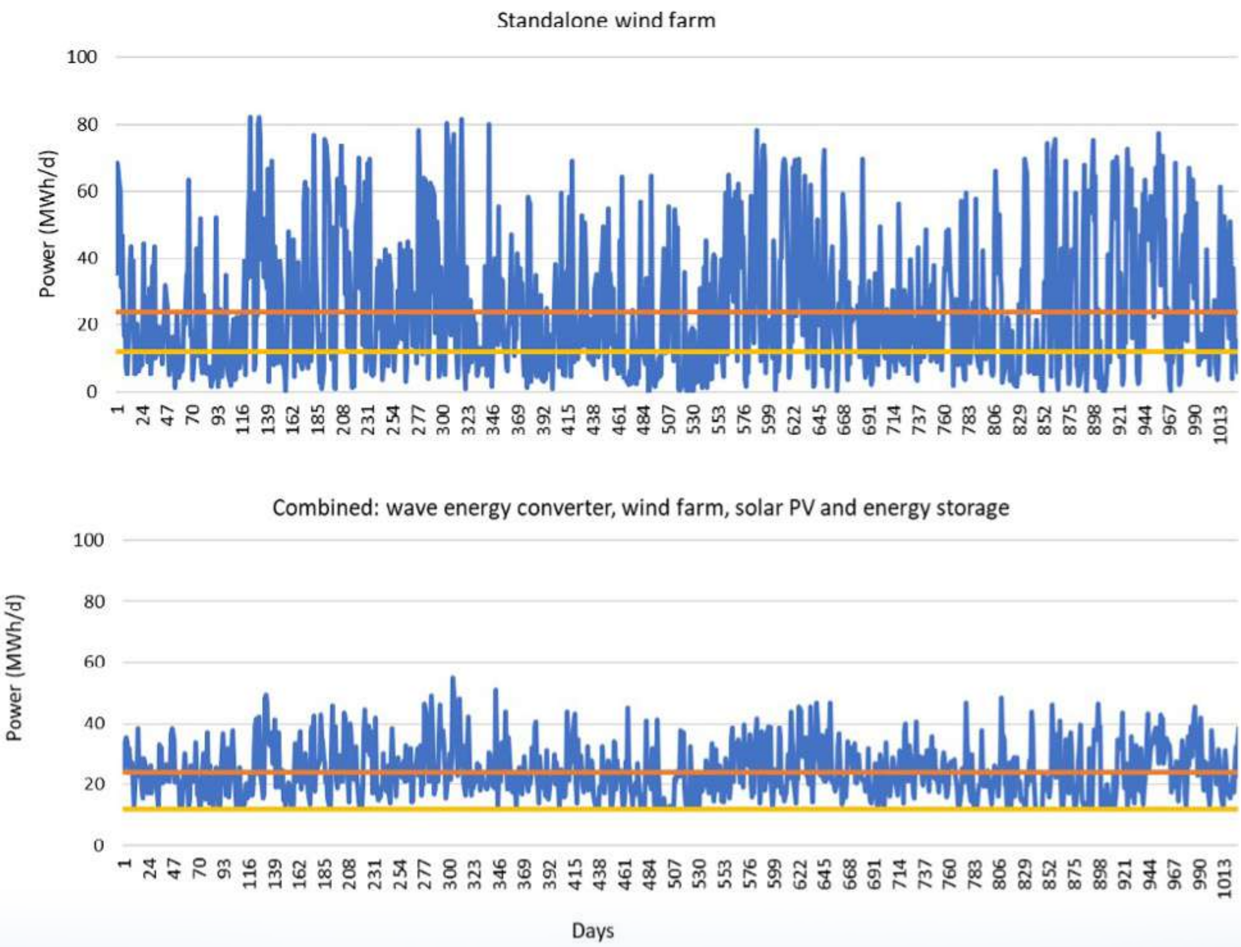
For example, if wind turbines are distributed across a State, there is a higher probability that at any time, at least some of them are likely to be working. Likewise, temporal complementarity describes a higher likelihood of guaranteeing power using several types of renewable energy to reduce the probability of power loss.

Examples include solar, wind and wave farms connected to a community microgrid, power company network, or national electricity grid.

As complementarity increases, dispatchable power increases, and the peak power and the amount of storage both reduce. Figure 4.5 is an example from Carpenter Rocks in South Australia. It shows how combining battery storage with wave energy converters, wind turbines, and solar power can improve dispatchability. The average power is shown as an orange horizontal line, and the dispatchability threshold is a light blue horizontal line. Power delivery is guaranteed (i.e. the power is dispatchable) for all power levels below the dispatchability threshold.

The standalone wind turbine power shown in the upper graph is intermittent, as numerous periods without wind cause the generator power to drop below the dispatchability threshold, shown as a yellow line. The lower graph shows that combining wave, wind and solar power and adding battery storage reduces the generator's surplus power by saving it so that it can be used to ensure the generator power never drops below the dispatchability threshold.

Figure 4.5. Using energy storage with wave, wind, and solar power to raise dispatchability threshold to 50%.



4.1.5. Complementarity and Australia's wave energy resource

Hemer et al. (2012) examined wind and wave resources around Australia (Figure 4.6), demonstrating that the availability of wave power along Australia's southern coastline was large enough to contribute a considerable proportion of Australia's renewable electricity supply. Nevertheless, the report concluded that economic considerations, based on the capital and maintenance costs of the generators and infrastructure, would limit the proportion of wave energy in Australia's National Electricity Market. However, the report also provided data that suggested the complementarity of wave and wind energy may significantly increase the reliability of electricity supply at these key locations. Figure 4.7 and Table 4.1 show that the wind power at Cape Sorell on the west coast of Tasmania drops below 25% of its mean value 42% of the time; likewise, wave power drops below this value 13% of the time, and wind combined with wave power drops below this value 16% of the time. The table summarises comparable results for locations around Australia.

A key finding is that combining wave energy with wind energy in these locations reduces the probability of power loss events by factors of about three, and combining wind and wave power from multiple locations can reduce them by factors of up to six.

The report recommends that "the optimal mix of renewable energy sources, with both cost and temporal variability taken into account, should be further investigated" (Hemer et al., 2012, p. 40). Subsequent work on this aspect of the Australian wave energy resource has included combining energy storage with solar PV arrays, wind turbines and wave energy converters. The impact of these combined resources on the probability of power loss has been modelled for three locations on the southern coast of Australia at dispatchability thresholds ranging from 0 to 0.7 (Osman et al., 2022).

Figure 4.6. Australia's high-energy wave buoy sites (Hemer et al., 2012)

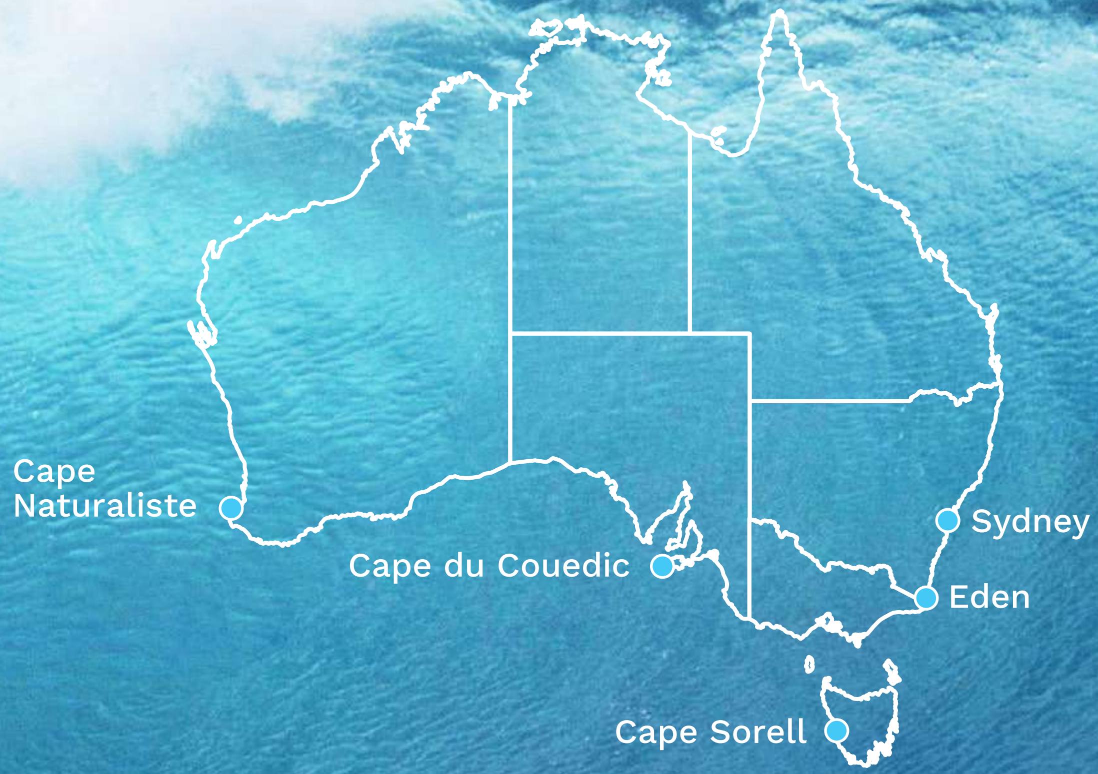
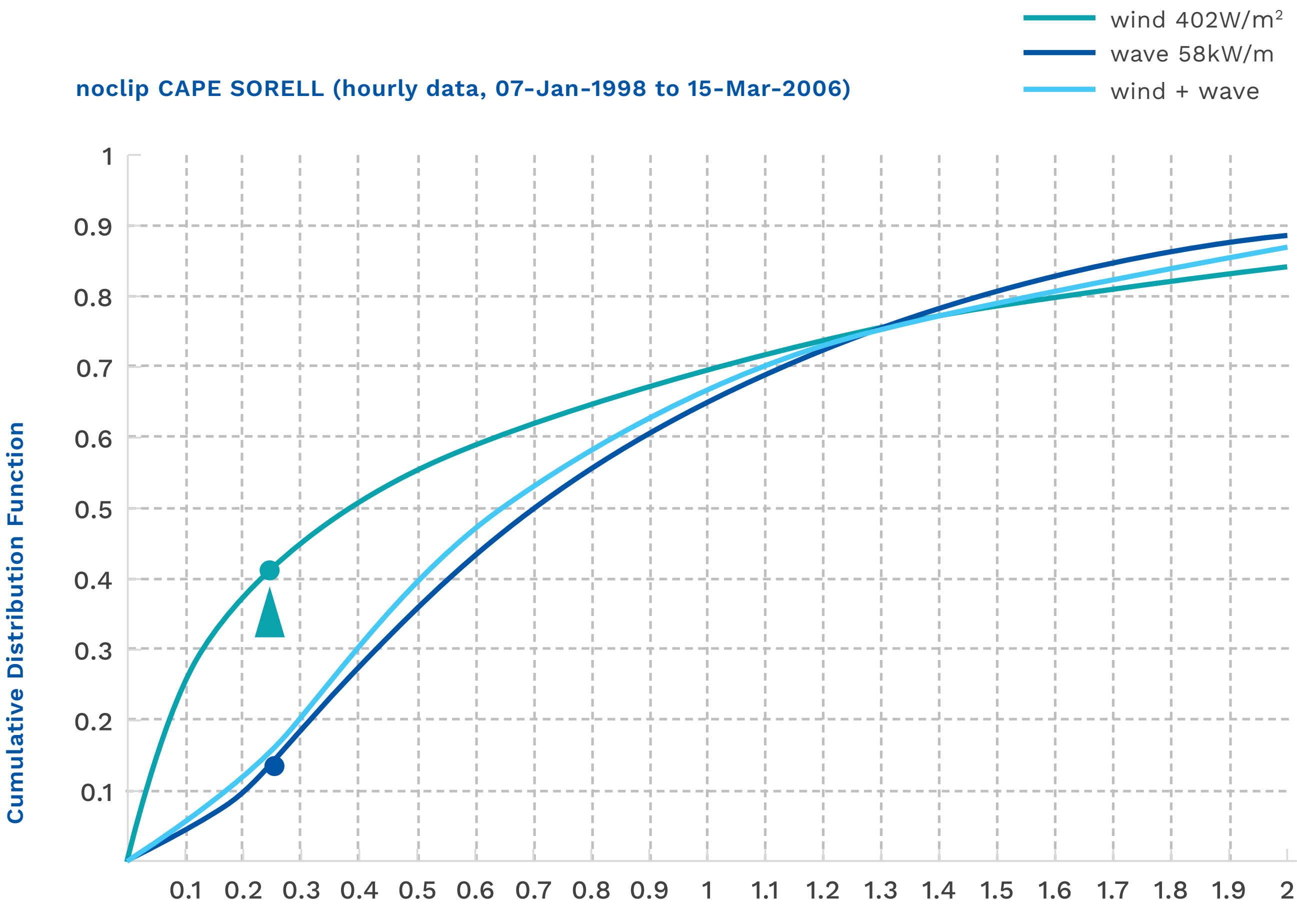


Table 4.1. Statistics of hourly wind and wave power computed from observations throughout the year at several sites from 1998 to 2005 (Hemer et al., 2012).

Site	Mean wind W/m²	Mean wave kW/m	Per cent time power < ¼ (LoLP)			Improved wind LoLP
			Wind	Wave	Wind + Wave	
Cape Sorell	402	58	42	13	13	3.23
Cape du Couedic	563	47	26	11	11	3.25
Cape Naturaliste	372	51	25	12	12	3.57
Sydney	253	14	35	14	14	2.33
Eden	421	14	37	8	8	3.36
CS + CdC	447	55	29	10	10	3.22
CS + CdC + Eden	436	39	19	5	5	4.75
CS + CdC + CN + Eden	422	42	12	2	2	6.00

Figure 4.7. Cumulative probability distribution function of wave and wind power (normalised by their respective mean values shown in the legend) at Cape Sorell (Hemer et al., 2012).



4.1.6. Calculating complementarity and dispatchability resource

Variability can be well represented by correlation coefficients, which are widely but not exclusively used in measures of complementarity (Jurasz, 2019). However, intermittency may be better represented by indices constructed for rare event occurrences such as power loss. One of the best-known and earliest examples is based on the LoLP. This approach demonstrated that combining wave, wind and solar energy can reduce variability and the amount of power held in reserve to guarantee that power can be delivered (Denault et al., 2009; Halamay et al., 2011; AEMO 2024a). Many complementarity indices have subsequently been designed for renewable energy resources (Freris et al., 2008; Beluco et al., 2008; Jurasz et al., 2019).

Between 2016 and 2018, there was a peak in papers on renewable energy complementarity, focusing on solar-wind, solar-hydro, and wind-hydro power. These were comprehensively reviewed by Jurasz, who described the need for further work on indices that link models and measured data focused on wave and tidal energy resources (Jurasz et al., 2019). The AUSTEn initiative in Australia used modified versions of the LoLP index to optimise battery storage for combined wind, solar and tidal energy (Penesis et al., 2020; Osman et al., 2021). From 2021 to 2022, CSIRO and Wave Swell Energy collaborated in applying the same approach to wave energy using hindcast data from the Australian Wave Energy Atlas (Hemer et al., 2017 and 2018b) for three sites along the Australian southern coast. The wave data were combined with six years of wind farm and solar power data to demonstrate the potential for substantial reductions in the storage capacity and costs required to achieve dispatchabilities up to 70% of average power (Osman et al., 2022). Wang (2022) carried out a study for a site in Albany, Western Australia, again showing that the introduction of wave energy substantially reduced the storage capacity required to manage intermittency. In addition, Wang determined optimal wind and wave renewable energy configurations for a range of energy storage and wave energy converter costs (Wang 2022).

The analysis method used in this report comes from the AUSTEn and Wave Swell Energy studies (Osman, 2022). It links an LoLP for multiple renewable energy resources to the minimum energy storage required to meet power demand for a given period. The algorithm estimates the energy storage, dispatchable power capacities, CapEx costs and LoLP for a specified power demand time profile. It operates by applying a set of dispatchability thresholds to a renewable energy generation time series that represents the energy resources used in the hybrid generator. It identifies a set of the shortest independent time windows in which the power level repeatedly rises and falls across the threshold and where for each window the net energy deficit is zero. The maximum energy deficit in this set is used to assess the required battery capacity for the system and the complementarity of the renewable energy hybrid components. The model is checked to ensure that essential energy storage management constraints such as overcharging, energy conservation and the management of diurnal variability are controlled. These calculations were made for a six-year time frame resolved to hourly intervals. The calculations use a Wave Swell Energy power matrix and CapEx; the approach taken to CapEx is discussed in the next Section.

4.1.7. The projected cost of wave energy 2025 - 2055

As an early-stage technology, the technical advantages of wave energy converters are currently offset by their high CapEx cost. Much of the cost disadvantage is because few wave energy converters have progressed beyond a Technology Readiness Level of nine (i.e., several pre-commercial machines tested at sea for an extended period) and a Commercial Readiness Index of two (i.e., small-scale commercial trials). At these levels, wave energy converters have yet to take advantage of a commercialisation learning curve. Three scenarios and associated learning curves were considered in this report, using the CSIRO GenCost scenarios (Graham et al., 2024).

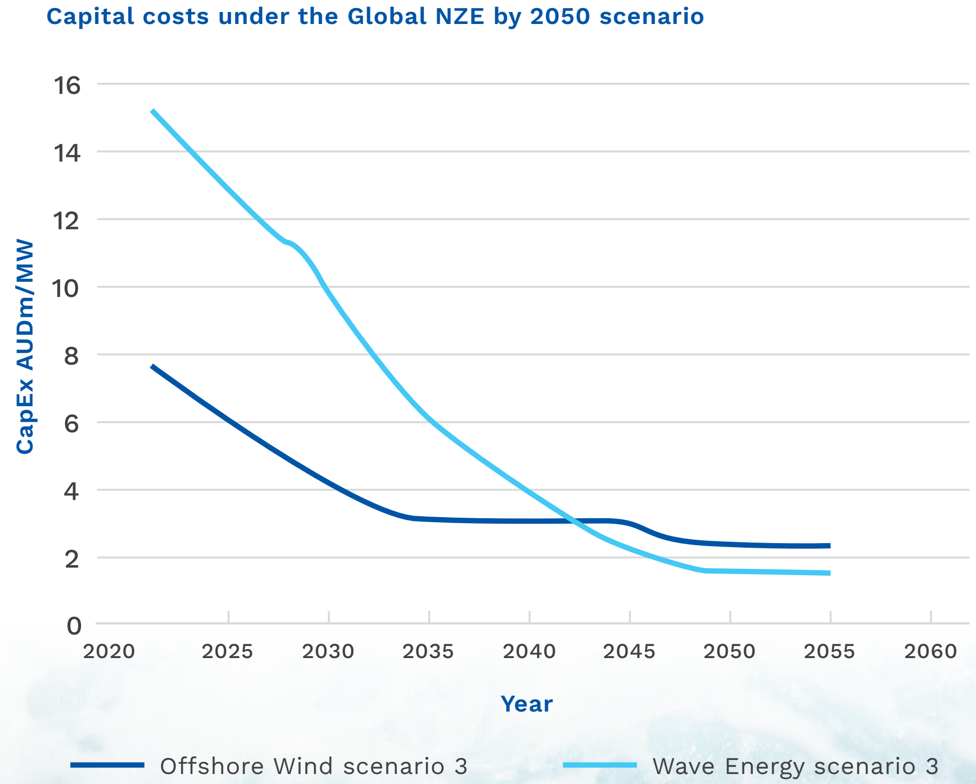
- In Scenario 1 there is no emissions abatement beyond recent commitments, access to global renewable energy resources is highly constrained, and technology learning rates are at their slowest.
- In Scenario 2 global net zero emissions targets are achieved later than 2050. It assumes mid-range learning rates and some incentives for the deployment of the low-emission technologies required to meet longer-term net zero-emission targets.
- In Scenario 3 global net zero emissions are achieved by 2050. It assumes a strong international climate policy to keep global warming within 1.5 degrees. This target is supported by measures to achieve the fastest possible technology learning rates and the least possible constraints on accessing renewable energy resources.

In Scenarios 1 and 2 wave energy converters have not reached commercial maturity by 2050 and thus the capital cost reductions have not reached their full potential as they have for Scenario 3. The two scenarios may also be associated with an elevated level of economic and environmental uncertainty that impacts infrastructure development, including renewable energy projects. For example, increases in rainfall and cloud cover may reduce the efficacy of solar energy in tropical and temperate regions of Australia, and wave energy could then be an option to help maintain acceptable levels of dispatchability. For these reasons, Scenario 3 is the most relevant projection for examining the full potential of wave energy.

Hypothetical CapEx values were estimated using Scenario 3 to compare 2050 wave energy converter costs against solar PV arrays and wind turbines. The cost curves assume 2024 as a starting point for commercialisation. Delays in commercialisation can be managed by adjusting the starting point of the learning curve.

Figure 4.8 shows the offshore wind and wave energy converter CapEx reductions following commercialisation through to 2050. The chart focuses on CapEx rather than the Levelized Cost of Energy (LCOE) as it is too early in the wave energy converter commercialisation cycle to publish multi-year operation and maintenance data (Graham et al., 2024). The estimates in Figure 4.8 do not include the earnings if a price was negotiable for wave energy's enhanced dispatchability. Nor does it include the considerable reduction in CapEx cost associated with the reduced energy storage requirement when wave energy is introduced into an electricity grid powered by renewable energy.

Figure 4.8. Capital costs under the Global NZE by 2050 Scenario 3. Derived from GenCost data (Graham et al., 2024).



4.1.8. Comparative standalone and hybrid generator CAPEX costs projected for the year 2050

The data that follows are from one of three studies (Figure 4A- 1) using a six-year time series of measured solar exposures, wind turbine data and wave energies from the Australian Wave Energy Atlas and a Wave Swell Energy WEC power matrix. The data were taken from three locations along the south coast of Australia: i) an ocean-facing beach near Carpenter Rocks, ii) off the headland at Cape Nelson Lighthouse, and iii) a beach east of Warrnambool. All three locations provided similar results, with the inclusion of wave energy greatly improving the dispatchabilities of both solar PV arrays and wind turbines.

There was a strong seasonal complementarity between solar and wave energy in all three locations studied.

In addition, there was a particularly strong wind wave complementarity at Warrnambool. The example described here is from Carpenter Rocks. The energy storage capacities and CapEx costs of standalone wave energy converters, wind turbines and large-scale solar PV arrays are compared in Figure 4.9 and Figure 4.10. Figure 4.10 shows the cost per the average power generated. (Figure 4B- 1 and Figure 4B- 2 show the cost per the rated power of the installation. The rated power costs are included because they are a conventional marker for CapEx. However, caution is needed when using rated power as a reference for cost estimates, as the amount of electricity that can be supplied for any given dispatchability also depends on the capacity factor. Cost comparisons using measured dispatchable power per unit average power are the preferred reference in this report.)

In practice, using a battery with isolated solar PV arrays or wind turbines to achieve dispatchability is extremely costly due to the seasonal variability of solar power and the intermittency of wind (Figure 4.9 and Figure 4.10). Increasing the size of solar PV or wind turbine farms might be an alternative to energy storage, but this wastes energy, can lead to grid instability and penalty payments for oversupply. Wind farms distributed across a large network can have significant levels of spatial complementarity, but the storage costs are still high.

However, combining wave energy with solar PV arrays and wind turbine resources can greatly reduce the intermittency and seasonal variability of solar PV and wind turbine power supply, as demonstrated in Figure 4.11 and Figure 4.13.

Figure 4.9. Battery capacities for standalone renewable energy resources to achieve from 0.1 to 1 dispatchability.

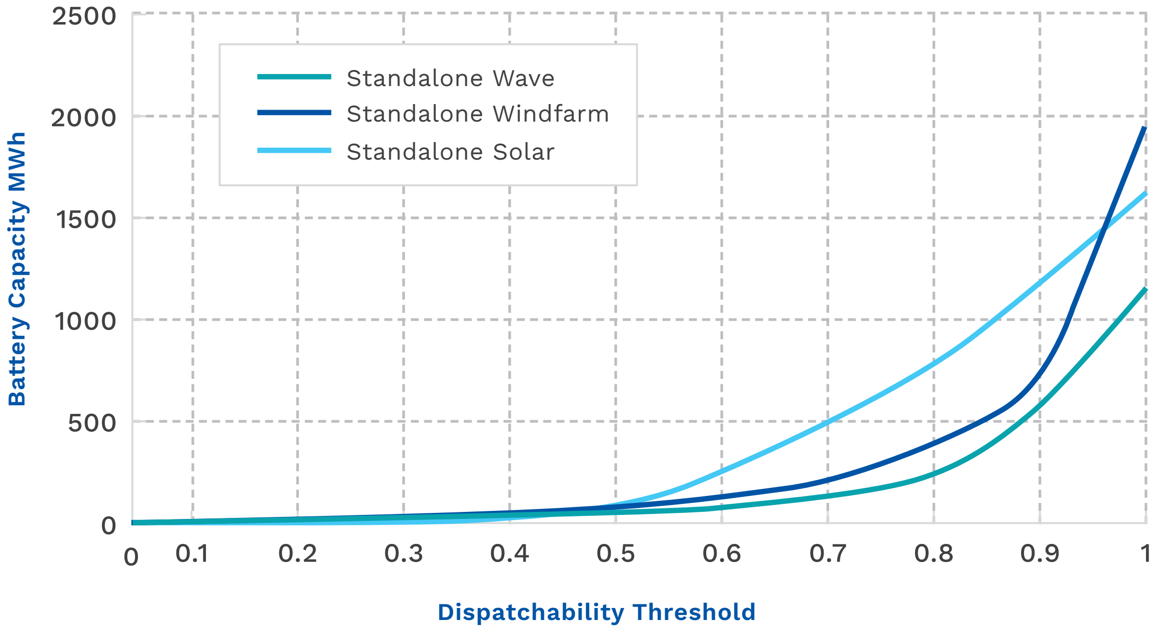


Figure 4.10. CAPEX estimates per MW average power for standalone renewable energy resources to achieve from 0 to 0.7 dispatchability. (A version of this figure in terms of rated power appears in Appendix B).

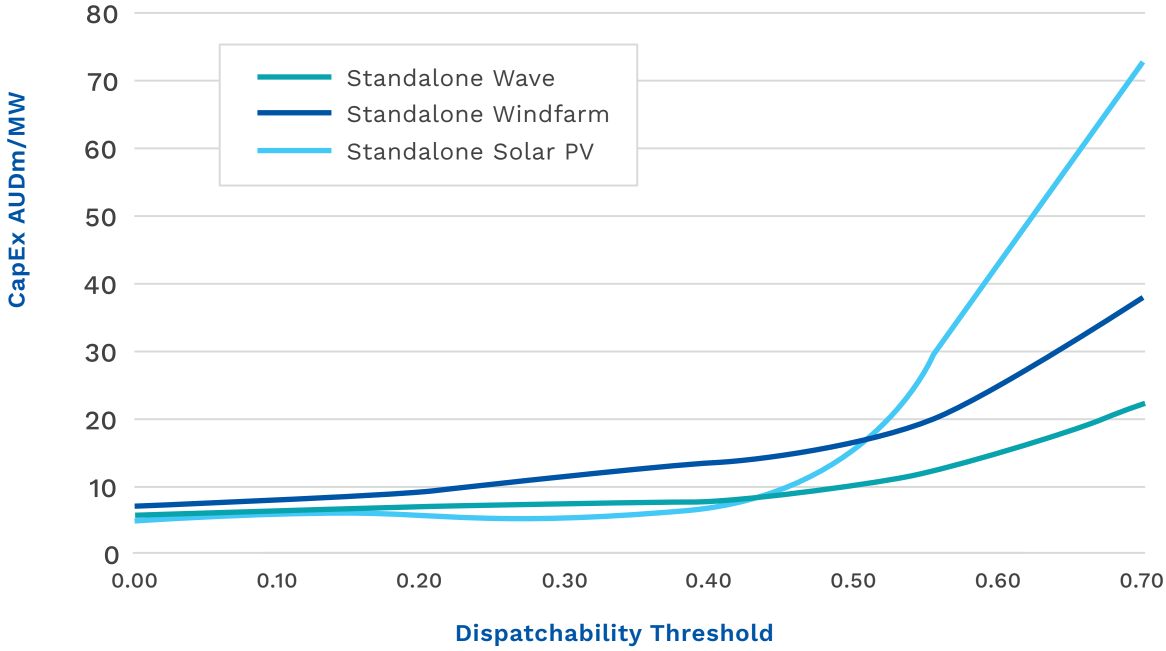


Figure 4.11 and Figure 4.12 show the energy storage requirement and cost associated with different combinations of wave energy converter, wind turbine and solar PV power. They demonstrate that the systems that included wave energy required the least energy storage for all dispatchability thresholds. For example, a dispatchability threshold set at 0.7 requires six times the energy storage capacity when using just solar PV arrays compared with combined WECs, wind turbines and solar PV arrays.

Figure 4.11. Battery capacities for a range of hybrid renewable energy resources to achieve from 0 to 0.8 dispatchability. Location Carpenter Rocks.

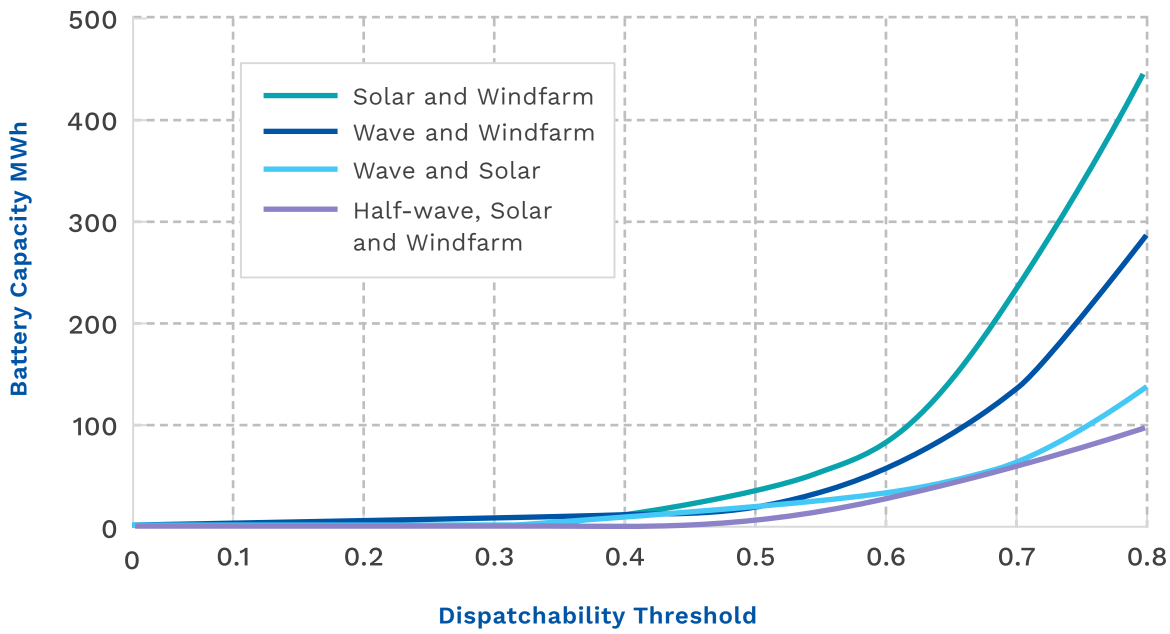
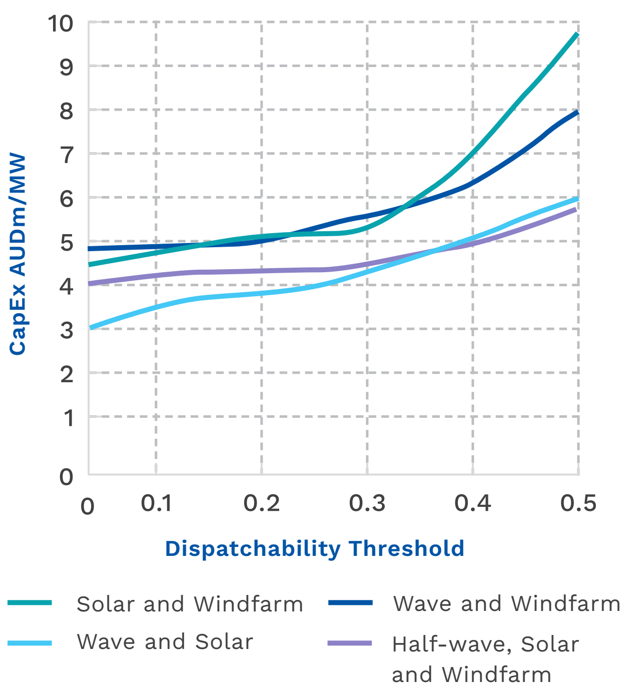


Figure 4.12. CAPEX 2050 estimates per MW average power, for a range of hybrid renewable energy resources to achieve from 0.1 to 0.7 dispatchability. Location Carpenter Rocks. The CapEx for dispatchabilities of zero reflect the cost of the generators rather than energy storage, except for solar arrays where some energy storage is included to allow for the diurnal average. (A version of this figure in terms of rated power appears in Appendix B).



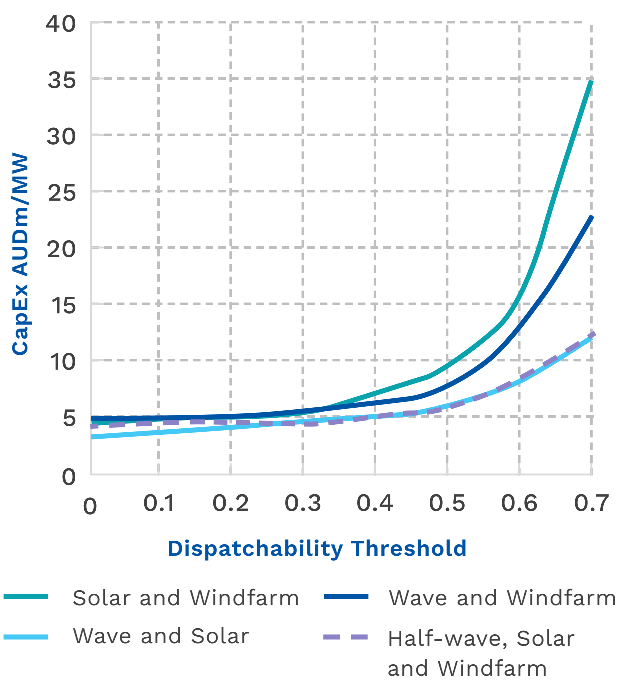
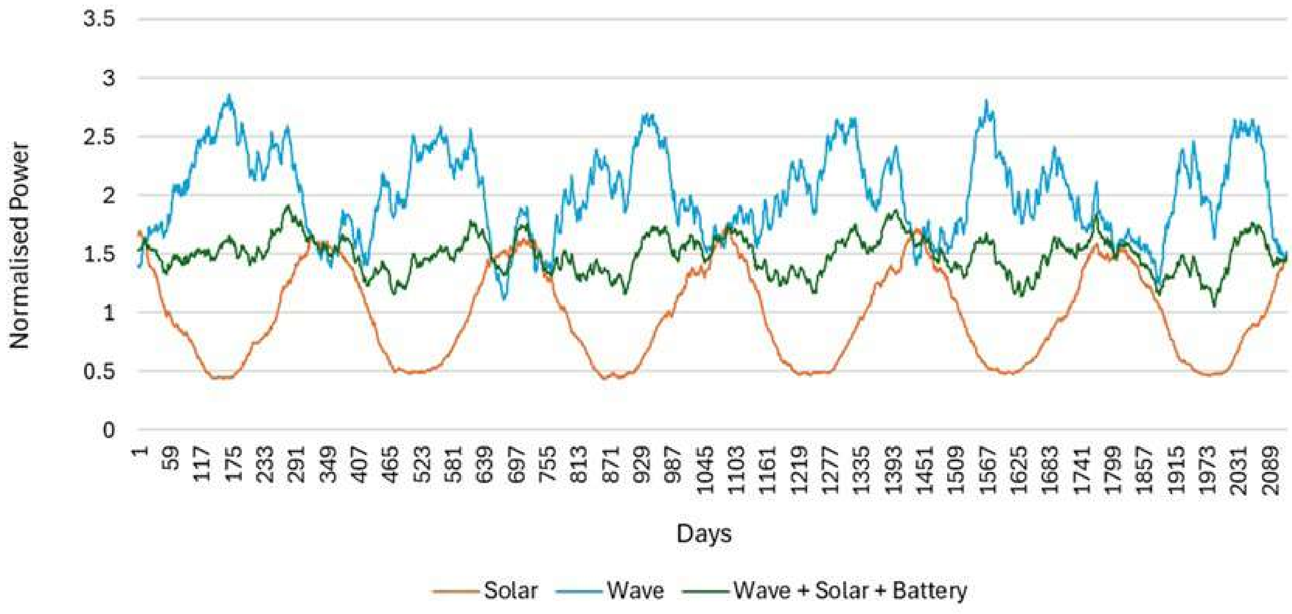


Figure 4.13. Inverse seasonal correlation between wave energy converter and solar PV power at Carpenter Rocks.



Offsetting solar PV seasonal variability

Adding wave energy converter power to solar PV array power greatly reduces the need for energy storage capacity, as shown here in Figure 4.9 to Figure 4.12. At a dispatchability threshold set at 0.7 of the average power generated, this combination reduces the energy storage capacity by a factor of 6.0, compared to a factor of about 2.7 for wind and solar combined.

This factor of six reduction is due to inverse seasonal correlation between solar PV and wave power, as shown in Figure 4.13. In winter, wave power compensates for the reduced solar power; in summer, solar power takes over and compensates for the wave power. At Carpenter Rocks, they balance each other when there is twice as much wave power as solar power. The 2x ratio is because the wave power at Carpenter Rocks varies seasonally about half as much as solar power. This kind of seasonal variation has also been reported for other locations, although not in the context of offsetting solar PV seasonal variation. Wave powered electricity production, with summer lows and winter highs, has been described at Albany Western Australia (Cutler, et al., 2020), at Orkney, UK (Orszaghova, et al., 2022), and at Mutriku in northern Spain (Ibarra-Berastegi et al. 2018). However, the seasonal changes at Mutriku are much larger than found along the southwestern coast of Australia, owing to greater variability of the wave resource along the western Europe Atlantic Ocean coastline (Cutler et al 2020, Orszaghova et al 2022).

The potential of wave energy to significantly reduce seasonal solar power variability, energy storage capacity, and cost is a key advantage.

This could be particularly beneficial for remote communities along the south coast where the solar exposure is less likely to be compromised by cloud. It also holds promise for cost-effectively reducing the seasonal variation in solar PV power on state and national grids, but this will require a more comprehensive assessment.

Figure 4.11 and Figure 4.12 also show that wind turbine power can be added to solar and wave power without compromising dispatchability or cost savings. Wave energy was required to achieve the lowest CapEx at all dispatchability threshold settings. Wave, wind, and solar power combined in the ratio 2:1:1 had very similar CapEx to wave and solar above dispatchabilities of 0.3, so that adding wind power to the wave and solar power did not compromise the ability of combined solar and wave power to reduce the LoLP.

4.1.9. Wave energy and grid-connected devices

There have been many demonstrations of functional wave energy converter systems, but few have operated over multiple years while connected to a local grid that included solar and wind energy resources. As such, measured data usable to demonstrate dispatchability is scarce. Notable examples of grid-connected arrays operated over multiple years are the Mutriku wave energy plant in the Bay of Biscay and the Eco Wave Power wave energy array in Gibraltar.

Mutriku wave energy farm

The 296 kW Mutriku wave energy farm has operated since 2011 and is planned to be upgraded in 2026. It cost AUD10.7 million and comprises 16 Wavegen oscillating water column converters installed on a breakwater. This is the longest-running grid-connected wave energy plant, having generated 3 GWh since 2011. It is also the first to have published its multi-year operating data, including electricity production, capacity factor, and plant efficiency index (Ibarra-Berastegi et al. 2018).

The system sells electricity to the grid 74% of the time with an average hourly production of 37.4 kWh, a maximum of 158 kWh and a minimum of 1 kWh. The generated power varies seasonally, peaking in winter and dropping to a minimum in summer.

The capacity factor based on 14 operational turbines varies from 0.22 in winter to 0.03 in summer. However, it should be noted that, on average, only 9 turbines were active during the study period. A study of the plant efficiency factor suggested that significant improvements could be made (Ibarra-Berastegi et al. 2018).

The Mutriku wave energy farm's inverse seasonal variability could make it a useful complement to solar PV's seasonal variability. The farm is not yet connected to a solar or wind renewable energy resource. Still, it is mentioned here because of its longevity, publicly available data, and exposure to a wave climate with mean wave energy flux similar to the east coast of Australia between Eden and Brisbane (Shand et al., 2011; Sharp et al., 2022).

Eco Wave Power Plant

Eco Wave Power completed a pilot trial of its 100 kW grid-connected pilot wave energy array in 2022. It has operated since 2016 under a Power Purchase Agreement with Gibraltar's National Electric Company, GibElectric. In its last year, the unit reported an OPEX of 3.2% of the CapEx and generation of 73% of the forecasted electricity for the site. A forthcoming project is to construct a 1 MW wave energy converter at Porto in Portugal, with plans to extend it to 20 MW. Gibraltar also has access to 6 GW of wind power and 3.9 GW of solar power, suggesting a potential opportunity for assessing the dispatchability of wave, wind and solar PV energy combined in a local community electricity grid (Eco Wave Power, 2024).

Wave Power Plants – Approaching Technology Readiness Level 9

Several wave energy converters are approaching the TRL 9 stage, including grid connection to systems that include solar and wind energy. So, there is a reasonable expectation that some of these will commence long-term trials of electricity production for commercialisation and that, subsequently, there will be a reduction in cost as they traverse the learning curves associated with commercial production and development. In the meantime, Wave Swell Energy and CorPower Ocean are two companies approaching TRL 9 that have recently published assessments of the potential for improved dispatchability through complementarity with solar and wind power.

In 2022, CSIRO partnered with Wave Swell Energy in a study to assess the value of wave energy, particularly focusing on its capital and operating costs and its ability to improve dispatchability, reduce CapEx and reduce the energy storage capacity required to guarantee electricity supply. The results of this study informed the present report. Concurrently, Wave Swell Energy trialled its UniWave200 unidirectional oscillating water column wave energy converter near Grassy Harbour at King Island in Bass Strait. The unit's rated power was 200 kW, and it commenced exporting power to the King Island grid on June 18, 2021. The trial was completed in 2023.

CorPower Ocean commenced trials of their C4 point absorber wave buoy at their Aguçadoura site in northern Portugal in 2023 (CorPower Ocean 2024). The unit's rated power is 300 kW, and it can be tuned to sea state conditions for electricity generation and detuned to manage extreme conditions. CorPower Ocean collaborates with EVOLVE, a European marine renewable energy research partnership. In 2023, EVOLVE produced reports describing opportunities for deploying grid-connected ocean energy at sites on the European mainland and islanded sites. The reports provide estimates of the potential power system benefits from using wave and tidal energy to increase the dispatchable renewable energy proportion. In the UK, for example, EVOLVE reported a potential for up to 30% less installed capacity and 50% less storage to meet demand, with total CapEx and operational costs reduced by 20%. They project that for the UK, installing 10 GW of wave energy would mitigate 1.06 Mt CO^2 by 2030 and provide annual cost savings of up to AUD2.76 billion, by 2040 (EVOLVE, 2023).

4.1.10. Market opportunities for wave energy

Hindcast wave energy models (Hemer., 2018b) combined with solar and wind turbine measurements suggest that wave, solar and wind energy operating separately can only guarantee electricity supply at below 10% of the average electricity demand in local grid systems without spatial complementarity. However, recent modelling of wind, wave, and solar resources along the southern coast of Australia demonstrates that combined solar, wind and wave energy in this region can guarantee supply over periods of years despite multiple days of solar or wind droughts and for a much lower level of energy storage than would be required by wind and solar energy alone.

In a local network, the CapEx savings could be as high as AUD10 million per MW dispatchable capacity to guarantee that the power supply does not drop below 50% of the average electricity (i.e. 50% dispatchability).

In a larger network, these savings may be somewhat offset because the spatial complementarity of wind turbines and solar PV arrays distributed over large regions or states already provides some dispatchability (AEMO 2024a; OpenNEM 2024).

The National Electricity Market

The Australian Energy Market Operator (AEMO) Integrated System Plan for the National Electricity Market (NEM) includes a description of the dispatchable capacity requirement from 2024 to 2050 (AEMO 2024b). It suggests that from 2040, there will be a market for technologies other than fossil fuels that can supplement solar and wind renewable energy shortfalls. These include balancing loads, coordinating consumer energy resources (CER), and managing and providing additional dispatchable capacity from renewable energy complementarity. Figure 4.14 provides more detail, showing the power capacity components that will contribute to the national grid power supply over the next 25 years (AEMO, 2024b). The chart shows how these components sum to a dispatchable power level, which is indicated as a black line.

We have added an orange line that shows estimates for the average power available from these resources.

The letters A and B in Figure 4.14 indicate two potential markets for wave energy's low cost and high dispatchability. The dispatchable capacity forecast and the average estimate suggest the National Electricity Market is currently providing a dispatchability threshold of 0.8 in 2024, falling to 0.7 in 2030 and 0.6 in 2050. The gap, indicated as 'A' in Figure 4.14, shows the region between the average and dispatchable lines where the capacity is intermittent and variable. Adding wave energy can reduce this gap by raising the dispatchability, reducing curtailed power from wind and solar overproduction, and reducing the quantity of wind and solar plant needed to achieve the required average power.

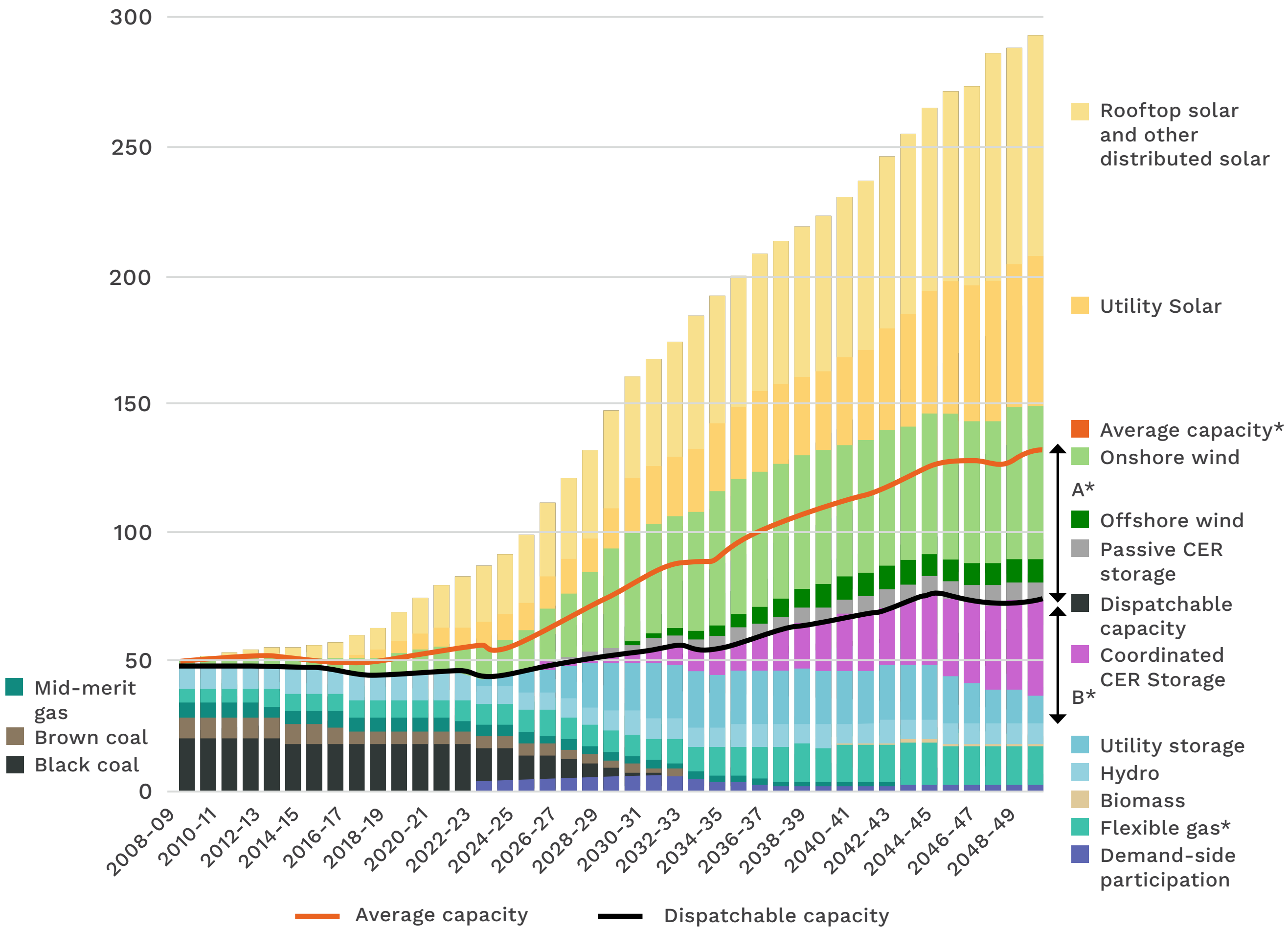
Introducing wave power with a comparatively low level of energy storage could significantly reduce the cost of filling the 2050 dispatchable power gap.

The NEM projections in Figure 4.14 show that by 2050, the storage component of dispatchable capacity will be about 49 GW, implemented using both utility-scale energy storage and coordinated consumer energy storage (comprising vehicle or household batteries). The energy storage requirement to achieve the projected dispatchable capacity in 2050 is indicated by 'B' in Figure 4.14. The capital value for this level of utility-scale energy storage is extremely high. Wave energy could reduce distributed energy storage costs by a factor of two to six compared with using solar and wind energy alone.

In summary, key national grid markets for ocean wave energy could, therefore i) support solar and wind resources so that their complementarity can more cost-effectively reduce the 2050 dispatchable capacity deficit and ii) significantly reduce distributed energy storage costs by reducing the amount of coordinated CER and utility-scale storage required to maintain grid power dispatchability.

Figure 4.14. NEM Average and Dispatchable power Projected to 2050. © Australian Electricity Market Operator (AEMO), Source: Integrated System Plan 2024 (AEMO, 2024b). Reproduced with the permission of AEMO.

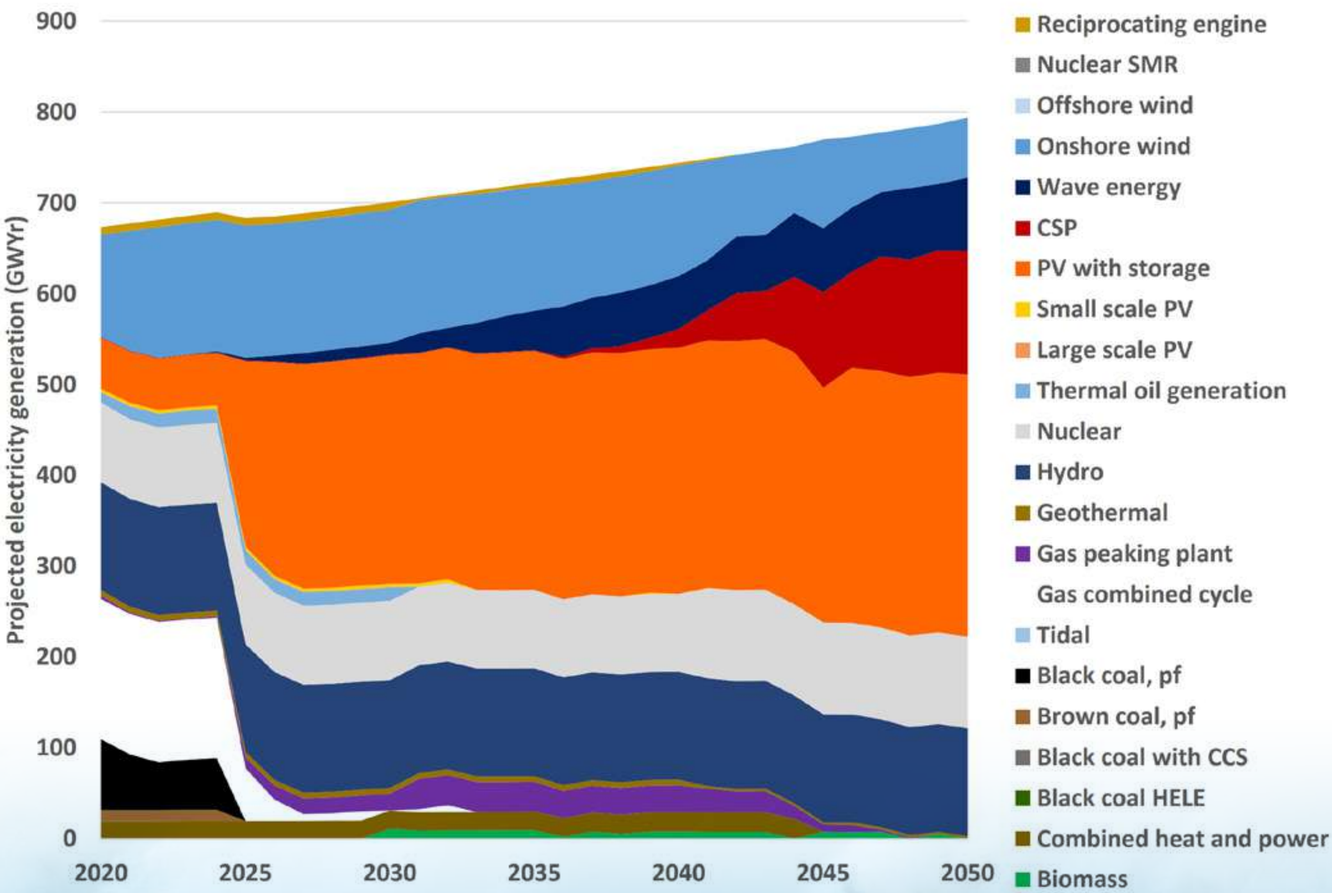
**We have modified the AEMO figure by adding 'A' and 'B' to the chart to represent potential market opportunities for dispatchable renewable energy as described in the text. The average capacity line was also added to the AEMO chart, by applying generic capacity factors to each of the AEMO chart's renewable energy components. Dispatchability thresholds can be derived as the dispatchable capacity divided by the average capacity.*



Wave energy's market potential

Hayward (2021) suggests how wave energy might enter the electricity market (Figure 4.15). The region of North America is projected here to be a globally predominant user of wave energy. Under scenario three, wave energy may enter the North American market in 2033 with an installed capacity of 29 GW, contributing 113 TWh annually. This could expand to 8% of the total energy supply by 2050. Similar projections for the United Kingdom have been made by the European industrial research consortium EVOLVE, as noted earlier in this Chapter.

Figure 4.15. Projected North American electricity generation under the Achievable scenario 3.



4.1.11. Case study

Overview

This case study outlines hypothetical systems for power generation at Carpenter Rocks in South Australia. It estimates the increase in dispatchability of an electricity supply generated from combining local wave, wind, and solar PV renewable energy. Such a system could be adapted for local town use, regional use, or for exporting electricity to a state electricity grid.

Carpenter Rocks is well placed to take advantage of the wave, wind, and solar resources along its coastline. Using the renewable energy resources in this region might allow 100% renewable power to be generated with 70% dispatchability. This matches dispatchability estimates derived from AEMO's 2024 Integrated System Plan for the National Electricity Market.

Carpenter Rocks is close to a wind farm complex, Bonney Lakes stages 1, 2 & 3, which is rated at 278.5 MW. AEMO data from the Bonney Lakes complex was used to represent the wind power data, and solar exposure measurements were obtained from the Pelican Point, BoM station 026111. The low power duration for solar diurnal variability was set at 20 hours, and a capacity factor of 0.15 was used for the rooftop solar PV calculations (Graham, 2022). The solar and wind energy resources were screened for artefactual loss of power events. Wave power values were taken for a period of six years from the Australian Wave Energy Atlas (Hemer et al., 2017 and 2018b), and a power matrix supplied by Wave Swell Energy was used to estimate the wave power generation time series. A wave height cutout value of 5.5 metres was used to assess its impact on the minimum energy storage requirements. Table 4.2 describes the wave energy environment at the site, and Table 4.3 summarises the generated power statistics.

Table 4.2. Wave characteristics at Carpenter Rocks wave energy converter study site.

Latitude	37.92510	° S
Longitude	140.38700	° E
Depth	10	m
Offshore	1.24	km
Max Hs	6.26	m
Min Hs	0.81	m
Avg Hs	2.84	m
Max Tp	17.64	s
Min Tp	6.12	s
Avg Tp	12.06	s
Nulls	31.00	
Mean Energy flux	61	kW/m

Table 4.3. Single WEC wave power generation at Carpenter Rocks wave energy converter study site.

	Average power (MW)	Maximum power (MW)	Minimum power (MW)	Capacity factor	Dispatchability	Annual Energy Generated (MWh/yr.)
2016	0.35	0.70	0.07	0.50	0.20	3065
2017	0.32	0.68	0.02	0.48	0.08	2823
2018	0.34	0.67	0.04	0.50	0.11	2944
2019	0.34	0.70	0.05	0.49	0.15	3025
2020	0.32	0.72	0.05	0.44	0.14	2773
Average	0.33	0.69	0.05	0.48	0.14	2926

Performance

Figure 4.16 shows a probability chart for three power supply systems: a standalone wind farm, solar PV arrays, and a combined wind, solar, and wave farm. The loss of load probabilities for each can be estimated from the chart by selecting the required normalised load from the generated power axis and adding the probabilities for the bars to the left of the selected load. Figure 4.17 shows a similar probability chart for combined wind, wave, and solar power systems.

Hypothetical loss of load probabilities (LoLP) were calculated (Table 4.4) for the renewable energy configurations in Figure 4.16 and Figure 4.17.

Data was acquired from 2015 to 2021 for a dispatchability threshold of 0.6. That is, for a loss of load greater than 60%.

Table 4.4. Loss of load probabilities for hypothetical renewable energy configurations at Carpenter Rocks.

Wind	32%
Solar	18%
Wave	16%
Wind and Solar	14%
Wave, Wind and Solar (2:1:1)	6%
Wave, Wind, Solar (2:1:1) and Battery	0%

Figure 4.16. Impact of wave energy on generated power probability distribution for single and combined renewable energy resources.

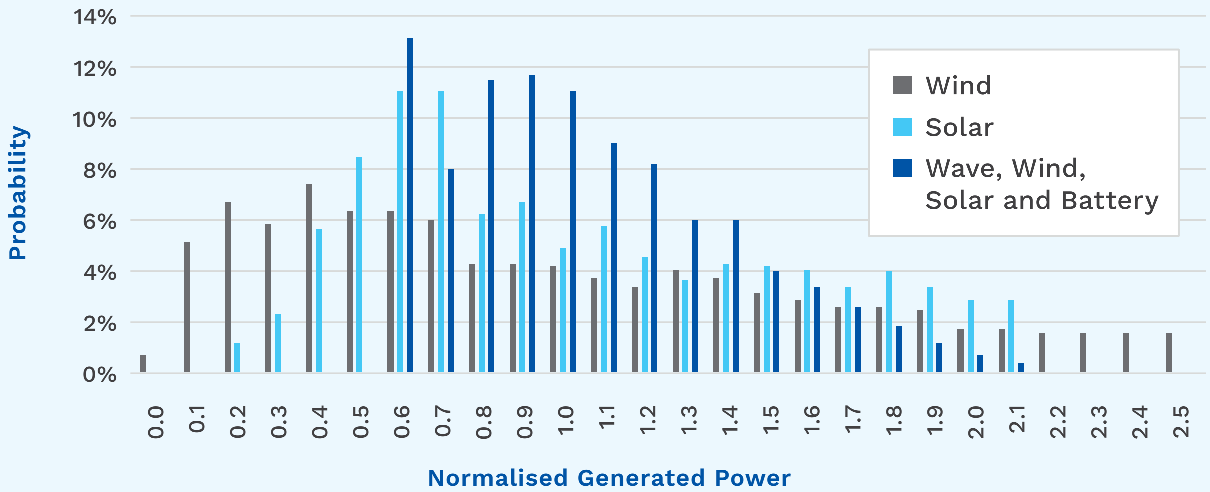
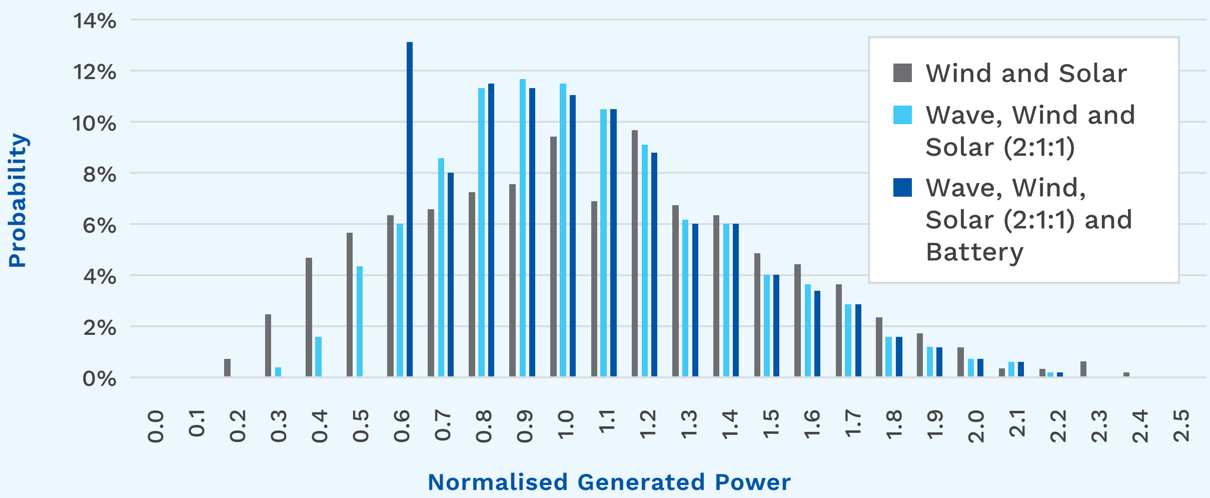


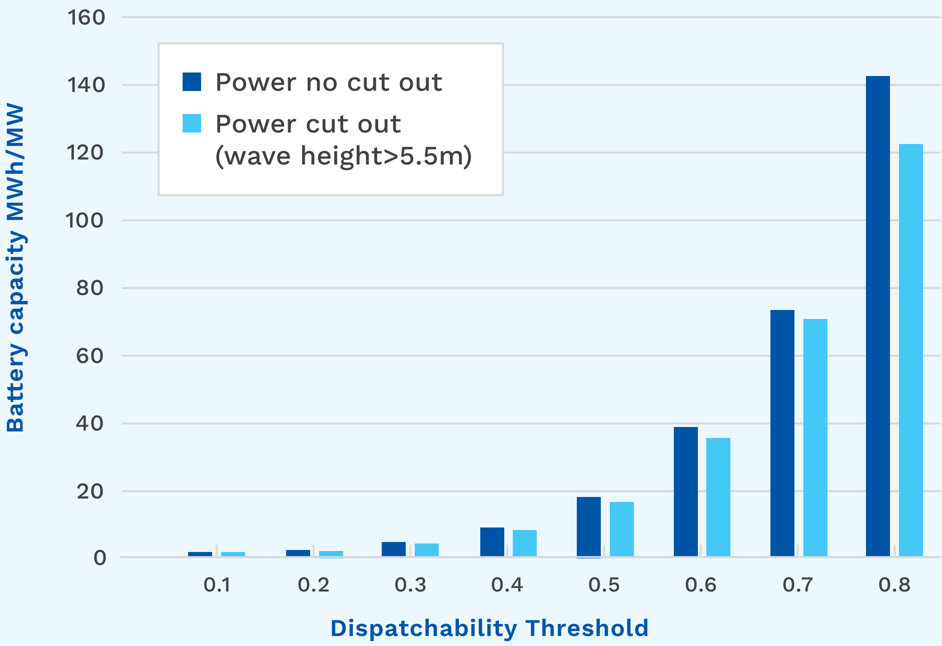
Figure 4.17. Impact of wave energy on generated power probability distribution for combined renewable energy resources.



The impact of wave height cut-outs on dispatchability

The largest significant wave height at Carpenter Rocks, over a six-year period, was 6.3 m. Power limiting, power cut-outs, and load shedding may be used to manage the impact of such waves. Power cut-outs on a stand-alone renewable generator would increase the intermittency issue and the required battery capacity. In this case study, the correlation between wind speed and wave height is high so that the loss of load probability from cutouts and the need for battery capacity reduces rather than increases as shown in Figure 4.18. At 70% dispatchability, the cutouts reduce the required battery capacity by 7%. This is because the system rated power had to be increased by 4% to maintain the average power, which is otherwise reduced by cutouts occurring 4.7% of the time.

Figure 4.18. The low impact of the power cut out setting on required battery capacity.



Dispatchable renewable energy for local and regional communities

There are already 15 MW of rooftop solar PV systems installed in the region, and Lake Bonney currently has a capacity of 278.5 MW wind turbine power and a 25 MW / 52 MWh energy storage system. By adding wave power to similar resources, it would be hypothetically possible to supply dispatchable power to 100 homes with rooftop solar power in Carpenter Rocks (Table 4.5), or 2000 homes with solar power in the surrounding region (Table 4.6).

Table 4.5. Carpenter Rocks community: 70% dispatchable power.

Residences (ABS)	100
Rated wave energy converter power (MW)	0.15
Rated solar PV power (MW)	0.18
Rated wind turbine power (MW)	0.10
Total rated power (MW)	0.42
Total average power (MW)	0.10
Energy storage without wind or wave energy (MWh)	59.38
Energy storage with wave, wind and solar energy (MWh)	7.65

Table 4.6. Surrounding region communities: 70% dispatchable power.

Residences (ABS)	2000
Rated wave energy converter power (MW)	2.98
Rated solar PV power (MW)	3.52
Rated wind turbine power (MW)	2.00
Total rated power (MW)	8.50
Total average power (MW)	2.08
Energy storage without wind or wave energy (MWh)	531
Energy storage with wave, wind and solar energy (MWh)	153

The tables assume an average daily electricity consumption of 25 kWh per household. They show how adding a 0.15 MW wave energy converter and a 0.1 MW / 7.1 MWh battery could work with existing wind and solar resources to provide 100 houses in Carpenter Rocks with locally generated 100% renewable and 70% dispatchability power. Using solar PV alone, the energy storage requirement increases to 57.4 MWh.

Likewise, adding a 2.98 MW wave energy converter with 2 MW / 142 MWh of energy storage could supply 2000 houses in the surrounding region with locally generated 100% renewable and 70% dispatchable power at 70% of the average power generated. Using wind turbines alone, the energy storage requirement increases to 534 MWh.

4.1.12. Summary

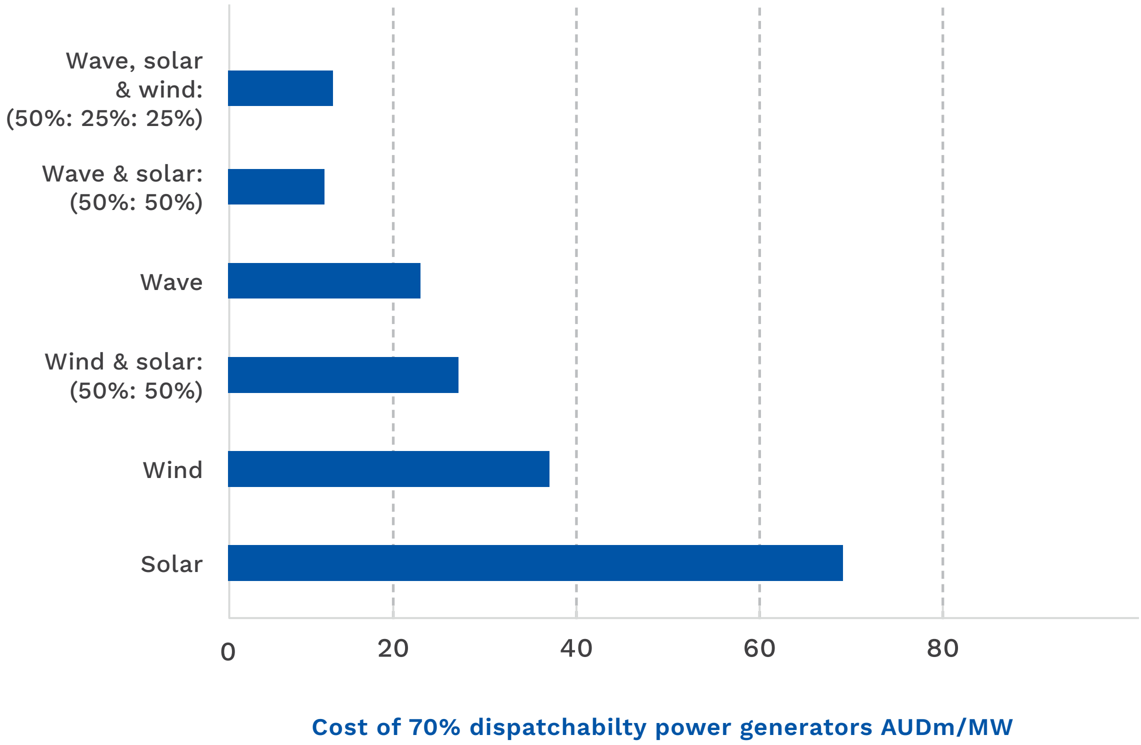
Including wave energy with wind and solar at Carpenter Rocks in South Australia reduced the required energy storage capacity and cost by factors of 7.8 compared to solar power by itself, and factors of 3.5 compared to wind power by itself, while achieving dispatchable (guaranteed) power levels at 70% of the average power generated. This is at a similar level of dispatchability as the NEM grid.

At Carpenter Rocks, hypothetical wave, wind and solar renewable generators connected via a local grid were a factor of two more effective in reducing the energy storage capacity and cost required for dispatchabilities of 70% than solar connected to onshore wind, a factor of three more effective than wind operating by itself and a factor of six more effective than rooftop solar operating by itself.

Introducing wave energy into a state or national grid system may significantly reduce the cost of energy storage required to maintain acceptable levels of dispatchability. Further work needs to be done to confirm and estimate the potential savings. A similar scenario evaluated for the United Kingdom by the EVOLVE Consortium suggests the potential for up to 30% less installed capacity and 50% less storage to meet demand, with total CapEx and operational costs reduced by 20%. Potential annual cost savings of AUD2.76 billion per 10 gigawatt of wave power installed were estimated.

Energy storage costs dominate the evaluations above. Battery costs are projected to fall by a factor of about three, and to reach parity with pumped hydro. The analysis used in all the examples is for the lowest cost of energy storage. Figure 4.19 shows that wave power's competitive advantage remains for all wave, wind and solar combinations by 2050.

Figure 4.19. 2050 cost of renewable energy power generators with 70% dispatchability. Costs are given per megawatt average power.



4.2. Coastal Protection

4.2.1. Coastal Protection: Principles

There are many circumstances in which wave energy is damaging to natural or human assets: beaches, dunes, and cliffs; or coastal housing, roads, railways and ports (Figure 4.20). Man-made Australian coastal assets were valued at AUD226 billion in 2011 (Commonwealth of Australia 2011) with over AUD25 billion thought to be at substantial risk in 2022 (Ellis and Bajracharya 2023). The prevention or mitigation of wave-induced damage, due to coastal flooding and erosion, as well as other coastal natural hazards, is termed coastal protection. Coastal protection has been forecast to cost up to USD71 billion per annum globally by 2100 (Hinkel et al. 2014) owing to sea-level rise alone.

Figure 4.20. Sign on the sheltered side of the breakwater protecting the harbour at Warrnambool, Victoria. The concrete structure was completed in 1890. Despite being about 8 m high, it can be overtopped by large waves. *Photograph by Richard Manasseh.*

Wave Energy Converters (WECs), by definition, must remove energy from waves in order to convert this energy to useful forms such as electricity. Therefore, once waves have passed an operating wave-energy converter, they must have lost energy.

WECs could serve a dual purpose: both power generation and coastal protection.

This opportunity, which is unique to WECs, has been remarked upon in prior reviews (e.g. Falcão 2010; Manasseh et al. 2017; Hemer et al. 2018a; Clemente, Rosa-Santos, and Taveira-Pinto 2021). Furthermore, in recent years, many researchers have undertaken detailed studies on the coastal-protection benefits of arrays (i.e. 'farms') of WECs (e.g. Flocard, Simmons, and Splinter 2018; Rodriguez-Delgado, Bergillos, and Iglesias 2019; Battisti, Giorgi, and Fernandez 2024) and have begun optimising the layouts of WEC arrays for coastal protection (Cui et al. 2024).

Coastal-protection infrastructure has been constructed for millennia by many littoral and seafaring cultures. Originally, such defences were simple earth, wood and stone walls; today coastal protection is an established engineering discipline in its own right, with many sophisticated designs including breakwaters and artificial reefs that may be submerged, groynes controlling sand movement, and natural strategies such as re-introduced mangroves, all backed by advanced coastal-engineering simulation software and long-established physical scale-modelling methods. However, with notable major (and very expensive) exceptions such as the Thames Barrier and Venice Flood Barrier, traditional coastal protection consists of immovable structures, which might very loosely be classed as 'walls'. A wall in the sea inevitably and permanently alters the marine ecosystem shorewards of the wall, which may depend on wave-generated drifts and currents (Fulton and Bellwood 2005). Furthermore, interventions protecting a critical location on the coast may cause problems to emerge further down the coast, requiring further interventions in the future (Ranasinghe, Turner, and Symonds 2006; Phillips et al. 2017). If sea walls are thought impractical or counter-productive in a beach-erosion context, there may be no option but to pump or truck sand from one location to another, a procedure euphemistically termed beach nourishment and in use in several locations around Australia (Figure 4.21).

Figure 4.21. Main Beach at Noosa Heads, Queensland, was almost eliminated during storms in the winter of 2019, revealing the underlying rubble defences built in 1969 to protect what is now some of Australia's most expensive real estate. At this location, natural wave-driven processes can gradually cause the beach to build up again. As in previous such episodes, the approximately 1.3 km long beach was restored by sand pumping and other mechanical measures, estimated to cost AUD500k-750k per annum (Noosa Council, 2018). *Photograph by Richard Manasseh.*

Most wave-energy converters resonate, that is they can be tuned to move in time with a wave. In doing this they take advantage of the antenna effect (mentioned in Chapter 2) to extract power from a width of wave crest (the capture width) that depends only on the wavelength (Budal 1977). The capture width can be much larger than the physical size of the machine. To operate at maximum efficiency, WECs in an array must not be too close, and should be spaced an ideal distance apart. Presume that a WEC array is tuned to a problematic wavelength, for example, a wavelength that in a particular location may be associated with gradual coastal erosion. This array could, in principle, remove energy from the problematic wavelength while still permitting other waves, drifts, currents and associated marine life to continue to pass between them, analogously to a camera-lens filter that only blocks a specific colour. It was noted in section 4.1 that most WEC designs enter 'survivability mode' during extreme-weather events, when they do not generate electricity. Some designs thus become quite transparent to extreme waves while other designs, notably those Oscillating Water Column (OWC) designs that are fixed to the seabed, may, by closing a simple valve, close off the moving parts from extreme conditions, but continue to resonate and hence continue to modify the wave field appreciably.

The only continuously-operating wave-power plant in the world at present, the Mutriku facility noted in section 4.1 (Figure 4.22), was originally designed solely for coastal protection, not power generation (Torre-Enciso, Marqués, and Marina 2012). It was intended to be a conventional breakwater, based on hollow concrete caissons that are typically filled with rubble. An intervention late in the design process by the provincial-government energy authority led to modifications of 16 of the caissons that turned them into OWC-type WECs. The development was not the most efficient or sophisticated, nor perfectly tuned for the location, but it was well-established, simple and cost-effective - and it is still working, 13 years later.

Incorporation of wave energy converters in existing or new pieces of traditional coastal infrastructure along the lines of the Mutriku plant is one way in which wave energy can feature in coastal protection schemes. Such hybrids may lead to positive outcomes through the revenue brought in by the wave energy converters and possible reductions in loads on the infrastructure due to operation of the wave energy system. However, this approach is built on standard coastal-protection infrastructure, so the wave-energy converters do not add significant coastal-protection benefits. Dedicated wave-energy arrays designed with the dual purpose of coastal protection and power generation are fundamentally new. This latter opportunity is considered in the remainder of this section.

Figure 4.22. The world's only continuously operating grid-connected wave-power plant at Mutriku, Basque Country, Spain, is the longest-lived in the world and the one with the most hours of operation.
(Image courtesy of www.bimep.eus).

4.2.2. Design procedure for coastal protection with WECs

A nine-step procedure is recommended for assessing and designing coastal protection using WECs: measure; calculate; select; layout; cost; finance; revenue; benefit; and decide. These steps should be seen as specific to the novel application of WECs for coastal protection, and are in addition to the general environmental, social and cultural recommendations discussed in Chapter 6, which continue to be applicable to these cases. Further, these steps are presented sequentially but, as in all design, will undoubtedly require iteration in practice.

Step 1: Measurement programmes for oceanographic and geomorphological data

Both oceanographic data (wave conditions) and beach-morphology data are required as a function of time. That is because in many locations, it is not a simple matter of waves steadily removing sand from a beach at a constant rate (Figure 4.23).

Figure 4.23. Rapidly-eroding dunes in Geraldton, Western Australia, July 2024, showing a toppled fence-post. Between 2021 and 2024, the beach eroded approximately 70 m inland, requiring the demolition in June 2024 of a marine-rescue building. However, in 1942, the sea was actually 50 m further inland than in 2024. Land advanced from 1965 to 1988, retreated to 1997, and advanced to 2007. (City of Greater Geraldton, 2024). *Photograph by Richard Manasseh, with thanks to Wade Greenaway, Mid-West Ports Authority.*

An 'eroding beach' may be a complex and dynamic situation in which the beach takes several 'steps forward' at some times, but several 'steps back' at other times; in crude terms, if the number of steps backwards tends to exceed the steps forwards, the beach is on average retreating. The number of positive and negative steps may be almost, but not quite, equal. Furthermore, considering multi-year climatic phenomena such as the El-Niño-La-Niña and Indian Ocean Dipole oscillations, one could imagine examining data over longer timescales than a year before trends become clear; even then, some trends might reverse over decades. Thus a 'step' might be as brief as a stormy winter's day, or as long as a year during a climatic oscillation.

Since waves may be responsible for depositing sand on the beach (accretion) as well as removing sand (erosion), it would be important for a WEC array to reduce the heights of waves associated with erosion, but minimally affect the heights of waves associated with accretion. A poorly-designed WEC array could conceivably achieve the opposite effect to that intended.

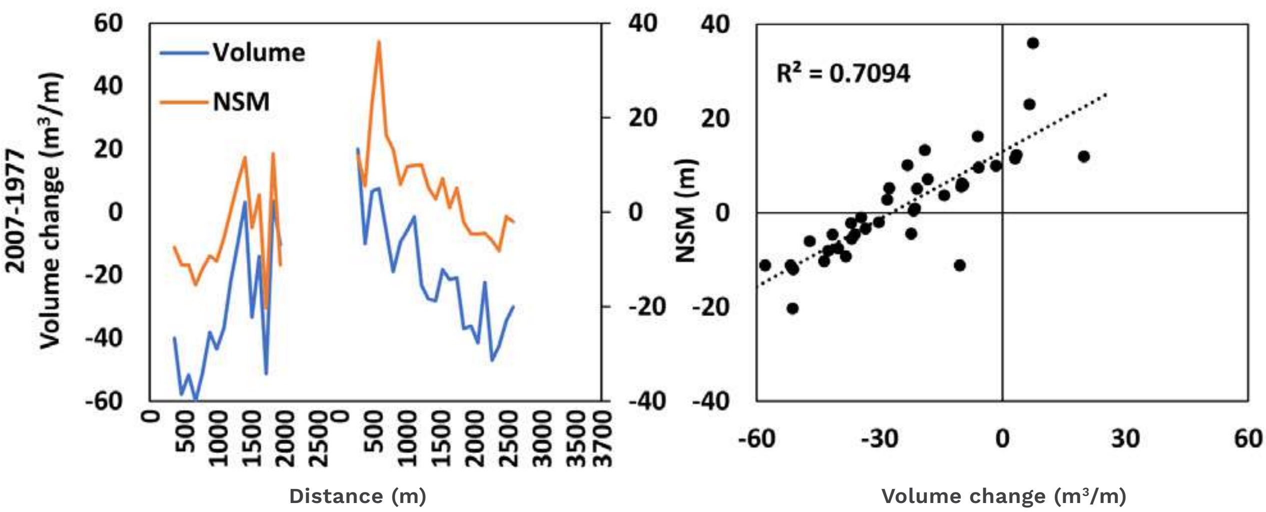
This complexity, and the importance of understanding impacts on both waves and wave-driven flows and their effect on sediment transport has been remarked on in reviews of traditional coastal structures and WECs (e.g. Ranasinghe and Turner, 2006, da Silva et al, 2022).

Oceanographic data is best obtained from a dedicated wave buoy (Figure 4.24) at the location of interest. However, if a buoy has not been deployed, it is likely that reasonable data could be obtained from historical meteorological data, fed through standard wave-prediction models already shown to produce very good comparisons with buoy data (e.g. Liu et al. 2022). The models also allow longer records to be used. Buoy data from the Coastal Wave Buoys program run by the Integrated Marine Observing System (IMOS) could be useful if the site is near an already-operating wave buoy.

Figure 4.24. Wave buoys operated by Deakin University. *Photograph by Richard Manasseh, with thanks to Daniel Ierodiaconnou, Deakin University.*

Historical information on shoreline locations is often available, for example, in old maps, reports or photographs, and with significant effort, self-consistent data can be extracted (e.g. Figure 4.25). However, to appropriately engineer a WEC array for the dual purpose of coastal protection and electricity generation, more precise data on the beach morphology are required. Storms lasting less than a day can be responsible for large alterations in beach morphology. Thus, the data required are ideally on a daily basis.

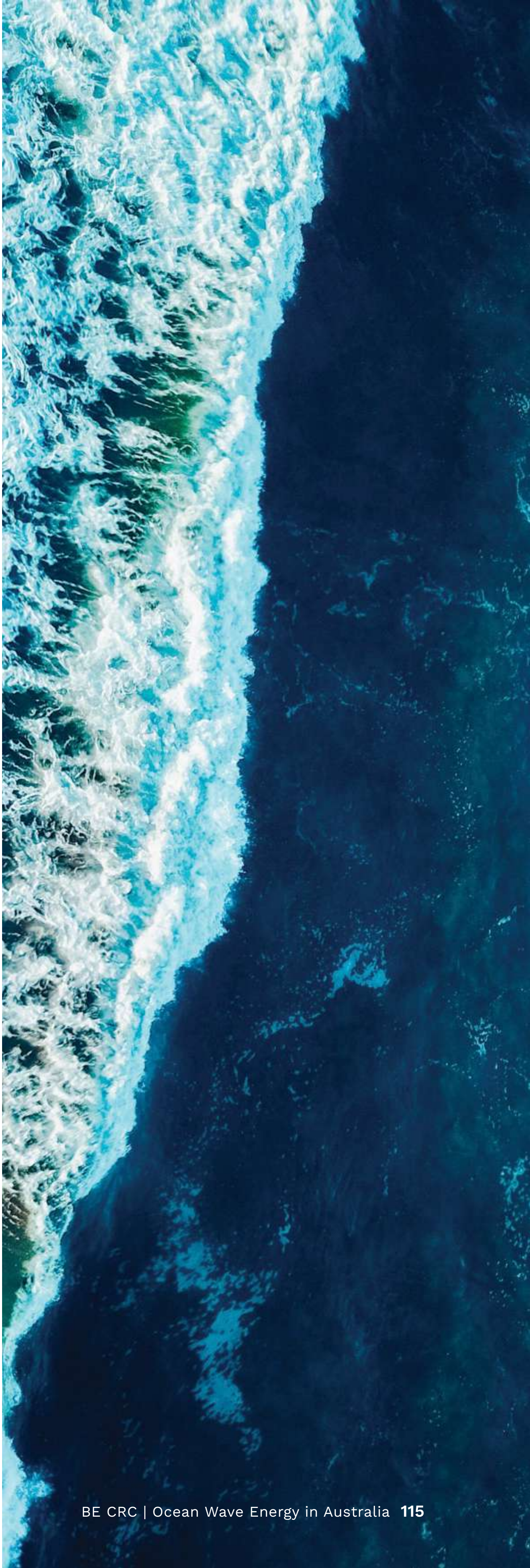
Figure 4.25. Comparison of the change in volume of sand on the beach with the movement of the shoreline (Net Shoreline Movement; NSM), estimated from aerial photographs taken from the 1970s through to modern drone mapping techniques. Left-hand panel shows how these two measures are related at various distances along the coast; right-hand panel demonstrates self-consistency. *From Carvalho et al (2021). Reprinted with permission.*



WEC development is costly and to be fit for purpose their design requires the installation of professional scientific instruments (e.g. Drummond et al. 2021) to monitor the beach morphology. Nevertheless, historical data over longer periods should also be used. These could be sourced from the existing 'citizen science' efforts in which local residents have been trained to fly drones equipped with photogrammetry equipment, calibrated to known, geo-referenced sand-height points (Ierodiaconou et al. 2022). Earlier programmes involved regular community measurements of sand height on posts, and in other regions, 'citizen science' programmes involve mobile-phone images taken from dedicated phone-holding cradles (Harley et al. 2019).

Provided the oceanographic and geomorphological data are available, have a suitable temporal resolution and span a sufficient number of years to genuinely represent the situation, the next step is to undertake a correlation between these two classes of data. This should firstly identify wave frequencies corresponding to 'erosive' waves whose heights should be reduced, and wave frequencies corresponding to 'accretional' waves whose heights should be maintained. Caution should be exercised in making such interpretations, since it is not only the wave height but also the gradient in wave height with distance that generates the currents responsible for sand transport (Cui et al. 2024), so the calculations of Step 1 should be part of an iteration with Step 4. This first step would create an 'erosion-accretion wave spectrum', in which the rate of sand-height change (in mm per day, for example) is a function of wave height and wave frequency.

If this analysis identifies a wave-frequency band associated with undesirable erosion (or other undesirable coastal impacts), it is possible to proceed to Step 2. If such a frequency band cannot be identified, it may be best to consider other coastal-protection or coastal-adaptation strategies.



Step 2: Calculation of desired WEC operating parameters

A first-order analysis would assume an array of WECs behaves as if it were composed of machines that behaved independently. The machines could be assumed to be point absorbers, defined for the purposes of this section as being machines much smaller than the wavelengths they are designed to affect (Manasseh et al., 2017). The array's effect on the waves can then be approximated as that of a number of individual, linear oscillators, each withdrawing power from waves over the 'capture width' of the machine. Depending on the class of WEC selected following Step 3 below, the presumption of point-absorber behaviour may need to be revisited in a second iteration.

It is common in WEC literature to refer to a machine's 'power matrix' (e.g. Babarit et al. 2012) which takes into account not only the frequency response of the machine but also its cut-off at higher input wave heights and possibly a cut-in at very low wave heights. However, these details are a function of WEC engineering rather than of the machine's fundamental natural frequency and damping, which are the primary factors of relevance to this Step. Considering only WEC natural frequency and damping for power generation leads to predictions of different machine parameters in different regions of the Australian coastline (Illesinghe et al. 2017). Thus, considering only these two parameters should be the first stage for a coastal-protection analysis as well. The fundamental WEC operating parameters need to be determined such that they will achieve the desired alteration to the wave climate at the shore. It may be that the estimated reduction in erosion and the estimated reduction in accretion are calculated to be almost the same, apparently rendering the WEC array almost useless from the perspective of actively controlling the shoreline, or, in other words, little different to a fixed wall. However, the part of the beach that is eroding cannot be accreting simultaneously; if it were, that beach would not be at risk. 'Winter-like' erosion events and 'summer-like' accretion events do not occur simultaneously. Thus, if the WEC array is estimated to reduce beneficial accretion as well as reducing detrimental erosion, operation can be restricted to those conditions when erosion occurs. This in turn implies a class of WEC that can readily be 'turned off', or at least 'turned down' in terms of the machine's effect on waves.

Some WECs are designed to be 'turned off' by sinking them temporarily to the seabed. Of course, this behaviour is intended to assist survivability in storms as noted in section 4.1. However, for coastal protection, operation in larger waves associated with erosion is desirable; the machines should be robust enough to require 'turning off' only to survive the most extreme events, and, possibly, to preclude attenuating waves associated with accretion. Regarding 'turning down' the machines, point-absorber WECs, if correctly understood to be much smaller than the wavelength (Manasseh et al. 2017), should have an influence on the wave dominated by the extent to which power is withdrawn as electricity, which is controllable.

Step 3: Selection of preferred class of WEC

Having selected the WEC operating parameters, the broad class of machine can be considered. The apparent variety of WEC designs is so great that there are several methods of classifying them. It was suggested by Manasseh et al. (2017) that the first stage in selecting a WEC design for a particular proposal is to determine which classification system is appropriate. For example, what Manasseh et al. (2017) called the 'Morphological' Classification (MC) groups WEC concepts according to what appears to be their mechanism, rather like the original way of classifying animals in a zoo according to their appearance rather than their underlying genetics. This may be useful where details of deployment and maintenance as well as visual appearance are paramount. Two alternative classifications, the 'Directional' and 'Operational' Classifications, organise WECs according to their influence on waves (DC), or according to if and how they achieve resonance (OC), respectively. Table 2 of Manasseh et al. (2017) suggests what classification system to use for various applications, proposing the DC and to a lesser extent the OC for two general forms of coastal protection: protecting industrial regions, or tourist regions.

The next stage would be to select the most appropriate technology type. Table 3 in Manasseh et al. (2017) suggests the most appropriate classes of WEC for coastal protection in tourist regions and in industrial regions.

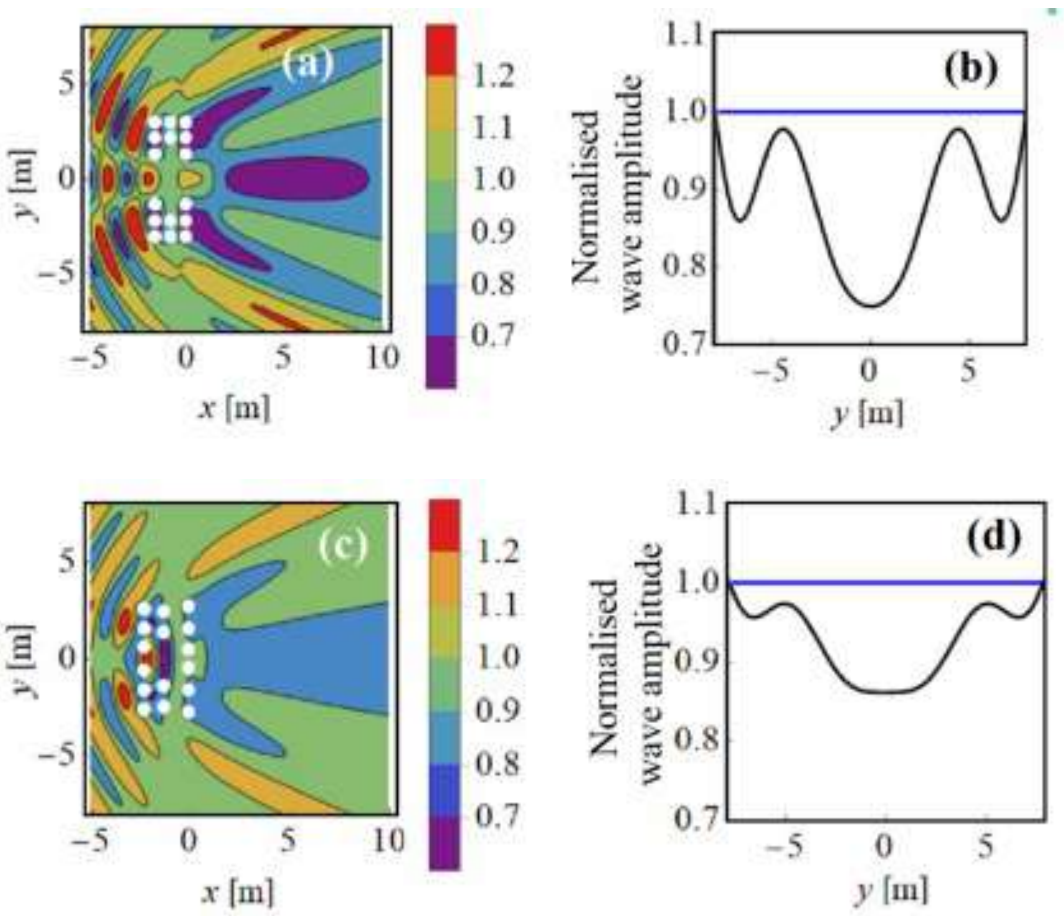
The depth of water is the next consideration. For a bottom-mounted rigid-pendulum class of WEC, the depth of water must be close to the length of the pendulum, a length that is related to the wave frequency to be affected. Therefore, unless the seabed has a very shallow slope, the WEC array must be located a fixed distance from shore that cannot be varied to suit other considerations. For a heaving buoy, the amplitude of motion when resonating, plus the device draft, cannot exceed the depth. For an oscillating water column, water deeper than the resonant length implies the WEC must be floating.

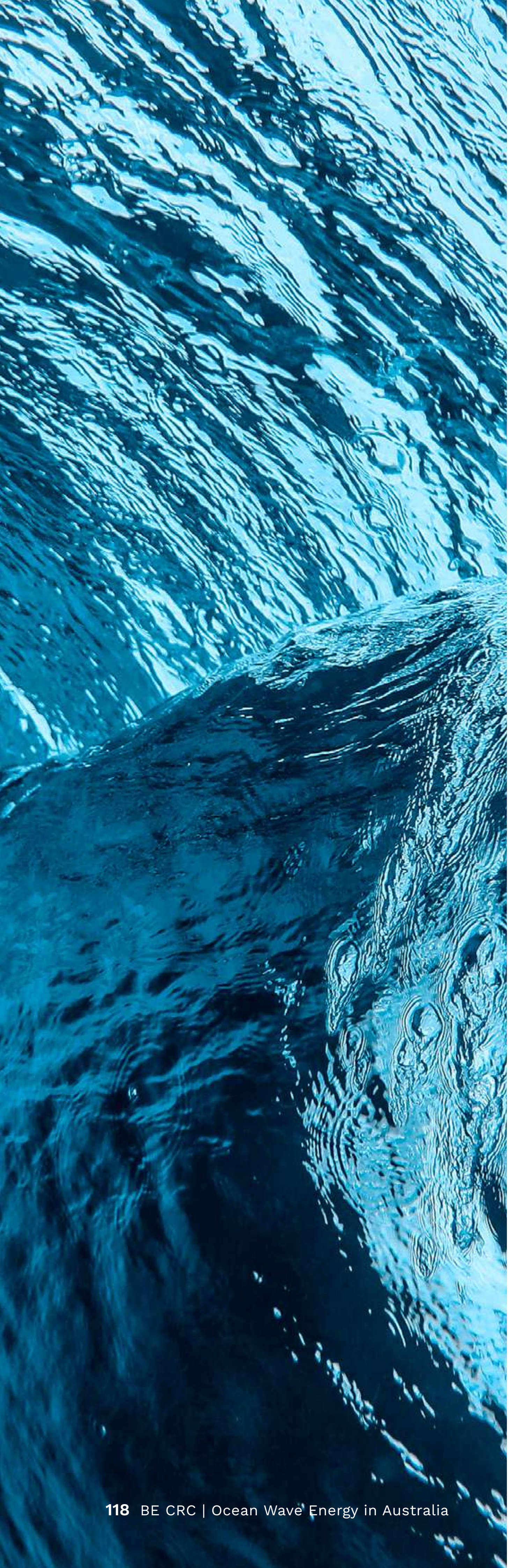
A floating, moored device versus a bottom-fixed device has a greater ease of installation and maintenance, but also faces a greater risk of damage during storms. As discussed in Step 2 above, this risk might be ameliorated by entering 'survivability mode' in which the machine sinks temporarily to the seabed, but this strategy also means the erosive damage of the worst storms cannot be mitigated.

Step 4: Optimising the array layout for the specific location

Having made a preliminary selection of the desired WEC technology, the next stage would be designing the layout of an array of many machines that achieves the desired reduction of wave height of the problematic wave frequencies. Array interactions, in theory and laboratory experiments, can lead to significantly more power generation than the same number of machines operating individually (Budal 1977, Manasseh et al. 2018). Similarly, it was shown by Cui et al. (2024) that there is an array-interaction benefit for coastal protection. A simplified mathematical model could achieve an array layout optimised for wave-height reduction, permitting order 10^6 combinations to be assessed in a reasonable time and the best identified. Care should be taken to ensure the optimum arrangement minimises longshore gradients in wave heights (e.g. Figure 4.26), since these are associated with currents causing sediment transport (Bowen 1969). Coastal engineering models incorporating WECs can be used to conduct detailed assessments of designs (e.g. David et al, 2022).

Figure 4.26. Layouts of 16 WECs intended to: (a)-(b) minimise wave height; (c)-(d) minimise longshore gradients in wave 'radiation stress', usually associated with sand transport. In (a) and (c), waves travel from left to right, WEC locations are white dots, wave amplitudes relative to the original state (amplitude 1.0) are in colour scale. In (b) and (d), amplitudes of waves arriving at the right-hand boundary model effect at shoreline. Calculated using methods detailed in Cui et al. (2024) Distances are at a laboratory scale.





Step 5: Producing engineering-costing relations

At this stage, a generic class of WEC would have been chosen, but not a specific machine. The basic parameters determined in Step 2 define the physical size of the machine. There would also have been a first-pass determination of the number of machines and their layout to achieve a desired stabilisation of the beach.

For all classes of machine other than those made of concrete (so far, only the oscillating water-column class has been made of concrete), it is likely the largest machine parts (generally the buoyant parts) would be made using standard shipbuilding techniques, for which generic costing formulae and data obtained from some key jurisdictions are publicly available. Input-material costs, such as marine-grade steel costs, are known. Other relevant costs, such as marine-grade steel pipes and cables, generators, power electronics, machinery, and undersea cabling, are also publicly available. Costs of heavy-lift ships that can transport multiple devices (depending on their size and weight) from the shipyard or final-assembly port to the deployment site are also publicly available. Installation costs, and the number and salaries of engineering-design and operational staff can all be estimated from openly-available information. For concrete devices, local costing for the large parts (which form the hollow chambers) is required, since it may be necessary to cast the parts locally.

Costings should use relationships that allow the cost to be recalculated as the number of WECs in the array is varied.

Any such costings would have to be preliminary, since decisions on, for example, whether machines would operate only at night are yet to be made; such decisions could have a large effect on the number of machines required.

Local manufacturing may potentially provide considerable tangible and intangible benefits. The cost of local manufacturing may not be as readily available as the generic global data. Nevertheless, global data would provide a first-pass estimate. It is also likely that local manufacturing costs would only be known as part of a commercial-in-confidence negotiation between the particular wave-energy developer tendering to undertake the development and the local manufacturer.

Step 6: Producing finance-costing relations

The cost of financing the development should be added to the engineering cost. This may involve debt or equity financing.

Step 7: Producing revenue relations

If machines cannot be tuned at the design stage (Step 2) to only resonate at the erosive wave frequencies and not the accretive frequencies, turning WECs off during accretive wave events may result in a lower electricity output compared to that if power production were the only aim. Furthermore, as noted earlier, to maintain the complete aesthetic of the beach environment for tourists, as well as maintaining unadulterated wave heights for surfers, operation may be restricted to night-time hours. This may in turn imply a greater number of machines is required for economic viability.

Step 8: Determining community financial benefits

Alongside the development of generic and variable costings, the community must be surveyed to determine their priorities. As noted earlier, owing to the manifold ramifications of a coastal-protection project, there are different categories of stakeholders, all of whom might benefit from a development, but would not necessarily benefit equivalently. An example of a decision that should come from the community is on which hours of the day a coastal-protection WEC array should run.

A further, and important financial benefit is property values and associated insurance costs. Publicly-available property data and standard hedonic pricing models (e.g. Fraser and Spencer 1998) permit such estimates to be made.

The community would itself need to be informed by data on the tourist revenue, information on the local sub-sectors of the economy to which this revenue accrues, and estimates of the value placed by tourists on assets such as the beach, versus other attractions. Revenue data are routinely available to local governments, while contactless payment systems provide a high level of granularity.

The outcome of these community investigations would permit iterative steps in which the number of WECs as well as operational conditions are varied. The layout optimisation procedure noted in Step 4 should be re-run to maximise the net benefit minus cost, including not just the coastal-protection benefit but also the revenue-generation benefit for various operational scenarios. Considering all these factors, the method of Cui et al. (2024) could take one or more orders-of-magnitude longer time to calculate an optimum: many days instead of hours. However, utilising high-performance computing facilities and AI-training approaches means this is easily feasible. As in Cui et al. (2024), the top-few candidate array layouts and operation protocols could be checked with conventional mesh-based numerical models.

Step 9: Empowering community decision making

Once the optimum WEC development is calculated, its cost would be estimated, and its benefit would be estimated. It is possible that the benefit would be less than the cost. However, there remain intangible factors that are hard to quantify, such as the preservation of species habitats, and any deficit of quantified benefit versus cost may be presented to the community as the cost of retaining the intangibles. Community engagement according to the guidance in Chapter 6 would have been occurring throughout the project. Coastal protection projects justify 'empowered' community consultation (see Chapter 6.3.5), such that ultimate decision-making is done by the community, on a maximally-informed basis using the costs and benefits determined. If the decision is to proceed, a financial model can be put forward and tenders solicited for the development. Recalling that only the generic WEC class would have been specified, any successful tender submission would have more precise costings, which should replace those in the generic cost-benefit model. At this stage, final community consultation could occur, leading to a decision on whether or not to contract the development.

4.2.3. Coastal Protection: Case study of SW Victoria

Background

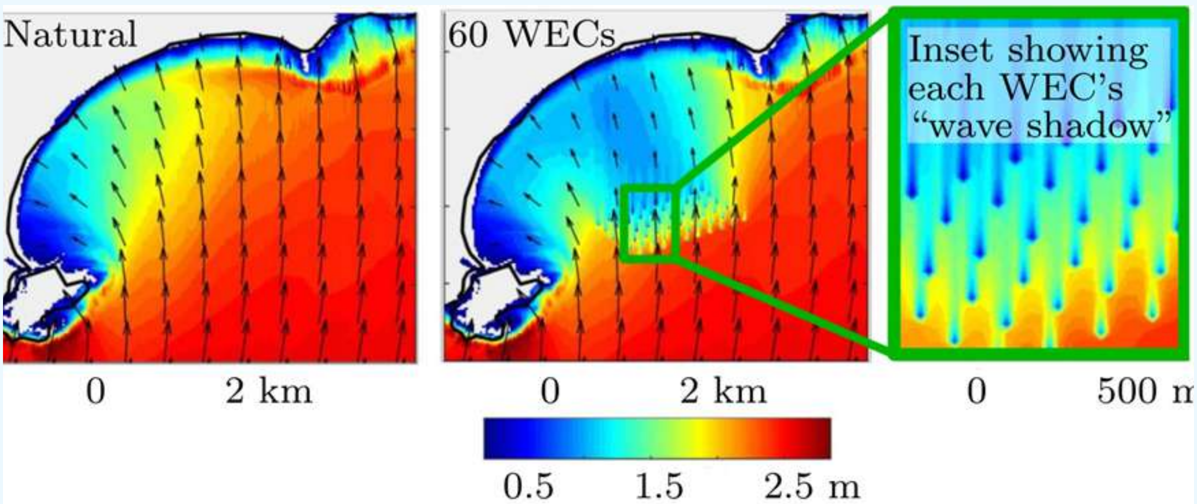
As detailed in Chapter 3, South-west Victoria has one of the best wave-energy resources in Australia, second only to the west coast of Tasmania (Behrens et al. 2012). Furthermore, SW Victoria has outstanding electricity infrastructure supplying an aluminium smelter located at the only deep-water mainland port between Melbourne and Adelaide, serviced by an industrial workforce. There have been a number of wave-energy proposals and one major wave-energy trial in the region. SW Victoria also hosts many onshore wind farms as well as being a designated offshore-wind-prospecting region. Offshore natural gas is also extracted from the seabed and processed in the region.

SW Victoria also receives substantial tourism revenue, based on the outstanding natural beauty of its coastline. There are also beaches that are popular with summer visitors and with surfers year-round. The region hosts significant habitats, including for endangered maritime species. The coastal geomorphology and biology is interconnected with a human history tens of millennia old, aspects of which have been accorded UNESCO World Heritage status.

A beach-erosion scenario in SW Victoria

Depending on the local geology, sections of the SW Victorian coastline may feature high cliffs and bays penetrating far inland, engendering formations such as the Twelve Apostles, a single site receiving 2.8 million visitors annually (Thomson 2019). Other sections of the coastline may be subjected to a predominantly-eastwards longshore sediment transport, causing erosion and accretion (Short 2020; Sharp et al. 2022). However, longshore transport has been interrupted in places by engineered breakwaters, groynes and river-mouth training walls (Leach et al. 2021). Interruptions to natural sand transport has led to erosion that in some locations poses a hazard to domestic properties as well as to tourism income (e.g. Flocard et al. 2013; Short 2020). The possibility of managing one erosion hotspot in SW Victoria with the use of WECs was assessed by Flocard and Hoeke (2017) (Figure 4.27). This preliminary study showed that an array ('farm') of 60 WECs could reduce wave height during annual storms by 30%. A later study linked wave-height reductions to erosion rates (Flocard, Simmons, and Splinter 2018). However, these studies did not consider the array-interaction effects: the machines were treated as energy-absorbing reefs that did not interact.

Figure 4.27. Simulation of East Beach, Port Fairy, Victoria, showing reduction in wave height from an array of non-interacting wave-energy converters modelled as energy absorbing 'reefs'. Colours: significant wave height; arrows: wave direction. *Adapted from Flocard and Hoeke (2017).*



Recession of the shoreline poses a threat to houses and other infrastructure on and behind sand dunes (Flocard et al. 2013). To address this issue, actions already taken include the construction of rock revetments (sloping 'walls' made of boulders) and staggered fences on the sea faces of the dunes. These have been effective in preventing dune erosion (Figure 4.28), while sand continues to be removed from the beach that is exposed at low tide. The consequence is that in some locations the high tide now reaches the rock revetment on many days so that the beach effectively exists only during low-tide hours (e.g. Figure 4.29). Since beach-oriented tourism contributes to local economies, a contribution that can be valued financially in an Australian context (Prayaga 2017), the loss of usable beach may have a local economic impact. Furthermore, some properties protected by rock revetments are short-term rentals for tourists, while others are permanently-occupied homes.

Figure 4.28. A wave-energy dissipation structure (wall made of large stacked boulders) has prevented over 10 m of dune erosion at this location in SW Victoria. Buried in the dunes behind the wall is a 19th- and early-20th-century waste dump, the contents of which should not be released into the ocean. *Image: Google Maps, ©Airbus, CNES / Airbus,Maxar Technologies, Map data 2024.*

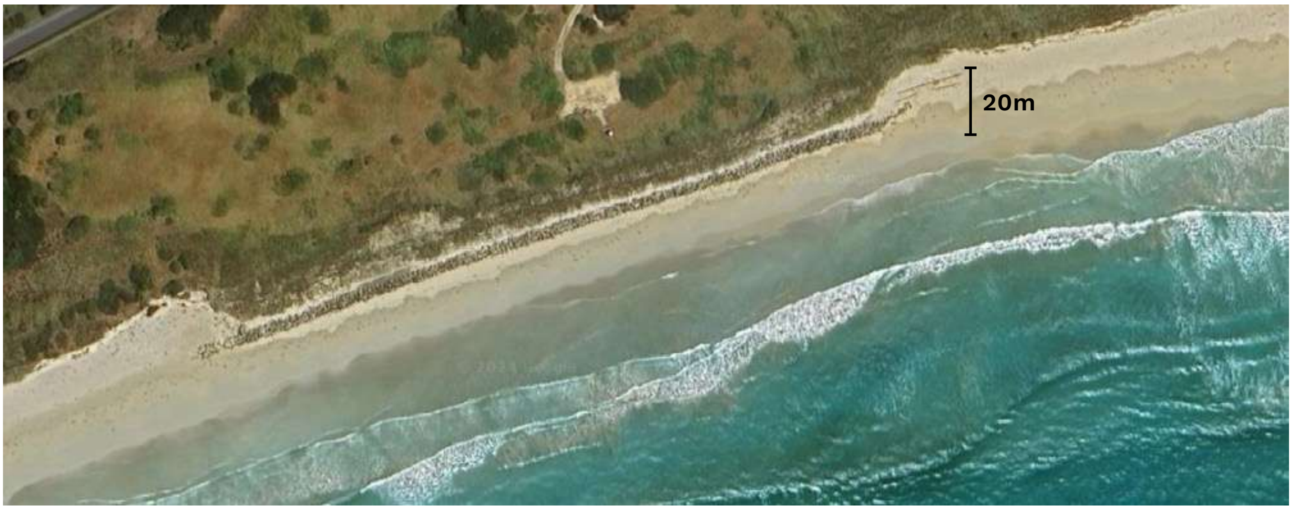


Figure 4.29. Erosion of unprotected dunes (foreground) compared to a housing zone protected by a rock revetment (middle ground). The unprotected shoreline has eroded about 8m. *Photograph by Richard Manasseh.*

An endangered seabird, the hooded plover (Figure 4.30), nests in the sand above the high-tide line (Maguire, Cullen, and Mead 2013), so its nesting sites may be eliminated in those locations where the high tide reaches a rock revetment.

Thus, quantifiable financial interests of stakeholders with varying criteria, as well as less-tangible biodiversity-asset values, need to be considered. Coastal-protection measures may provide both benefits and detriments. Furthermore, the balance between benefit and detriment may shift when consideration shifts from the near term to the long term.

Figure 4.30. Nesting sites of the hooded plover (Charadrius cucullatus) are threatened by dune erosion. *Photograph by Richard Manasseh.*

Case Study: Step 1

In some locations, certain wave conditions, such as those typically encountered during winter, are anecdotally associated with beach retreat, while other wave conditions, typically encountered in summer, are anecdotally associated with the same beach advancing.

As detailed in the SW Victoria case study under Chapter 3, there are several wave buoys deployed off this coast, providing data available for public download in which the wave statistics are provided as hourly averages. Depending on the make and model of buoy, raw data may be available on request from appropriate authorities at sub-one-second resolution.

Thus, as recommended in Step 1 the data required are on the wave conditions on a daily basis (or on a finer timescale), and also on the daily rate of change of sand height.

Data on the historical variations of the shoreline are generally available on an ad-hoc basis for many parts of SW Victoria (e.g. Flocard et al., 2013). In SW Victoria, established coastal-monitoring programmes (e.g. Ierodiaconou et al. 2022) may provide enough data for an initial assessment of the geomorphological changes with time recommended in Step 1. Wave buoy data is available and can be obtained at high temporal resolution if required. Nevertheless, as recommended in Step 1, for beaches in particular, daily sand profiles would be ideal. Thus, for a specific beach or other specific location, a coastal camera (Drummond et al. 2021) is recommended.

Case Study: Step 2

Problematic wave frequencies in SW Victoria may be very low indeed - less than 0.07 Hz (a period of more than 14 s) potentially implying very large machines.

The SW Victorian coast is particularly dynamic, with sand building up on some locations and eroding from others. Moreover, as noted above, local experience is consistent with very preliminary analyses that suggest that accretion (build-up) and erosion occur at different times. This implies, as noted in Step 2, that machines in SW Victoria may need to be of a type that can be routinely 'turned off', for example by sinking to the seabed in 'survivability mode', but here to permit wave conditions estimated to be environmentally beneficial to be unaffected. However, some of the most erosive or otherwise problematic wave conditions may occur during storms. As discussed in Step 2, 'survivability mode' may be inappropriate, because it is the storm waves - or at least near-storm conditions - that may cause the most significant erosion. Thus, a class and make of WEC that is robust enough to survive storms but also readily 'turned off' may be best for this coast.

Alternatively, during the worst storm conditions, the WEC could enter survivability mode, abandoning its coastal-protection duties, but emerging later to attack more modest erosive waves.

Case Study: Step 3

Following the guidelines in Table 2 of Manasseh et al. (2017), for coastal protection of a tourist region, the Directional Classification of WECs has high relevance, owing to the need to reduce wave heights at a specific location (the beach), while the Morphological Classification has medium relevance, owing to the need to keep the devices completely submerged for aesthetics. Then, following Table 3 of Manasseh et al. (2017), the best type of WEC defined under the Directional Classification is the Point Absorber and under the Morphological Classification is a Wave Activated Body. Therefore, a device that is small relative to the prevailing wavelength, absorbs waves in a preferred direction and is completely submerged would be ideal.

As noted in Step 3, devices rigidly fixed to the seabed, as opposed to anchored with cables, would be the most robust. Given the occurrence of very large storm waves in SW Victoria, this implies the rigid-pendulum class of WECs may be preferable to the heaving-buoy class.

Indeed, it was a rigid-pendulum machine that was installed as a trial in SW Victoria; as detailed in Chapter 3, it never operated, but it also remained submerged in place through winter storms, surviving several years over which it was never intended to last.

A pendulum class of WEC would need to be quite large to absorb significant energy at the very low frequencies associated with erosive storms. If it is a rigid pendulum, as noted in Step 3, it would have to be far enough out to sea that the water is deep enough, in turn implying a longer power cable and more expensive deployment and maintenance. Meanwhile, it may be too long to be optimal for electricity generation.

Case Study: Step 4

The generic approach outlined in Step 4, if applied in SW Victoria, needs further considerations. The seabed slope may be a factor, particularly if the layout that appears optimal comprises more than one shore-parallel row, and the depth varies significantly between rows. It will be important to first parameterise a proposed array layout so that it may be imported into a standard coastal-engineering model. The standard model can then be run to predict modifications to sediment transport.

Case Study: Step 5

As outlined in Step 5, once the WEC parameters, WEC class, and array layout are known, costings are possible based on generic manufacturing formulae and data. However, given the industrial capabilities and workforce in SW Victoria mentioned in this chapter and the case study in Chapter 6, a second-pass costing based on local manufacture, if possible without commitment, would be beneficial.

Case Study: Step 6

A commercial development, based purely on electricity generation, is clearly possible in SW Victoria and has been actively pursued. However, financing costs may be absent if the development occurs on a non-commercial basis, in which the benefits outlined in Step 8 below justify a community or public investment.

Case Study: Step 7

The development should generate electricity, and indeed would need to do so in order for the coastal-protection effect to be controlled to suit varying wave conditions. Sales of this electricity would provide revenue that would depend on the wholesale price of electricity. Electricity prices in Australia have been estimated over the 20-30-year lifetime of a typical WEC development (e.g. Hayward and Graham 2017). However, it would be important to consider the diurnal variation in electricity prices, both now and considering future societal changes. As noted earlier, it may be decided to operate the WEC array mostly during the night, but if this is done, operation should include morning and evening peak times when electricity prices in Victoria may be many times higher, and other renewable supplies such as solar photovoltaic power may be absent.

Case Study: Step 8

As discussed in Step 8, community-benefit considerations might lead to an operational schedule that preserves waves for tourism purposes. Surfing is not possible at night, and most other beach-oriented activities, including those that attract tourists and tourist revenue, are daytime-focused. However, in SW Victoria, daylight hours in midwinter are roughly six hours less than in midsummer, implying greater operational hours may be possible in winter. This would be doubly beneficial, in that greater erosion mitigation may be required from winter wave conditions, and more revenue would be obtained, since both morning and evening peak electricity prices occur while it is dark. This synergy between the need to generate more power in winter for both optimum complementarity with solar (as discussed in Section 4.1) and coastal protection is a valuable feature.

Case Study: Step 9

In SW Victoria, there would be an interwoven set of community, commercial and ecosystem benefits from any development. Therefore, all the aspects outlined in Step 9 would need to be presented to the community.

4.3. Co-location

4.3.1. Offshore wind industry

The combination of wave energy with offshore wind provides potential technical, economic and socioeconomic benefits for both technologies, in addition to the utility-scale power production, outlined in Section 4.1.

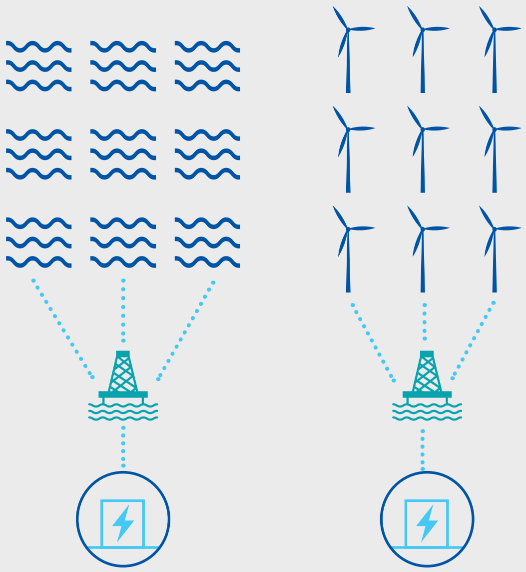
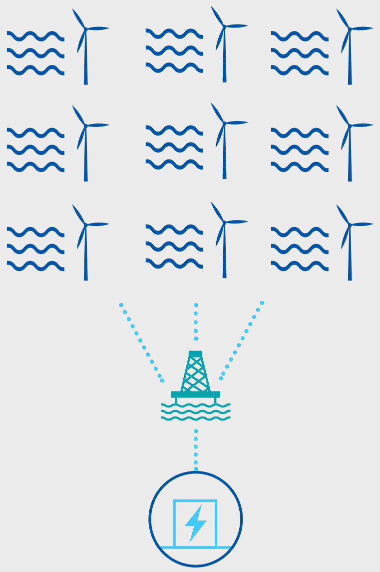
Size of the opportunity

Australia has the potential to generate up to 2,233 gigawatts (GW) of electricity from offshore wind, far in excess of the projected electricity demand (Briggs et al., 2021). After the announcement of offshore wind zones in Australia, 12 offshore wind projects have already been granted feasibility licences. At present, only Victoria has explicitly included offshore wind development in its Transmission Investment Framework, Renewable Energy and Storage Targets (AEMO, 2024b). The Victorian government's target is to achieve 2 GW of offshore wind energy generation by 2032, 4 GW by 2035 and 9 GW by 2040. Given the pace of offshore wind development and the number of projects proposed, it is estimated that Australia will have at least 23 GW of offshore wind capacity by 2040, representing an increase of AUD40 billion to the country's GDP, 0.2% annual economic growth and between 7,000 and 14,000 permanent jobs in the sector (PwC Australia, 2023).

International examples

Wave Energy Scotland (2022) conducted a study to investigate the potential of co-locating wave and offshore wind power technologies across various levels of co-location (or asset sharing) scenarios. The sharing opportunities included: space or deployment site, assets (substations, transmission, electrical equipment), development (consenting, site surveys, engineering phases), supply chain (modularity or economy of scales), installation (port usage, vessel mobilisation and utilisation), operation and maintenance activities, and ownership of the project. Overall, 17 different scenarios were designed and studied ranging from completely independent wind and wave energy projects that only share the deployment site, to the most integrated case when all assets are fully shared including a hybrid floating platform (refer to Figure 4.31).

Figure 4.31. Examples of co-located wind and wave asset-sharing scenarios

Least-integrated co-location scenario	Most-integrated co-location scenario
Baseline (Scenario 1 and 2) 	**Scenario 16** 
Assets: No sharing **Development:** No sharing **Supply chain:** No sharing **Installation:** No sharing **O&M:** No sharing **Ownership:** Independent projects	**Spatial: Same site** **Assets:** ∆ Integrated/Hybrid platform ∆ All transmissions ∆ Anchors ∆ Inter array cables **Development:** Fully shared **Supply chain:** Fully shared **Installation:** Fully shared **O&M:** Fully shared **Ownership:** One project

The investigated wave-wind energy array consisted of a 100-MW wave energy system (125 units, 800 kW p.u.) and a 500-MW wind energy system (33 units, 15 MW p.u.).

All possible co-location scenarios were ranked based on the calculated LCOE value while also including factors not captured in the LCOE calculation (refer to Figure 4.32), such as (i) wider benefits associated with power smoothing, capacity factors, and load reduction, (ii) economic impact and attractiveness to the developers and (iii) feasibility of the project and associated risks.

Figure 4.32. Methodology for scoring co-located wind and wave scenarios.

All wave and offshore wind co-location scenarios were found to result in significant cost reductions for both technologies.

In addition, the largest LCOE reduction was achieved with the most sharing options:

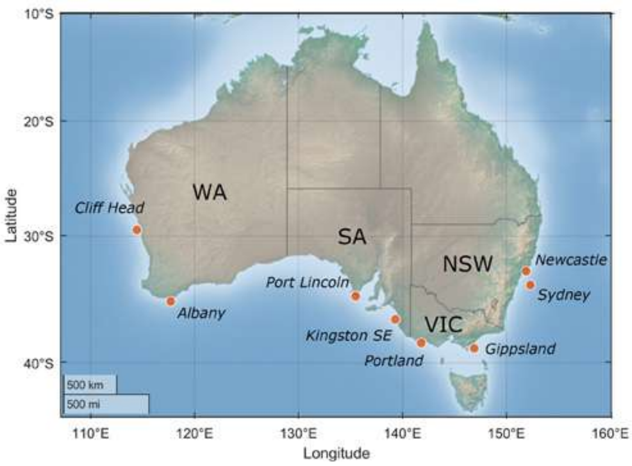
- Wind turbine developers can achieve 7% cost reduction by sharing aspects of their projects with wave energy developers;
- WEC developers can achieve 40% cost reduction by cooperating with offshore wind industry;
- The combined cost reduction for both systems could be close to 12%.

The study was done for Scotland assuming a specific deployment site, and using the ScotWind LCOE model.

Australia

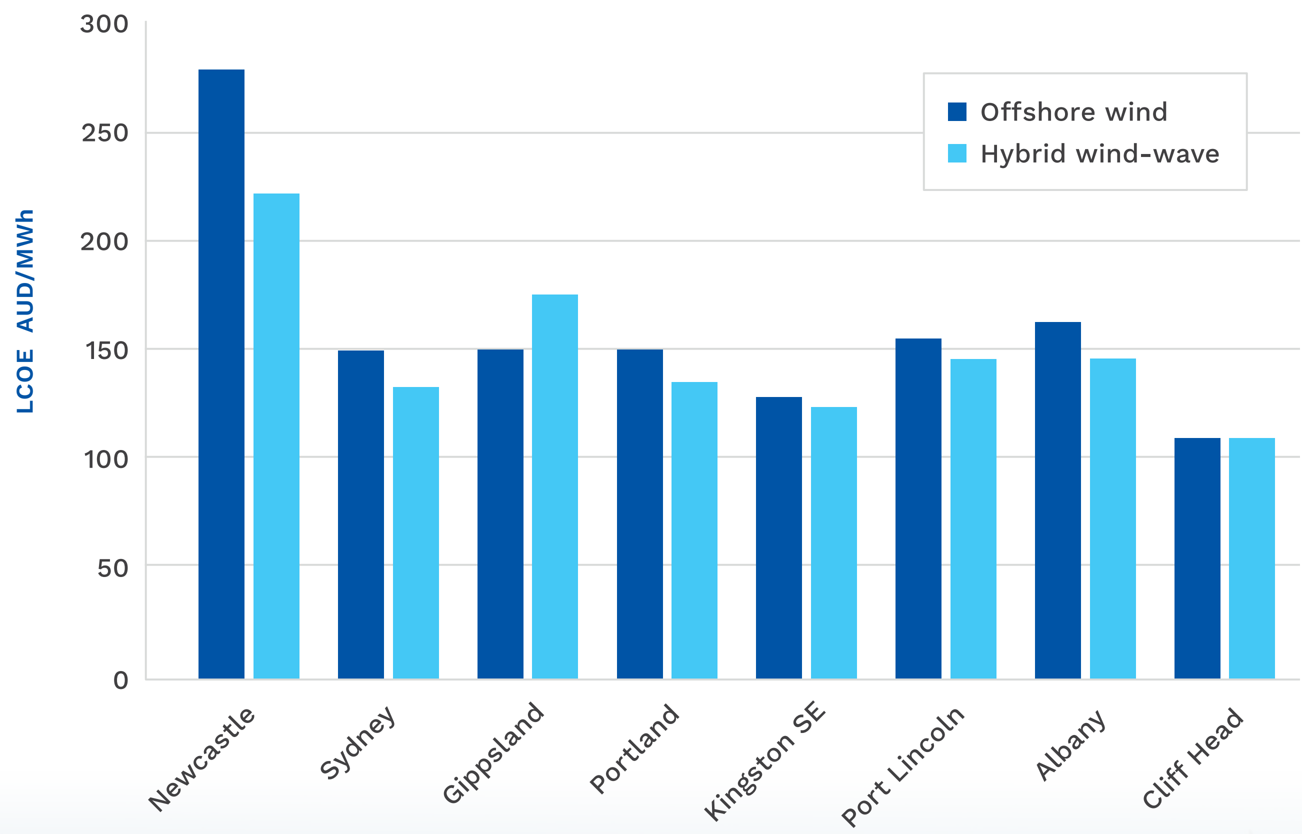
The benefits of the co-located wave and wind energy systems for eight Australian sites (refer to Figure 4.33) were investigated by Gao et al. (2022). Unlike the Wave Energy Scotland study (2022), only one asset-sharing scenario was studied that included the sharing of the offshore and onshore transmission infrastructure.

Figure 4.33. Locations chosen for detailed techno-economic assessment of co-located wind-wave energy system.



One hybrid wind-wave power unit consisted of a 5-MW wind turbine and four 600 kW WECs. The power from the wind turbine and WECs was delivered to the common coupling point offshore and then transferred to the offshore substation. The economic potential of the wind-wave energy system was estimated based on the combined energy farm with a 500 MW installed capacity (67 hybrid wind-wave power units) using environmental data from 2017 to 2021, and a life-cycle cost model as of 2023. The resultant LCOE values for the offshore wind farm and for the hybrid wind-wave energy farm across eight Australian sites are demonstrated in Figure 4.34.

Figure 4.34. LCOE value of offshore wind and wave energy farms in eight Australian sites from 2017 to 2021



This techno-economic assessment demonstrated that the combined wind and wave energy farm has unique advantages as compared with a standalone offshore wind farm, including lower LCOE, a lower regulation penalty from the electricity market, and higher energy production and carbon offset benefits. Across seven out of eight potential deployment sites, the co-location of offshore wind turbines with wave energy converters leads to a reduction in the cost of energy of between 1 and 14%. Only Gippsland in Victoria demonstrated worse performance of the combined energy system as compared to the offshore wind farm, mainly due to the insufficient wave energy resource. The most attractive locations for developing combined energy farms are Portland in Victoria and Kingston SE in South Australia.

4.3.2. Aquaculture and fisheries

Wave energy, co-located with offshore aquaculture, can supply reliable and renewable power for aquaculture operations while providing a potential market opportunity for the development and growth of wave energy technologies.

Size of the opportunity

The current value of Australian fisheries and aquaculture production is approximately AUD3.48 billion (Freeman et al. 2022). The operation of sea-cage aquaculture systems requires electricity (typically provided by a diesel generator) for feed barge operations, lighting, ventilation, and other miscellaneous electrical loads for monitoring and domestic use. It is estimated that daily stationary electrical demand for an offshore salmon facility is approximately 6000 kWh/day, with an additional 9000 kWh/day load for vessel transport. This translates to an installed capacity of approximately 1 MW offshore renewable energy generation.

International examples

According to numerous studies (e.g. Garavelli et al. 2022; Clemente et al. 2023), wave energy converters co-located with aquafarms can power 100% of on-site aquaculture power operations. However, WECs require sufficient wave resources to generate electricity, while energetic wave climates are undesirable for safe aquaculture operation and species growth potential (LiVecchi, 2019). There are a number of WEC prototypes that are designed to operate in less energetic waves and are suitable for offshore aquaculture farming.

One successful example of integrating aquaculture with wave energy was developed by the Guangzhou Institute of Energy Conversion, China. This innovative platform combines their Sharp Eagle-type wave energy converter technology with aquaculture in a single design that also has the potential to serve as an offshore tourism site. The Penghu platform, which has 60 kW capacity of wave energy and 60 kW capacity of solar energy, was deployed near Wanshan Island in 2019 and has completed 5 years of successful demonstration operations in the aquaculture base of Zhuhai city. These trials confirmed that a 50-100 kW WEC can meet the energy needs of a 10,000-20,000 m^3 offshore cage (IEA-OES, 2024).

Australia

Although aquaculture in Australia is predominantly based at sheltered nearshore sites, the industry is rapidly growing and planning to expand activities offshore. Currently, aquaculture operations are run on diesel fuel and grid-connected electricity, whereas diesel will remain the only power supply option for offshore locations.

Wave energy already has an LCOE competitive with diesel generation in remote locations, according to a case study for Wave Swell Energy (Hayward, 2021).

Moreover, the LCOE of wave energy is projected to be between AUD0.05/kWh and AUD0.15/kWh, which is 3–9 times cheaper than diesel fuel, subject to the wave energy learning rate and cumulative installed capacity.

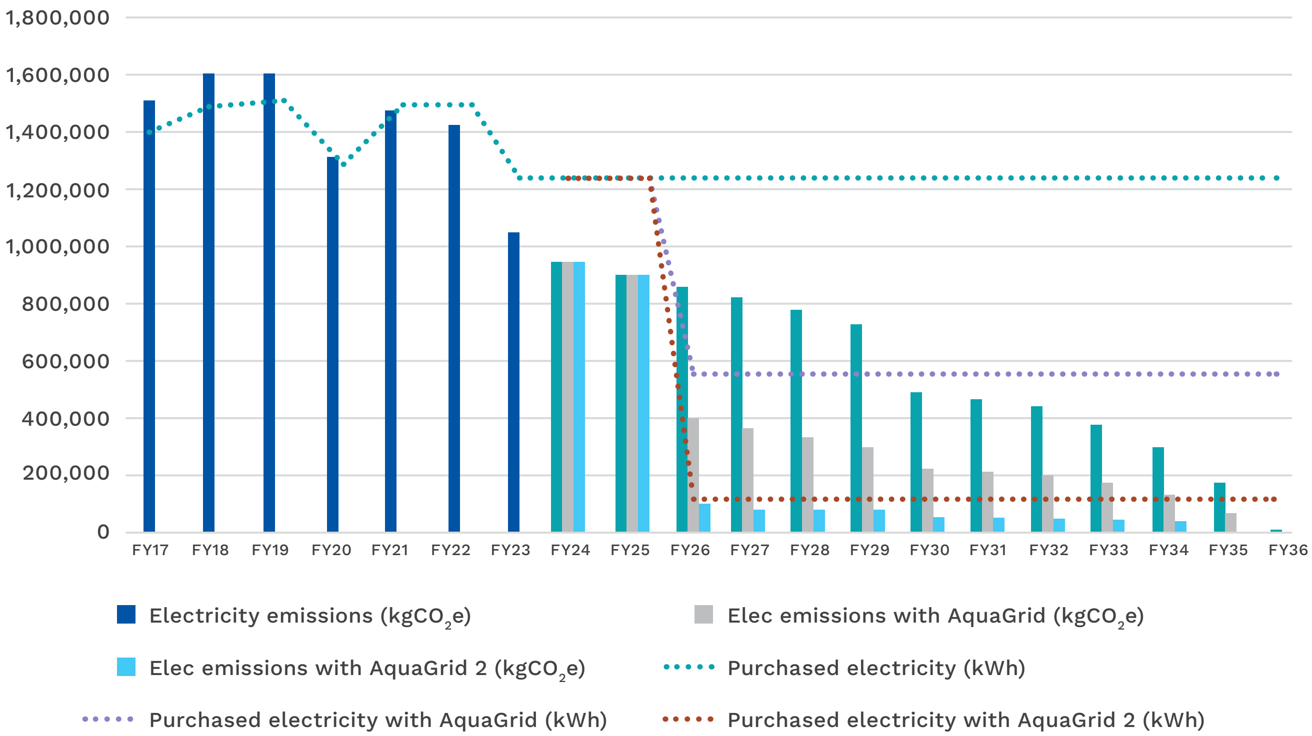
Powering aquaculture utilising wave energy could be done in two ways: co-locating the existing WEC technology with an aquafarm, or modifying an existing aquaculture facility to fit the wave energy generation unit. MoorPower (Figure 4.35) developed by Carnegie Clean Energy in collaboration with the BE CRC and industry partners is an Australian example of the latter option. The moored offshore vessel such as a feeding barge is equipped with power take-off units that convert the barge's motion in waves to ready-to-use electricity required for barge operations. The MoorPower Scaled Demonstrator project was deployed at an offshore test site in North Fremantle, Western Australia, and completed its initial operational phase in 2024. The Demonstrator achieved its initial goals of validating the design and functionality of the MoorPower modules and confirming the effectiveness of the power take-off architecture for offshore applications.

Figure 4.35. Carnegie's MoorPower wave converter system.

Image courtesy of Carnegie Clean Energy.

To achieve key goals of their 2020-2025 Strategic Plan, the Fisheries Research and Development Corporation (FRDC) launched a co-investment program to “develop scalable alternative energy solutions for aquaculture” to strengthen the resilience of Australian aquaculture to a changing climate and help the sector decarbonise. Project “AquaGrid”, submitted by Climate KIC Australia in partnership with Australian Ocean Energy Group (AOEG), was selected by FRDC for project investment and are a “early mover micro project” with Seafood Industry Australia’s (SIA’s) overarching 3-year aquaculture decarbonisation program. Thus, AOEG (2024) has investigated the feasibility of adding Azura™ wave energy converters to the existing Southern Ocean Mariculture aquaculture farm. At present, the aquaculture farm is powered by a microgrid that has a 250 kW solar PV system, a 440 kW diesel generator, and a battery energy storage. One Azura WEC has a rated power of 100 kW, and the possibility of adding two or four WECs to the microgrid was considered. The investigated possible off-grid and grid connected scenarios included: (1) grid connection, (2) diesel generator, (3) solar PV + diesel, (4) solar PV + battery storage, (5) solar PV + wave + diesel, (6) solar PV + wave + battery storage. These scenarios were assessed against a range of techno-economic performance metrics including LCOE, CAPEX, OPEX, Net present cost, annual carbon dioxide equivalent emissions, 10yr cumulative emissions, social licence, reliability, flexibility, scalability, affordability, and energy independence. The key findings of this study are that the integration of wave energy into the aquaculture microgrid can potentially reduce the carbon dioxide emissions by 94% before 2035 (refer to Figure 4.36) if a 400-kW wave energy system is added. Moreover, as in other studies, it was found that combining wave energy with other renewable energy sources (in this case solar) reduces the need for battery storage in off-grid situations.

Figure 4.36. Southern Ocean Mariculture historical (dark blue) and projected (green) emissions with addition of a 200 kW wave energy system (grey) and a 400 kW wave energy system (light blue). *Source: AOEG (2024)*



4.3.3. Off-grid solutions for remote coastal communities

Size of the opportunity

Around 2% of Australia's population (540,000 out of 27 million), live in remote areas without a connection to the electricity grid, whereas the electricity use in these remote locations is 6% of Australia's electricity use (approximately 5 GW) (AECOM, 2014). Figure 4.37 shows remote Indigenous communities where the power supply could potentially be improved by adding wave energy, and Figure 4.38 shows the fully off-grid electricity market in Australia, consisting of isolated or islanded energy systems where electricity is primarily generated from natural gas and diesel. In addition, Australia has more than 8,000 islands, including populated islands like Kangaroo Island in South Australia or Fraser Island in Queensland, whose economies rely heavily on tourism and use diesel as a primary power supply.

Isolated or islanded energy systems suitable for remote communities are usually called microgrids. By definition, a microgrid is a local electrical grid with clearly defined electrical boundaries that act as a single controllable entity, can be connected to the grid, operate in island mode, or only operate off-the-grid. Microgrid power output ranges from 10-100 kW to 1-10 MW and usually incorporate multiple sources of energy generation, including renewables (solar, wind) and battery energy storage. As shown in Section 4.1, solar, wind and wave energy complement each other in terms of improving dispatchability and reducing the use of battery energy storage. Therefore, the large wave energy resource along the south and west coasts of Australia suggests a significant opportunity for regional and remote communities, especially when combined with wind and solar power generation.

Figure 4.37. Adapted from: Map of Australia - discrete Indigenous communities and the Australian standard geographical classification remoteness structure. *© Commonwealth of Australia 2007, Source: Australian Bureau of Statistics, Community Housing, and Infrastructure Needs Survey 2006. Reproduced with permission of the Australian Bureau of Statistics.*

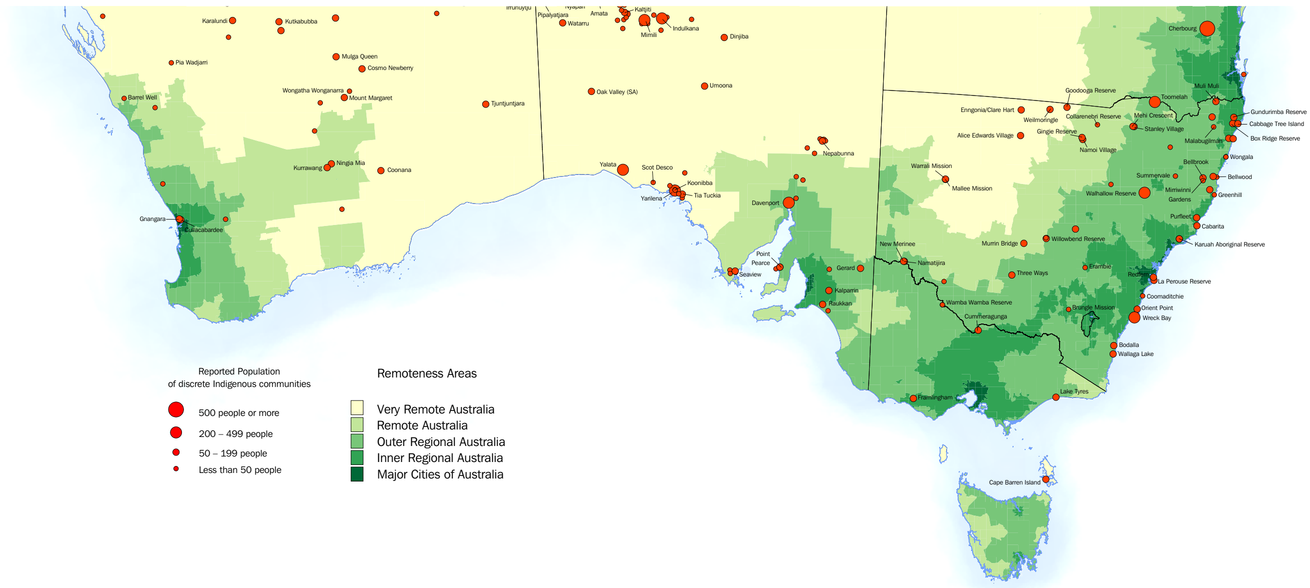


Figure 4.38. Off-grid power generation in Australia. *Source: AECOM, based on Geoscience Australia 2006 and 2012 power generation database.*

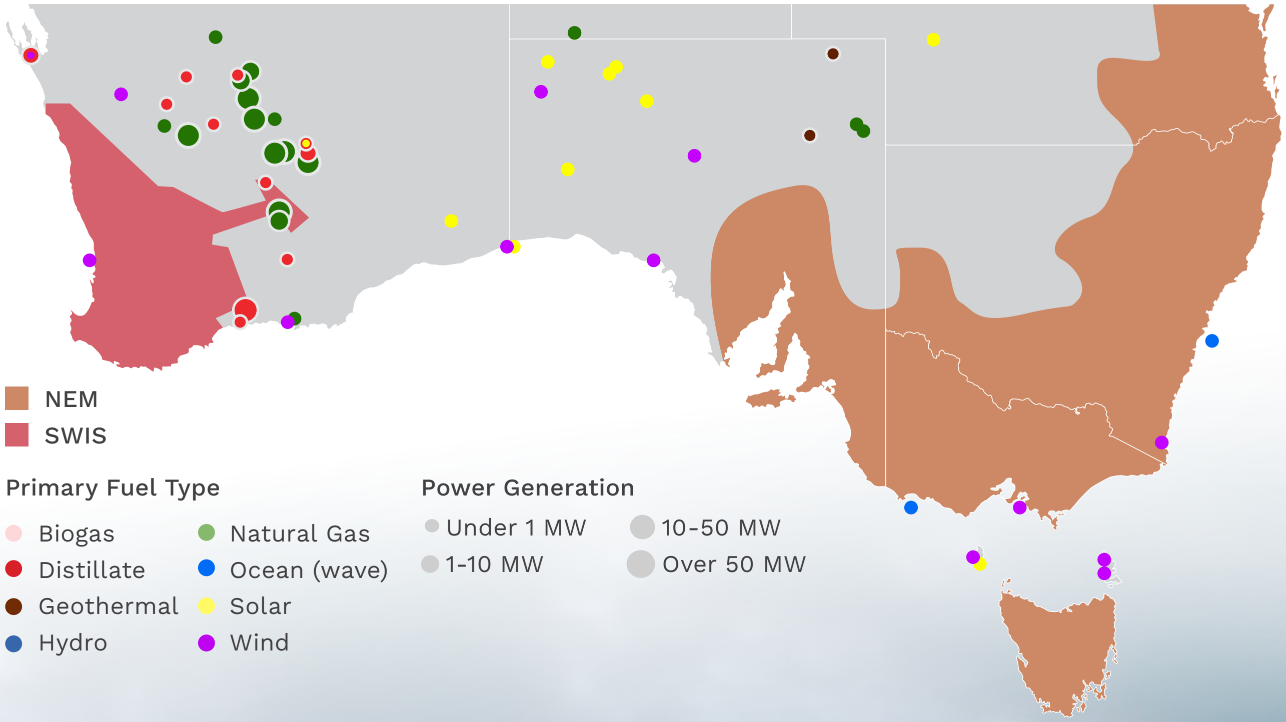
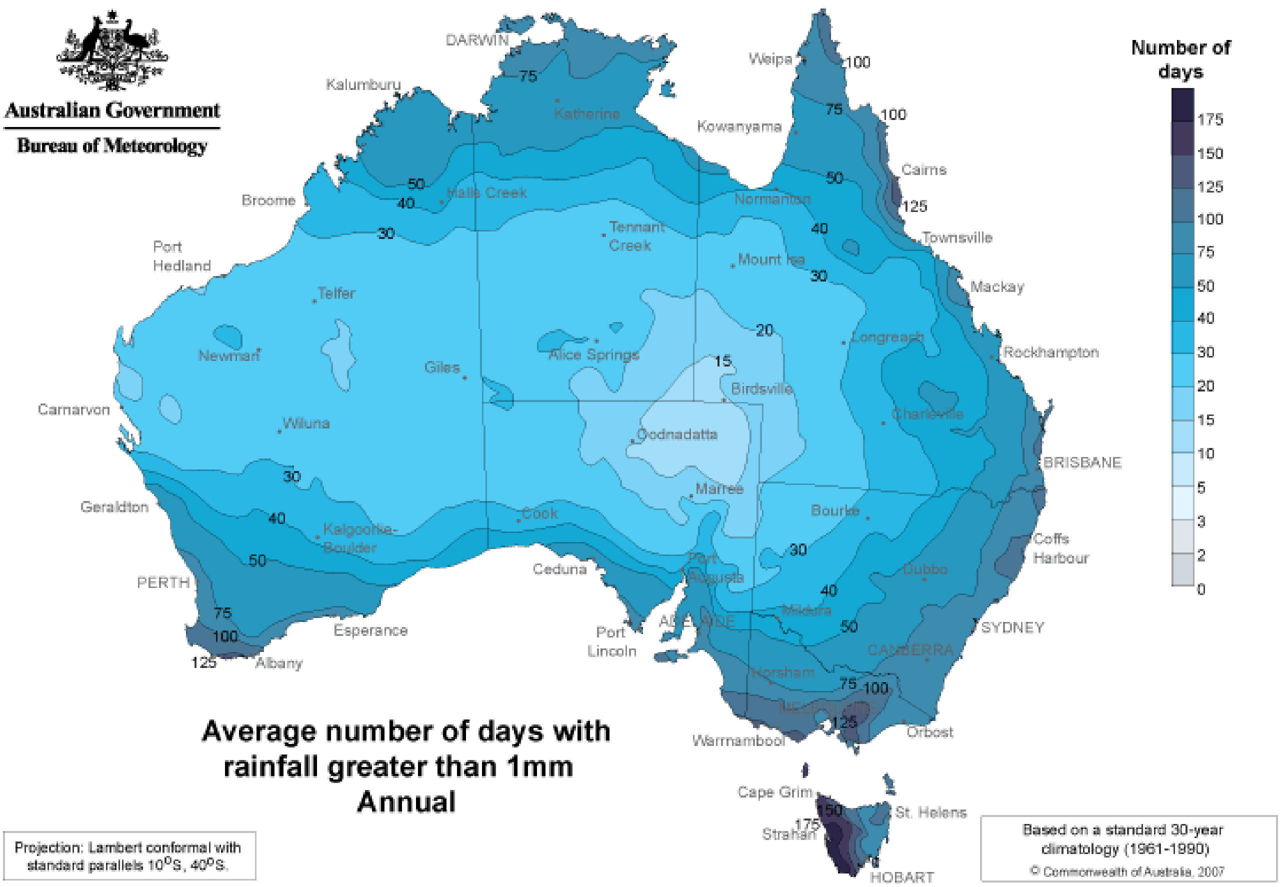


Figure 4.39 shows the average annual rainfall distribution across Australia. Remote communities along the Australian southwest coasts are in low rainfall, high solar exposure areas, notably Ceduna. Bureau of Meteorology data over the last decade shows no multi-day low solar exposure events in this remote area, with solar exposure falling to less than 10% of the average for single days and less than 30% in two-day events in a few months of each year. Nevertheless, Figure 4.12 and Figure 4.13 suggest that combining solar and wave energy could offset solar seasonal variability to provide a higher level of energy security in such areas.

The eastern coast of Australia, from Eden to Brisbane, has a greater number of remote communities, which are in areas susceptible to multi-day solar exposure and wind droughts. While these regions do not have the high energy waves of the western and southern coasts, their typically 1.6-metre significant wave heights and 10 to 12 second periods (Shand, 2011) are similar to those found in several European trials of small-scale wave energy converters, particularly the breakwater oscillating water column wave energy converter in Mutriku (Bay of Biscay) with a significant wave height of 1.5 m and 8.5 second wave periods (Ibarra-Berastegi et al., 2017). Wave energy converters along the south east coast of Australia might usefully supplement solar and or wind energy and be maintainable by local communities.

Figure 4.39. Annual number of days with rainfall greater than 1 mm. *© Copyright Commonwealth of Australia 2007, Bureau of Meteorology. Source: http://www.bom.gov.au/climate/map/raindays/1mm.shtml. Reproduced with permission of the Bureau of Meteorology.*



International examples

University of Alaska Fairbanks (2021) has undertaken a techno-economic assessment of integrating wave energy into a small islanded electrical grid for a small (600 residents) remote Alaskan community, Yakutat. At present, the power is supplied by diesel generators with an average power consumption of approximately 670 kW and a peak load demand of 1000 kW.

The study was designed to assess the impact of introducing wave energy, solar PV, and a battery storage system into the existing microgrid. The results of this study demonstrated that the installation of WECs and solar PV led to a 10-30% LCOE reduction. Moreover, it was found that wave energy generation had a higher capacity factor and was more stable as compared to solar PV, justifying the installation of WECs despite their higher costs.

Australia

ARENA has in the past supported several remote microgrid projects and programs. Projects have included Lord Howe Island in the Tasman Sea, and King Island and Flinders Island in Bass Strait. King Island in Tasmania is powered by a high-penetration renewable microgrid that combines four diesel generators (6 MW), a 2.4 MW wind farm, a 470 kW solar farm, a 1.5 MWh battery storage, a dump load, and two flywheels.

Thus, the installed renewable energy systems are capable of supplying 65% of King Island's community energy needs. Between 2021 and 2022, the microgrid was successfully integrated with a wave energy converter developed by Wave Swell Energy, UniWave200. The 200kW wave energy capacity added to the King Island hybrid grid by the UniWave200 WEC complemented the other renewable sources on the island and reduced diesel consumption on King Island by more than 3300 litres (Wave Swell Energy, 2024).

4.4. Summary

In this chapter we have presented information on the different roles that wave energy can play in markets and applications. To briefly summarise:

- When supplying power with wind and, especially, solar, wave energy contributes significantly to lowering the cost of achieving a given level of dispatchability, largely by reducing the amount of storage required. Wave energy is well-positioned to fill potential NEM dispatchability shortfalls in coming decades. Across different scenarios, wave energy is highly complementary to other sources of renewable energy;
- In addition to supplying power, wave energy converters can protect coastlines and coastal assets. This introduces new possibilities, and questions, for the role of wave energy in communities;
- Wave energy deployed with offshore wind can bring down the cost of power from the combined system. Wave energy can supply aquaculture facilities and remote communities where the cost of energy is presently high.

All opportunities in this chapter require further study in general and on a detailed site-by-site basis prior to application. This important work should better quantify the significant value indicated here. These initial estimates inevitably have some uncertainty, for example, in the role that renewable hydrogen plays in stockpiling energy as a replacement for the gas and diesel fuels currently used in peaking. An integrated view of wave energy's role in these various applications will be important, and valuable.

CHAPTER 5
DEVELOPING A WAVE ENERGY INDUSTRY

CONTENTS

Contents

5. Developing a Wave Energy Industry	**140**
5.1. Emission Targets & Renewable Energy Jobs	**140**
5.2. International Data on Workforce & Supply Chains in Marine Energy Industries	**143**
5.3. Research Capabilities to Support WEC Development	**146**
5.4. Potential for Australia's Wave Energy Industry	**147**
5.5. Conclusion	**152**
References	**215**

Figures

Figure 5.1: EMEC economic impact 2003-2023. Source: Cleary (2023).	**144**

5. Developing a Wave Energy Industry

The previous chapters of this report focused on the potential for wave energy in Australia's renewable energy mix and arising economic opportunities based on natural resources. In this chapter, the focus is on the potential for wave energy in Australia based on supporting industry and research infrastructure and human resources.

Almost 90% of the country's population lives within 50 kilometres of the coast, promising access to both critical skills and users of wave energy. Geographic challenges remain though, due to vast distances between potential wave energy hotspots and capabilities in technology development and manufacturing.

This chapter explores current Government commitments to develop an offshore renewable energy industry as part of job transition plans and showcase examples from elsewhere in the world where wave energy has demonstrated beneficial effects on regional economies.

5.1. Emission Targets & Renewable Energy Jobs

The Australian Government set its emission target of Net Zero by 2050 with an interim target of 43% reduction from 2005 levels by 2030.

As discussed in Chapter 2, publication of advice to the Government from the Climate Change Authority is imminent in preparation of submission under the Paris Agreement (UN Climate Change Conference COP21, 2015), on the most prospective technologies for cutting emissions in each sector of the economy.

An aspiration for Australia to gain renewable energy superpower status and an acknowledgement that the energy transition will require innovation and investment are included in the 'Net Zero Plan' (DCCEEW, 2022a).

Enabling technologies such as hydrogen are being considered, but there is no mention of marine renewables. Neither has the plan been matched with projections of job creation data, and the latest analysis of employment in renewable energy activities dates back to 2018/2019 (ABS, 2020).

Their report shows a continuous increase in jobs (direct full-time equivalent, FTE) of 120% over ten years and of 27% from the previous year 2017/2018, attributed largely to roof-top solar PV. Marine renewable energy is included for power generation data but not employment, stating that the sector is too immature and employment too small, such that data estimates were deemed unreliable.

Neither Australia's Clean Energy Council (Clean Energy Council, 2024), nor AusIndustry Cooperative Research Centres Program (Rutovitz et al., 2021) reports mention marine energy in their latest reports. The International Renewable Energy Agency (IRENA, 2020) estimated an approximate global workforce of 1,100 workers directly employed in marine energy, not including ancillary supply chains.

Direct employment in marine renewables, including wave energy, remains low globally and is clustered in a few leading countries but can be quantified where activities are long-term and program-backed.

Australia's aspirations in the 'Net Zero Plan' are not matched with significant activity for employment across all renewable energy technologies.

The report 'The Clean Energy Generation: workforce needs for a net zero economy' (Jobs and Skills Australia, 2023) identified 38 critical occupations and the skills shortages for a whole-of-government approach to address, such as large increases in trade skills development through cooperative partnerships between business, the vocational education and training (VET) sector and universities.

In their report, the only sectors with specific skills in marine industries relate to transport and retail which aligns with a general trend that the majority of marine energy activities require general operational, engineering, procurement, finance, and management skills shared with other sectors.

This lessens the importance of established offshore industries to transition a workforce; however, these specialist skills are by no means negligible to develop marine energy activities in coastal communities.

Individual State Governments in Australia have more ambitious targets and visions of the economic benefits from renewable energy. Legislated in 2024, Victoria has an interim target of 95% emissions reduction from 2005 levels by 2035 through major investment in offshore wind (4 GW by 2035). Victoria lists wave energy as an emerging technology to support this target and recognises the potential for wave energy in the development of renewable hydrogen (Rutovitz et al., 2023).

The State has developed a Clean Energy Workforce Development Strategy, with supporting Capacity Building Fund, Training Centres in wind, offshore wind, and hydrogen, and educational pathway programs. Victoria also has an excellent offshore wind and wave energy resource (see Chapter 3) and an existing offshore oil and gas workforce that can transition critical skills to the offshore renewable energy sector.

With two offshore wind zones declared off the Victorian coast (DCCEEW, 2022b), and twelve feasibility licences granted, Victoria might lead the exploration of workforce transitioning in the offshore energy industries. The other Australian State with an excellent wave energy resource and an existing offshore oil and gas workforce is Western Australia (WA), with an interim target of 80% reduction from 2005 levels by 2030.

The WA State Government is largely focused on solar and onshore wind to achieve this target and is challenged with an electricity grid that needs urgent upgrading for the transition to renewables (Government of Western Australia Department of Energy, Mines, Industry Regulation and Safety, 2024). Other focus areas are renewable hydrogen and critical minerals/ battery industries but job plans largely refer to transitioning mining communities.

WA has hosted and co-funded two fixed-term wave energy demonstration projects that were not grid-connected and that used contractors for marine operations. The diversity in wave energy technologies, as opposed to the largely consolidated offshore wind technology, results in different specific demands in offshore operations, engineering, manufacturing, health & safety, environmental assessment, and supply chain management.

A 'just transition of the workforce' is part of the Paris Agreement commitments, and Australia's next submission will map employment in the energy sector as fossil fuel extraction decreases and large-scale renewable energy projects expand. It can be expected that marine renewables, including wave energy, will not be considered as a prospective technology.

Inclusion as an enabling emerging technology is desirable to pave the way for programs that can give more confidence and longevity to investments and plant the seed to develop a workforce and create direct jobs. Support to the marine energy industries might also more readily come through community support programs to retain and/or upskill the workforce in rural, regional, remote (RRR) coastal areas.

5.2. International Data on Workforce & Supply Chains in Marine Energy Industries

The Ocean Energy Europe '2030 Ocean Energy Vision' report (Cagney, 2020) projects a potential for 400,000 jobs in Europe's marine energy sector (100 GW installed capacity) and 680,000 jobs globally (300 GW) by 2050, especially in coastal areas where there is co-location of the resource and supply chains such as manufacturing and marine operations.

Proximity to port facilities and other transport infrastructure is also highlighted as key to reduce costs in a developing wave energy industry, and to attract a sustainable workforce (Noble et al., 2023). While wave energy activity with presence of these factors has been created in some European regions, there are still notable gaps of untapped opportunity that will require policy-driven stimulus to local jurisdictions and technology developers.

In the UK Workforce Transferability Report (de Leeuw and Kim, 2021), it is stated that 90% of the UK's oil and gas workforce have transferable skills to work in other energy sectors, including in the offshore sector. The workforce in 2030 employed in the offshore energy sector is forecast to have grown from 160,000 in 2021 to around 200,000 with around 50% transferability from oil and gas to renewables and 45% penetration of renewables, including offshore wind and hydrogen.

The report has employment in wave energy included alongside other offshore energy activities in the UK, forecasting up to 15% of the workforce, between 5,000 (low case scenario) and 25,000 (high case scenario) people by 2030. The ORE Catapult (ORE Catapult, 2018) forecast predicted 8,100 jobs by 2040 in wave energy. These forecasts consider UK Government commitments and industry trends to integrate technologies and increase cost efficiencies, and reports emphasise that these two sectors should work together to increase opportunity and confidence to transition jobs.

Collaboration is key to avoiding labour shortages across supply chains and early development of specific training programs, informed by the international offshore wind sector experience (IEA, 2023).

Capturing indirect jobs and employment in supply chain activities takes marine energy involvement in the UK to over 850 companies nationwide that were participating or well placed to participate in the sector in the 2016 analysis by Marine Energy Supply Chain Gateway (MESCG), and to an estimate of around 1,700 people working in tidal and wave energy in UK coastal regions, with the equivalent of AUD860 million invested in the UK supply chain up to 2016.

A specific UK example where leadership and sustained commitment have been at the forefront and integrated across sectors is Scotland's engagement with marine renewables. The Scottish Government recognises wave energy as an economic driver and opportunity (Scottish Government, 2022). This level of commitment comes from decades of investment into marine renewables Research and Development (R&D) in RRR coastal areas such as the Orkney Islands.

The positive economic impact of test facilities such as the European Marine Energy Centre (EMEC), headquartered in the Orkney Islands, can now be quantified over two decades (Cleary, 2023 – see Figure 5.1). EMEC was created in 2003 to develop a marine energy industry in the UK as the world's first and only accredited grid-connected open sea facility for the testing of wave and tidal energy conversion technologies. Since then and until 2023, EMEC received the equivalent of AUD80 million in public sector funding and was able to raise additional funding which a recent economic impact assessment reports as having amounted to an 8-fold return on public funding, to the equivalent of around AUD250 million in return to the island economy, supporting 224 full-time equivalent (FTE) jobs.

The workforce directly employed at EMEC in Orkney grew from 44 to 85 between 2017 and 2023, making it one of the top 20 employers in the region, with an above-average salary. The wider economic impact of EMEC activities is stated as the equivalent of over AUD500 million to the Scottish economy and 406 FTE; and over AUD700 million to the overall UK economy and 540 FTE (all figures inclusive of benefit to the Orkney economy).

The report also concludes that EMEC has helped to build a highly skilled local supply chain and developed R&D collaborations around the world that further multiply its impact. EMEC activities were found to have had direct positive impact from initial construction of the site, to investment into ongoing onshore and offshore operations and salaries. The Scottish examples highlight that certainty of commitment, underpinned by an innovation mindset and investment, can grow a marine renewable energy workforce even via a pre-commercialisation pathway. Modelling of the commercial potential of Scotland's wave energy industry gives an estimated net revenue of the equivalent of AUD1.7 million per MW installed capacity (based on 10 MW array of point absorbers; Vanegas-Cantarero et al., 2022) and support of 18.7 jobs (measured in 'job-years', not FTE as per other figures in this report) locally.

Figure 5.1: EMEC economic impact 2003-2023. Source: Cleary (2023).

There are further examples in Europe from RRR coastal communities that historically experienced a decline in employment in shipbuilding, fisheries and fossil fuel extraction and now show particular benefit from marine renewables jobs.

In France and the Pays de la Loire region, regional councils focused on industrial strength, strong political support, dedicated infrastructure, focused R&D and innovation, and training and education and vouched to invest the equivalent of around AUD300 million into marine energy, including offshore wind, tidal, wave, and ocean thermal, by 2020 (Interreg North-West Europe FORESEA, 2018). The estimate was 17 businesses with very significant marine energy activities, employing 8 people in wave technology and another 56 in activities across marine renewables.

Economic modelling of the job potential in other European countries with marine renewables has predicted around 9 jobs per MW installed capacity for Ireland (Dalton & Lewis, 2011) and 150 jobs per MW (in lowest scenario of installed capacity) to 1,400 jobs per MW (in highest scenario of installed capacity) across job types for Greece (Lavidas, 2019).

Modelling for the UK considered direct employment in the wave energy industry from around 19 jobs (installation phase) down to 10 jobs (operational phase) across the country (Dalton and Lewis, 2011), not specifically RRR coastal communities. Portugal's wave energy industry has the potential of generating significant socio-economic benefits with an estimated equivalent of AUD4.6 million in net revenue per MW installed capacity and 54.27 job-years supported (Vanegas-Cantarero et al., 2022).

The US Electric Power Research Institute (EPRI) estimated about 25 direct local jobs per 100 MW installed wave energy capacity for the duration of device deployment (Bedard, 2007). In the US state Oregon, headquarters of the Pacific Marine Energy Center (PMEC) and Oregon State University (OSU), R&D has been closely linked with industry needs and has been shown to enhance technology testing and workforce preparation over the past two decades (Garret et al., 2022). OSU records a significant number of graduates who continue their involvement with wave energy by founding new companies.

The socioeconomic impact of PMEC is highly localised to that region and attributed to the co-location of an excellent wave energy resource, the education and research offering through OSU, and the existing marine industries on the Oregon coast. Modelling of a 500 MW commercial-scale, grid-connected wave energy farm off the coast showed potential to create 13,000 jobs and a state-wide economic net revenue of the equivalent of AUD3.5 billion.

Models considering a scenario of deploying 13 GW of wave energy capacity off the state's coast from 2026 to 2045 projected a potential for 5,500 jobs and the equivalent of AUD2.1 billion economic benefit for construction/installation, with additional net revenue of the equivalent of AUD0.9 billion in activity every year during operation. In the PMEC Research Summary Report (Garret et al., 2022), the shift of focus from commercial energy generation to innovation knowledge hub is named a key finding.

This therefore generally agrees with EMEC's impact assessment and provides strong support for wave energy related R&D activities outside of the requirement for commercial grid-connectivity.

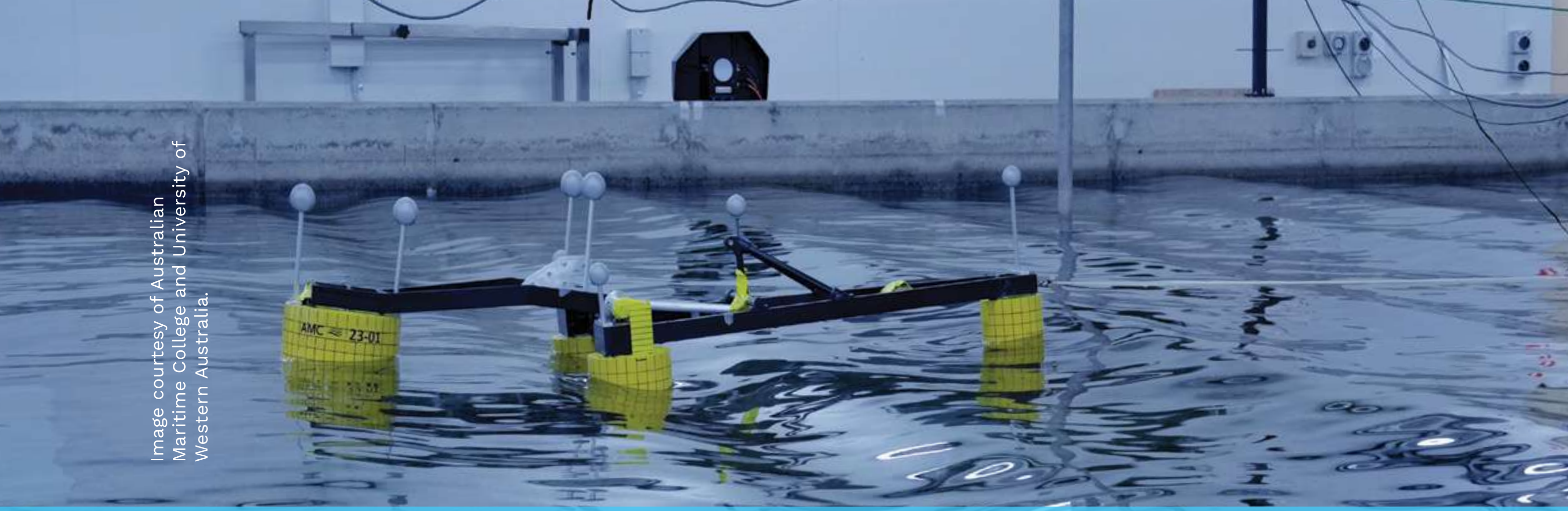


Image courtesy of Australian Maritime College and University of Western Australia.

5.3. Research Capabilities to Support WEC Development

Australia has research capabilities and facilities at Government institutes and several universities to support industry in the development of wave energy conversion technology (Hemer et al. 2018).

Some of these capabilities are transferable from decades of involvement in the offshore oil and gas sector and highly multi-disciplinary across ocean engineering (geotechnics, structural engineering, hydrodynamics, oceanography), marine spatial mapping, field instrumentation and surveying. Other research capabilities in marine and coastal engineering have grown more recently as part of the energy transition and rise of offshore wind. Research expertise in mechanical and electrical engineering and control is also critical for Power Take-Off development.

Collaboration between industry and academic partners can unlock Government grant funding, for example through Australian Research Council Linkage Grants, for basic technology research, feasibility, and technology development – hence, referring to Technology Readiness Levels (TRL) 1-5 (ARENA, 2014). Facilities such as the University of New South Wales (UNSW) Water Research Laboratory, University of Queensland (UQ) Hydraulics Laboratory, the University of Tasmania Australian Maritime College, and the University of Western Australia (UWA) Coastal and Offshore Research Laboratory allow for technology scale testing at TRL 1-4 as a crucial step towards pre-commercial technology demonstration projects (TRL 5-7).

The early research support activities are all crucial to de-risk any demonstration projects and build confidence with Government funding bodies for projects at larger scale. Australian research expertise needs strong networking internationally, strong advocacy nationally with all levels of Government, and partnerships with complementary industry and established supply chain (Hemer et al. 2018).

Wave energy demonstration projects have been funded in recent years (see case studies in section 5.5) but not through specifically targeted funding schemes that enable the advancement from pre-commercial to commercial scale activity. Rather, those projects were able to highlight synergies with other Government priorities (such as power purchase agreements or regional business engagement) to attract an individual project grant.

Australia is not equipped to enable the commercial development of wave energy technologies domestically, in the absence of full-scale testing facilities or funding schemes to support testing overseas but encourage deployment upon return home. There is therefore a risk that Australian technology developers can only benefit from local research support during early pre-commercial stages but they relocate their business overseas to leverage more favourable conditions to grow to commercial scale.

5.4. Potential for Australia's Wave Energy Industry

The Australian Government is developing a Sustainable Ocean Plan which provides an opportunity to include marine renewable energy in policy, planning, and programming.

There are currently no Government funding schemes that specifically encourage marine energy activity or target jobs creation or transition from the existing offshore sector to a new renewables supply chain. Australian federal and State job plans focus on RRR communities with closing coal-fired power plants, on committed offshore wind targets, or on new hydrogen technologies.

Australia has a significant workforce to transition, with approximately 5,000 jobs in coal-fired power and 40,000 – 50,000 jobs in coal mining, in addition to the 20,000 – 25,000 jobs in oil and gas (Briggs et al., 2021).

The country's southern coastline has an excellent wave energy resource (as detailed in Chapter 3), with five declared offshore wind development zones (DCCEEW, 2022b). As part of their respective State's energy transition and prospective offshore wind activities, the State-owned ports of Hastings (Victoria; for Gippsland offshore wind zone) and Bunbury (part of Southern Ports, Western Australia; for Indian Ocean offshore wind zone) reviewed their port infrastructure and readiness to support the logistics of offshore wind turbine freight and laydown (Port of Hastings, 2018; Southern Ports, 2022), also as a gateway to fulfilling hydrogen industry strategies.

These ports, and others along the south coast, could arguably be positioned to support wave energy logistics, noting that due to the different wave energy technologies, it is much harder for ports to follow a consistent set of requirements.

A general preparedness to assist with availability of laydown area and berth space pre-deployment may be sufficient, as coastal communities around these ports often have businesses that are active in marine operations and skilled in installations. The wave energy supply chain in these communities can therefore be developed in a more fragmented way than offshore wind, with wave energy related activities as part, but not the majority, of business operations.

The original location of wave energy technology developers (not referring to local offices during installation and operation) can be a meaningful conduit to the development of wave energy projects but has been shown in Europe's example as not critical to the site selection.

The specific logistics of wave energy projects and the identification of a supply chain are less of a challenge than the incentive to commence development – in the absence of policy-driven support and funding for R&D in wave energy technology and testing.

The rise of ocean-based or coastal commitments should be enabling for growing the wave energy industry in Australia, for example with investments into manufacturing capabilities or inclusion in powering new desalination plants (such as Wavepiston installation, Gran Canaria, Spain; Wavepiston, n.d.). However, there is a risk that the urgency attached to offshore wind developments and the high expectations on Australia's potential for renewable hydrogen leave little space to consider wave energy in planning around job transition, training, education, business readiness, and infrastructure.

The EMEC and PMEC examples have shown that an industry-support focus, and not commercial grid-connectivity, can be a catalyst for a successful wave energy industry, with additional proven impact on education, employment, and economy. At this time, with offshore wind development zones declared, there could be an opportunity to explore these business models and invest in wave energy R&D without an immediate deployed capacity target attached, and a very small initial wave energy workforce.

As electricity grids evolve, the value of wave energy devices or arrays might receive more recognition as beneficial contributions to coastal microgrids – in which case Australian examples have demonstrated that a domestic workforce exists that can participate across professions, especially engineering design, business operations, installation, and maintenance.

(Image courtesy of University of Western Australia)

The main challenge faced in the Australian context is the cost of manufacturing, compared to importing components from overseas, and fluctuations in the availability of businesses (Ai Group, 2024). Even with identified expertise, the cost of local fabrication of wave energy Power Take-Off systems, as a novelty project for any Australian business, can easily become prohibitive to the project. The above factors culminate in the overall assessment that there is no reason why Australia could not build a wave energy industry if sufficient policy-driven support, funding, and flexibility were provided to be valid by itself or in conjunction with other projects.

5.4.1. Case Study: Perth Wave Energy Project, Carnegie Clean Energy

Western Australia based technology developer Carnegie Clean Energy received AUD13 million in federal government funding, through the Australian Renewable Energy Agency (ARENA), for its AUD40 million total Perth Wave Energy Project (2012-2017). It was the world's first WEC array of three commercial-scale grid-connected CETO buoyant actuators and capable of producing desalinated water.

Electricity was supplied to the Department of Defence at the Garden Island naval base during the 12-month deployment period. The project was able to use local suppliers for support with approvals and installation and other local contractors. There were no established supply pathways for the Power Take-Off system or cost-competitive options for manufacturing of the buoyant actuator units, all of which instead were sourced from overseas.

The project provided upskilling opportunities, in particular in marine operations, employment for local graduate engineers, and a rich learning experience in approvals processes and stakeholder engagement in the wave energy context.

Image courtesy of Carnegie Clean Energy.

5.4.2. Case Study: UniWave200 King Island Project, Wave Swell Energy

Australian technology developer Wave Swell Energy led the full lifecycle trial of a 200kW unidirectional oscillating water column (OWC) device off King Island, Tasmania (2019-2024), with AUD4 million from ARENA of the total AUD12.3 million project.

For more than 24 months, the unit was deployed, spending most of that time connected to the local grid where, under the commercial terms of a power purchase agreement (PPA), the electricity was provided to Hydro Tasmania, the State's utility provider which already managed a hybrid network with integrated renewables.

The project utilised the tank testing capabilities at Australian Maritime College in Tasmania and the existing electrical and other infrastructure, along with operations and maintenance personnel, at the commercial harbour of King Island.

The gravity structure unit was constructed in Tasmania at Launceston and the Port of Bell Bay. The project included training and upskilling of workers in design and naval architecture, concrete and steel fabrication, marine and remote operations, and maintenance, decommissioning, and recycling works.

Image courtesy of Wave Swell Energy.

5.4.3. Case Study: Albany M4 Wave Energy Demonstration Project, UWA

The University of Western Australia has funding agreements with the Blue Economy Cooperative Research Centre (AUD2.8 million) and the Western Australian Department of Primary Industries and Regional Development (AUD1.55 million) for a non-commercial, reduced-scale demonstration project of the M4 'Moored MultiMode Multibody' wave energy attenuator to be deployed in Albany's outer harbour (2021-2025) for six months.

This research and innovation project has a mandate to maximise local procurement (minimum of 60%, aspiring to 80% of project value), identify an emerging supply chain, and demonstrate the potential of wave energy to decarbonise local aquaculture operations. Close collaboration with local contractors and project managers made it possible to complete manufacturing locally, with seven supply chain businesses involved, and while remaining cost-competitive to the overseas manufacturing option.

The only component sourced from overseas is the Power Take-Off system (for cost reasons), indicating that Australia's capabilities to grow its own supply chain for wave energy developments are predominantly constrained by funding and lack of sustained commitment.

Image courtesy of University of Western Australia.

5.5. Conclusion

The development of a wave energy industry in Australia can leverage a strong research capability base at Government agencies and universities to progress technology maturity at pre-commercial levels.

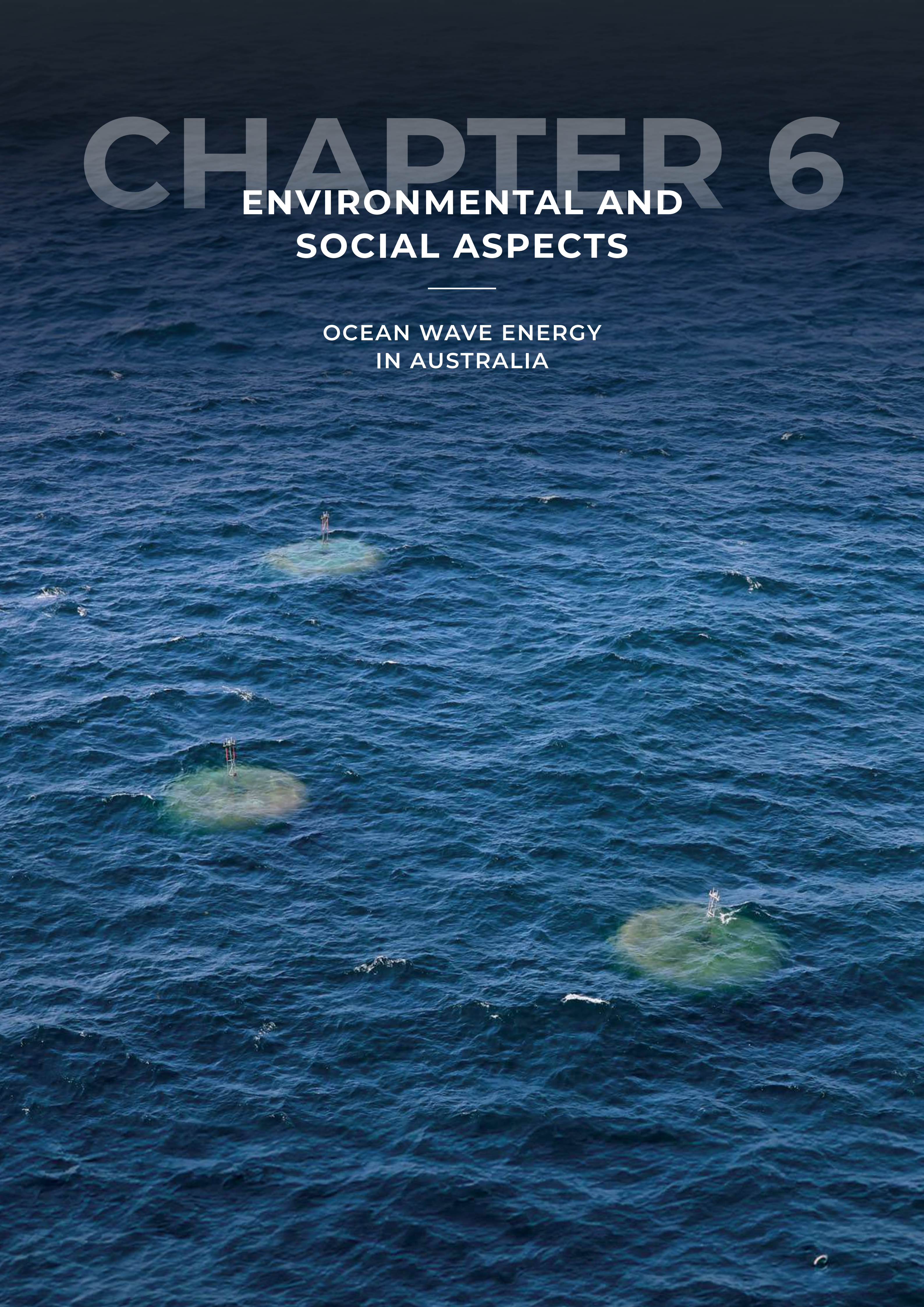
The feasibility of commercial projects and large investments into wave energy technologies as part of the energy transition is subject to many uncertainties.

Skilled workforces for marine operations and manufacturing have been demonstrated to be available in coastal communities for technology demonstration projects, and international examples suggest mutual long-term benefit if Government-backed initiatives can sustainably transition offshore industries to wave energy. More advocacy and connectivity between sectors are needed.

CHAPTER 6

ENVIRONMENTAL AND SOCIAL ASPECTS

OCEAN WAVE ENERGY IN AUSTRALIA



CONTENTS

Contents

6. Environmental and social aspects **156**

6.1. Environment **156**

6.2. Planning for Wave Energy Developments **172**

6.3. Wave Energy Ethics and Social Licence **181**

6.4. Cultural Licence to Operate **196**

6.5. Case study: south-west Victoria **200**

References **217**

Tables

Table 6.1. Key ethical promises and risks in wave energy development. **186**

Table 6.2. Pathways to obtaining cultural licence to operate, adapted from Wyatt (2016). Cultural licence to operate outcomes can be obtained through contributions of each type of collaborative arrangement. The efficacy of each arrangement in enabling each element of cultural licence to operate is identified on a scale of 'weak' to 'significant'. **199**

Figures

Figure 6.1. Conceptual diagram of potential environmental effects of wave energy converters. Note: wave energy converters differ in design, size and shape. This wave energy converter depicts an artist's impression of a point absorber design with single seabed attachment, many other designs with alternative attachment configurations exist, but all are associated with the same general list of potential environmental effects. **158**

Figure 6.2. Social Licence to Operate and the continuum of community sentiment. **187**

Figure 6.3. Licence aspects of social licence. **188**

6. Environmental and social aspects

This chapter considers environmental, planning, social and cultural aspects of wave energy. As a developing industry there is relatively little local knowledge about wave energy-specific environmental impacts, so that lessons from overseas studies and policy approaches will be important.

The planning landscape for wave energy is complex, with federal, State and local authorities potentially involved; in this context, marine spatial planning offers great promise. Ethics and social acceptance require attention from the beginning of wave energy projects and continuing throughout, if success is to be achieved. Similarly, Indigenous Peoples should be recognised from the beginning as rights holders for offshore and submerged landscapes considered for wave energy development, if a true cultural licence is to be achieved. To date, no environmental, social or cultural barriers have been identified that would restrict the growth of a well-executed wave energy industry.

6.1. Environment

6.1.1. Introduction

Because of the nascent state of marine renewable energy (MRE) in Australia, the realised environmental impacts of current wave energy developments are limited and highly localised (Trebilco et al., 2021; Hemer, 2021). However, with the rapid expansion of the MRE sector, potential environmental impacts associated with larger scale developments will require careful consideration, regulation and management.

The environmental risks and impacts of wave energy projects in Australia have been studied to a limited extent, although there is a growing body of literature from the US and Europe that can be drawn upon for understanding the likely environmental impacts of wave energy development in the Australian context. Globally, long-term datasets are limited due to the relatively early stages of technology deployment.

Direct observation of effects can be logistically challenging in high-energy, remote or turbid waters, which has made in-situ data collection more difficult. This means modelling has been called upon when considering change, especially in physical properties (as described further below).

Most efforts to synthesise knowledge of environmental effects of MRE in general, and WEC technologies in particular, have done so in terms of stressor-receptor models (e.g. Copping and Hemery, 2020; Hutchison et al., 2022). For the physical environment, assessment of potential impacts has focused on oceanographic change and shoreline modification (Whiting et al., 2023) or electromagnetic fields (EMFs; Gill et al., 2014; Figure 6.1).

Other potential changes to the physical environment associated with WECs could include reduced water quality due to release of contaminants (e.g. drilling fluids, hydrocarbons used in Power-Take Off) and/or changes in suspended sediment load (turbidity). In addition to these physical environmental changes, there are numerous ways that marine fauna may interact with WECs, such as avoidance, encounter, evasion, and entanglement and collision interactions (Hemery et al., 2024).

Marine fauna interactions with MRE devices can be difficult to monitor, with device placement often distant from the shore and because potential interactions vary with species-specific behaviour and sensory capabilities. These factors add to uncertainty around the true magnitude of potential effects from WECs.

Despite the abovementioned uncertainties, the key stressor-receptor interactions for marine fauna and the marine environment more broadly with MRE devices are generally considered to be collision risk (mostly relevant to operating tidal turbines), underwater noise and vibration (especially during installation, Popper and Hawkins, 2019), EMFs, changes in habitat, changes in oceanographic systems, entanglement, and displacement (Copping and Hemery, 2020; Figure 6.1). The outcomes of these interactions could include altered behaviour of fauna potentially resulting in bioenergetic effects (Sparling et al., 2020); changes in predation or competition levels (Copping et al., 2021); changes in migratory routes (Hasselman et al., 2023); changes in biodiversity and food webs (Martinez et al., 2021); spread of invasive species (Macleod et al., 2016); degradation of habitats (Martinez et al., 2021); shoreline modifications (Whiting et al., 2023); and changes in ecosystem connectivity (Miller et al., 2013).

Also considered in evaluating potential environmental impacts of MRE developments are social and economic impacts, such as job creation, impacts on communities, displacement of or competition with common users of the marine environment, and equity in the distribution of the costs and benefits of projects. These latter factors are explicitly discussed later in this chapter and in Chapter 5 of this report.

Image courtesy of Mocean Energy.

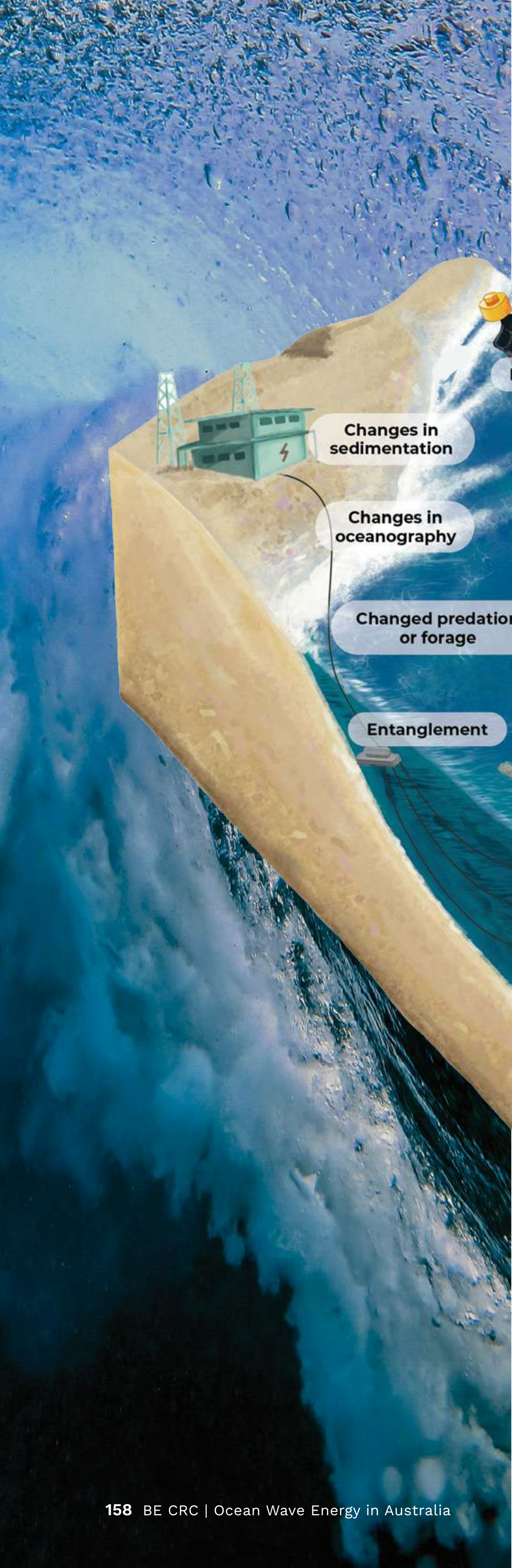
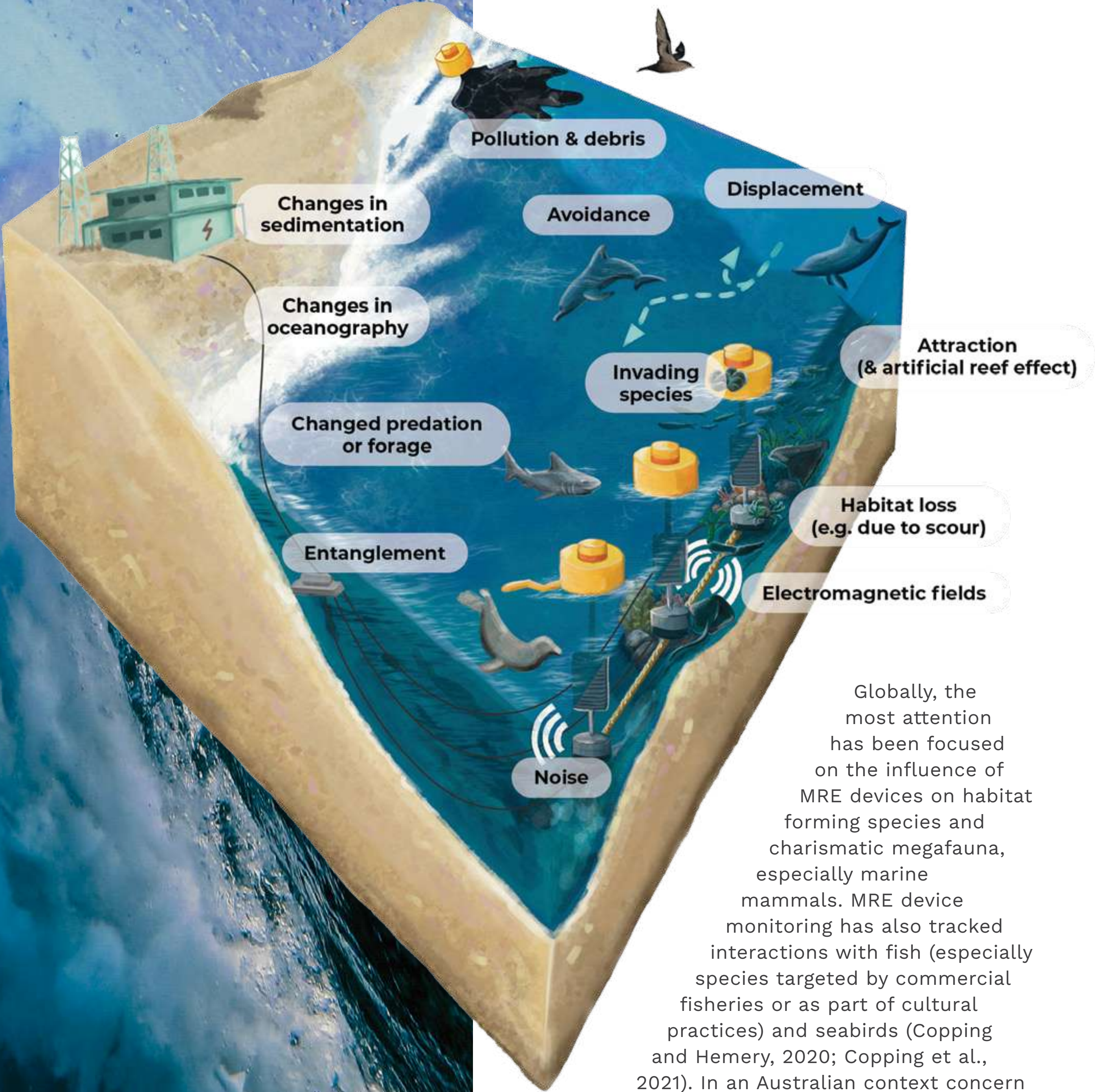


Figure 6.1. Conceptual diagram of potential environmental effects of wave energy converters. Note: WECs differ in design, size and shape. This WEC depicts an artist's impression of a point absorber design with single seabed attachment, many other designs with alternative attachment configurations exist, but all are associated with the same general list of potential environmental effects.



Globally, the most attention has been focused on the influence of MRE devices on habitat forming species and charismatic megafauna, especially marine mammals. MRE device monitoring has also tracked interactions with fish (especially species targeted by commercial fisheries or as part of cultural practices) and seabirds (Copping and Hemery, 2020; Copping et al., 2021). In an Australian context concern extends to other species of conservation concern, such as sharks, rays, penguins and marine reptiles (e.g., sea turtles, sea snakes). In general, less attention has been paid to potential interactions with mobile invertebrates.

The potential mechanisms for devices to interact with marine fauna are many including via modification of habitat or forage fields, direct interaction (collisions), or disturbance of behaviour (as described below).

However, to date, observation and modelling studies suggest that the risk of any of these interactions is low (Copping and Hemery, 2020), though some (like behavioural modification) are less well understood than others and some taxa (especially invertebrates) have not received the same degree of research focus.

Most wave energy deployments have focused on temperate Australia, which means there is little direct information available for tropical species (a pattern repeated globally). As warmer water (tropical and sub-tropical) ecosystems have higher biodiversity and (typically) more complex food webs, additional research on potential effects and alternative assessment approaches to impact assessments will be required (Fulton et al, in review).

Environmental impacts can vary considerably depending on the specific technology, location, scale and duration of a development. Developers should aim to work with Government, researchers and industry to minimise significant impacts through careful site selection, environmental monitoring, and adaptive management. The nature and magnitude of potential impacts will also change across the project lifecycle for a WEC deployment i.e. those effects associated with construction/deployment vs operation vs decommissioning.

Potential impacts are addressed below: 1) physical oceanographic change; 2) noise impacts; 3) EMFs; 4) collision; 5) entrapment; 6) entanglement; 7) habitat displacement; 8) habitat impacts; and 9) pollution (Figure 6.1).

Much of the discussion herein is focused on the operational phase of WEC deployments. There are impacts that may be associated with or more significant during installation and decommissioning and these are noted in the relevant sections below. With the exception of overtopping devices, WECs typically do not have the same kind of intensive construction and decommissioning activity seen for other forms of MRE devices (such as monopile offshore wind installations). Consequently, the main potential installation and decommissioning impacts are related to being towed – such as vessel noise, collision, or being lost and creating debris or pollution fields, as noted below. Overtopping devices have construction and decommissioning profiles consistent with other 'built in place' marine infrastructure developments.

6.1.2. Potential environmental impacts of wave energy in Australia

Physical oceanographic change

Individual, isolated WECs have little detectable physical impact on the surrounding oceanographic environment (i.e. the physical processes related to the movement of ocean water, and the direct or indirect influences of these processes on the broader marine environment). However, the potential effects of large arrays of multiple WECs are less understood and likely to be more significant.

In addition to the direct removal of energy from the system, the operation of large numbers of MRE devices could alter water circulation, wave heights, or current speeds in the lee of the devices (Whiting et al., 2023) – a recent simulation-based assessment in the Caspian Sea predicted as much as 25% or more reduction in significant wave height downstream from an array of WECs (Moradi and Ilinca, 2024). These changes, in turn, could affect sediment transport (sediment dispersal and seabed disturbance including beach erosion), water quality, and/or marine food webs (Martinez et al., 2021). Not all of these effects are necessarily negative; reduction of wave energy reaching the shore can protect the coast (e.g. Bergillos et al., 2019 – see a full discussion in Chapter 4) or prevent undesirable sediment build up in ports (Moradi and Ilinca, 2024) – with factors influencing the effectiveness of such benefits being array layout, distance to shore, wave direction, and seasonality of relevant oceanographic conditions (Rijnsdorp et al., 2020; Moradi and Ilinca, 2024).

Noise impacts

WECs can produce underwater noise and vibration which can potentially affect marine life, especially marine mammals and fish. Many forms of marine fauna rely on sound for communication (including aggregating to breed), foraging, predator avoidance and for navigation (or to stimulate other behaviours). For example, the primary sensory modality of marine mammals is hearing (Richardson et al., 1995). Sound is a highly effective means of communication as it travels efficiently underwater (five times faster than in air). However, noise in the oceans is increasing from human contributions, such as from shipping, various mooring types, seismic activity and maintenance and construction of marine infrastructure projects (Duarte et al., 2021), and WECs are not unique in this respect. This cumulative underwater noise pollution may contribute to marina fauna behavioural and physiological disturbance, masking of communication and habitat displacement (Popper and Hawkins, 2019; Popper et al., 2023).

The different frequencies at which fauna hear and use sound also complicates responses to any new sources of human-made noise. For example, different marine mammals hear sound at different frequencies (e.g., low, mid and high frequency cetacean, otariid and phocid functional hearing groups; Richardson 1995). The surrounding background noise (ambient noise) also contributes to the way a species may react to noise produced from MRE devices (Risch et al., 2023). Consequently, when considering the risk of noise-based effects on marine fauna the amplitude, frequency, and directionality of the noise source must be considered along with propagation loss (influenced by environmental conditions, distance and topography), prevailing ambient noise and species-specific hearing thresholds and any behavioural or physiological responses (Copping and Hemery, 2020).

Knowledge regarding the implications of the sound level of construction, operation, monitoring and decommissioning of WECs has grown from a low base point a decade ago (Frid et al., 2012).

Research to date suggests that underwater noise from operational devices in small-scale MRE developments, including wave energy, does not pose a significant risk to marine fauna.

This statement is supported by a general consensus of existing work (Copping and Hemery, 2020; Copping et al., 2019; OES-Environmental, 2021; ORJIP Ocean Energy, 2022a; Polagye and Bassett, 2020; Tougaard 2015). However, noise associated with MRE is greatest during installation and subsequent maintenance activities (Grecian et al., 2010) but commensurate or likely less than in offshore oil and gas installations. Use of floating WECs minimises the potential impact of installation noise during construction through avoidance of more intrusive methods such as pile driving (which has the potential to cause auditory distress or injury to fauna in the vicinity (Snyder & Kaiser, 2009)), though noise associated with mooring and anchorage installations remains a potential risk.

Studies of MRE operations, including WECs, have shown that potential noise impacts are generally localised and less severe compared to other marine activities like shipping (Copping and Hemery, 2020; Raghukumar et al., 2022, 2023). This is because WECs generally produce low-frequency noise (up to 1000 Hz), though higher frequencies have been reported for some WECs (Risch et al., 2023). The most recent studies have focused on measuring noise levels from operational devices, comparing them to ambient noise and the hearing (or other physiological) sensitivity of specific species (Popper et al., 2023). Research is also characterising the acoustic particle motion component of sound generated by wave (and other) MRE generation, which may be important for fish and invertebrates (Merchant et al., 2022; Nedelec et al., 2016; Popper and Hawkins, 2018) which are responding to noise derived vibrations and pressure changes. Moreover, this is occurring within the broader context of the development of several new frameworks for assessing underwater noise effects that go beyond MRE generation (NOAA 2018; Popper et al., 2014; International Electrotechnical Commission (IEC), 2024), potentially forming the basis for regulatory thresholds.

For the majority of WEC designs, observations from existing operational devices provide no indication of potential injury through masking of communication (Buscaino et al., 2019) and behavioural changes (e.g. avoidance) in marine fauna (Zang et al., 2023f). Greater knowledge gaps exist regarding specific behavioural responses in fish and invertebrates (Solé et al., 2023; Zang et al., 2023). The uncertainty is one of the reasons regulators remain concerned (Copping and Hemery, 2020), and the potential impacts of larger arrays of multiple MRE devices are less understood, so comprehensive monitoring remains critical. Within an Australian context, current coverage is poor for monitoring of marine soundscapes nationally (Evans et al., 2021).

Oscillating water column devices – which rely on wave motion to push air through air turbines connected to a rotary generator to produce electricity – have a greater potential to generate undesirable levels of noise in their immediate vicinity, due to the air flow (de Moura et al., 2010). This above-water noise may impact on birds and marine mammals more so than fish and other aquatic fauna.

Another important factor in determining the type and amount of noise produced in the construction and operation of WEC devices is the type of mooring arrangement. For example, as pile-driving is among the most significant noise emitting activities in Australian waters (Evans et al., 2021), if the mooring construction and installation involves pile-driving, noise emissions will likely be significantly greater than mooring construction and installation methods where pile-driving is not required. Similarly, if mooring arrangements include chain (as many commonly do), noise emissions (resulting from the movement of chains) will be greater than if lower-noise alternatives are used (though substituting chain with lower-noise alternatives such as woven/braided lines may not be possible due to dynamic nature of sites and abrasion; Wave Swell Energy, 2022).

Image courtesy of Wave Swell Energy

Electromagnetic fields

A significant number of marine fauna are able to detect and react to EMFs, notably sharks, skates and rays along with some species of sea turtles, fish, crustaceans and molluscs (Nyqvist et al., 2020). As such, there is the potential for artificial EMFs – such as those associated with the generation and transmission of MRE – to cause changes in the behaviour and movement of susceptible animals (Gill et al., 2014). This could potentially lead to long-term changes in growth or reproductive success. The animals most likely to be affected by EMFs from MRE are organisms that may inhabit or aggregate near power cables over extended periods of time – mainly sedentary animals or benthic organisms with small spatial ranges (Nyqvist et al., 2020). While laboratory studies have shown limited behavioural or physiological effects at lower EMF intensities, more significant effects are possible at higher intensities (though these levels are often far beyond what an operational device emits; Gill and Desender, 2020). To date there has been little observed detectable evidence of any such impacts.

The current consensus is that EMFs from small-scale MRE developments are not harmful and do not pose a risk to marine fauna.

Therefore, EMF risks should not inhibit the installation of devices or require extensive monitoring (Copping and Hemery, 2020; Gill and Desender, 2020). However, as larger-scale MRE developments progress there will be a need to measure and evaluate the cumulative EMFs relative to what is known about marine animal sensitivities (Copping and Hemery, 2020). While lessons could be learnt from other undersea cable users, field measurements and modelling of EMFs from subsea cables are still limited overall (Copping and Hemery, 2020); few studies have quantified the in-field extent of natural and anthropogenic EMFs (Gill and Desender, 2020).

Experts in the EMFs internationally recommend considering the local geomagnetic field and water movement when modelling anthropogenic EMFs and WEC placement and design (Gill et al., 2023). There is also a need for realistic studies of EMF intensities and exposure durations relevant to Australian wave energy developments, as well as long-term in situ studies. Moreover, no published literature could be found distinguishing EMFs generated by WECs and their cabling from other forms of non-wind MRE. Consequently, the information summarised here pertains to all non-wind MRE rather than WECs specifically. Additional research (or future monitoring programs) would be required to determine whether responses of taxa to EMF are more (or less) frequent at wave energy sites compared to offshore wind installations or other forms of MRE.

Collision

Direct interaction of marine fauna and WECs or service vessels is considered a key environmental risk, however there is no data in the literature documenting marina fauna collisions with WECs – either above or below the waterline. No direct interactions are reported for other forms of MRE generation (e.g. tidal turbines) and marine fauna (Copping and Hemery, 2020).

Collision is considered to present an overall low risk of impact.

Seabird collision is possible for WECs both above and below water, and higher risk may be associated with either larger above water profiles (especially for crepuscular species active when light levels are low) or larger swivelling oscillating wave surge converters, which have larger “exposure profiles” for plunge-diving bird species (Grecian et al., 2010) or slower moving large-bodied fauna (such as whale sharks).

While no direct interaction between a WEC and marine fauna (e.g. fish, bird, reptile or marine mammal) has been reported, it is not possible to definitively eliminate potential impacts without direct observation. As noted above, the nature of WEC installation sites and associated logistical challenges can make such observations difficult, though remote monitoring methods such as cameras and other sensors are being developed internationally (largely around devices that have turbines in water). These technologies could support WEC-specific monitors and provide more certainty around actual rates of collision risk.

The growing utilisation of marine waters by commercial and recreational vessels has increased the risk of vessel strike (collision). Both nationally (Peel et al., 2018) and internationally (Schoemen et al., 2020), vessel strike is recognised as a cause of injury or death for many forms of marine fauna – including marine mammals, sharks, rays, reptiles, seabirds (including penguins), large pelagic invertebrates (such as squid) and fish. Use of vessels to install, decommission or operationally service WECs (especially if installing a large array) needs to include mitigation to reduce risk – such as not undertaking large-scale operations through migration corridors in migration periods, use of observers to notify when vulnerable marine fauna is in the area, tracking sensors, etc. (Copping and Hemery, 2020).

Entrapment

Only very few WEC designs (overtopping WECs) could potentially entrap marine fauna within their internal structures (Grecian et al., 2010), while surface attenuators could pinch fauna between their segments. Entrapment has the potential to injure or starve an animal but can be mitigated during device design (e.g. encasings, covering openings with protective mesh). As with collision, the risk of entrapment is considered very low and has not been reported to date, but purposeful monitoring of installations would be required to verify that this lack of data accurately reflects the rarity of the event.

Entanglement

WECs requiring mooring lines and underwater cables could potentially pose an entanglement risk for marine fauna, particularly marine mammals, large pelagic sharks and rays, seabirds, sea turtles, and large fish (Copping and Hemery, 2020). If entanglement occurs it may cause injury, death or act as a barrier to movement and habitat access (SEER, 2022).

Due to limited WEC deployments, entanglement risks are often inferred from other offshore industries. Across marine infrastructure in general, entanglement in rope is a top cause of death and injury in some marine mammal species. For example, the North Atlantic right whale off the USA is critically endangered, with rope entanglement a top contributor to near-extinction (Knowlton et al., 2012). Entanglement is a potential risk considered by environmental regulators from understanding of marine mammal entanglement in aquaculture infrastructure, fisheries gear and ghost lines. The risk of entanglement with any form of MRE generation depends on scale and duration of deployment and can be limited through engineering design and product material (taut cables, chains).

In absolute terms, if there is rope in part of the ocean frequented by marine mammals, then there is a risk of entanglement, especially if those ropes are slack (Copping et al., 2018). However, for entanglement to actually occur, specific conditions need to be met. Entanglement can occur if animals are not able to see the rope at night time, or in turbid environments, and so may swim into the rope (especially baleen whales who do not echolocate like toothed whales). Once a whale or dolphin reaches the rope, it cannot swim backwards, and so entanglement can occur. Once entangled, the animal may become stressed and may drag or damage a device, resulting in injury or mortality caused by tissue damage and/or infection (Moore et al., 2013). The animal needs to surface to breathe and if the animal is entangled at depths, then the animal can drown.

There are no reported entanglements for MRE devices in published literature, and modelling studies predict a low probability of entanglement.

This is true generally (ORJIP Ocean Energy, 2022b), and especially if taut mooring arrangements are used (Benjamins et al., 2014, Harnois et al., 2015) or materials utilised in the design are inflexible. There is the possibility for marine debris caught on mooring lines or in a WEC to create a greater entanglement risk, but even then, the risk of secondary entanglement is considered low (Copping and Hemery, 2020).

Modelling is one of the approaches used to consider the risk of marine fauna encounter and entanglement around WECs. The models employed include encounter rate models, collision risk models, and exposure time population models that can include 3D configurations and incorporate various parameters pertaining to device size and animal behaviour (Buenau et al., 2022; Copping and Hemery, 2020).

Stakeholder concern remains for potential marine fauna entanglement risk, especially for species of conservation concern, or where the number of mooring lines or mid-water cables is higher. Appropriate design and placement can mitigate these risks. Nonetheless, for assurance that the realised risk of this effect is negligible there is a need for improved monitoring technologies and expanded research into species-specific behaviours and seasonal variations and (if arrays are deployed) how individual interactions scale to population-level effects (Copping and Hemery, 2020).

Displacement

The presence of MRE devices, especially if deployed in large arrays, may cause displacement of marine fauna from their preferred habitats or migratory routes (Hasselman et al., 2023). This can occur due to attraction to a device (away from other habitats), avoidance, and exclusion (Hemery et al., 2024). The mechanisms causing this response involve the physical presence of the devices, but potentially a number of the other facets described in this chapter – such as underwater noise, EMF, and changes in hydrodynamics and habitats (Hemery et al., 2024). If displacement occurs this may impact on an individual's survivability or bioenergetics (depending on physiology, movement routes, home ranges and manoeuvrability), and access to essential habitats (e.g. haul out, breeding, resting or nursery sites), which in turn can have population level consequences if these were to happen at large scales (Sparling et al., 2020).

The placement of individual WECs should be considered to reduce any potential population level consequences to species, especially species of conservation concern.

Modelling can assist in evaluating the potential for displacement and the magnitude of any effects. A number of well-established modelling approaches are effective, including species distribution models, energy budget models and agent-based models (e.g. Baker et al., 2020; Grippo et al., 2020; Harwood et al., 2020; Sparling et al., 2020). The latter are particularly effective as they allow quite complex behaviours and sensory capabilities to be modelled, which is important for some of the larger bodied animals of interest (like marine mammals).

Observational data (e.g. from monitoring programs) are essential for understanding the true magnitude of potential displacement impacts. However, careful design will be crucial if the data collected during baseline and post-installation surveys are to be useful for understanding displacement mechanisms (Copping and Hemery, 2020). For instance, the surveillance may need to span an extended area, especially if noise or other at-distance features are causing the displacement.

Thus, a range of sampling methods may be required for gaining a complete perspective, including passive and active acoustic monitoring, telemetry arrays, aerial surveillance, unmanned or remote guided drones, boat based and underwater imagery/video surveys, as well as newer methods such as environmental DNA (Dahlgren et al., 2023; Hemery et al., 2022; Sanderson et al., 2023; Williamson et al., 2018).

Habitat impacts

MRE devices, including WECs, can alter benthic, pelagic and coastal habitats via physical environmental modification (as described above), including direct habitat loss, sediment disturbance (with turbidity shifts), reduced water quality (both from suspended sediment and contaminants associated with operational use such as hydrocarbon lubricants and antifouling coatings), bottom scour, increased turbulence or changed current flow conditions (Davis et al., 1982; Hemery, 2020; Hemery et al., 2021; Martínez et al., 2021; Taormina et al., 2018). If the installation is nearshore, these physical shifts in sediment transport or local hydrodynamics create the potential for additional sedimentation on rocky shores or more fine sediment accretion on sandy shores (Hemery et al., 2021). In addition to impacts in the ocean, terrestrial impacts on coastal habitats also require assessment and consideration – this includes both potential impacts resulting from changes to coastal oceanographic processes and sedimentation and impacts on coastal habitats associated with on-shore infrastructure.

Experience in Australia (e.g. Wave Swell Energy's UniWave200 King Island Project) found that, despite extensive preparation and assessments prior to deployment of the WEC, development of scour from the subsea mooring lines was much faster and with greater magnitude than anticipated (Wave Swell Energy, 2022), likely due to the type of device and proximity to shore. This gives some indication of the possible direct seabed impacts of arrays, though the seabed substrate type, method of attachment and proximity to shore/water depth will determine the nature of effects and could (to some extent) be mitigated via design choices including site selection. In general, subsea installation foundations and mooring arrangements where chains/lines contact the bottom (other than at the point of attachment) will result in more significant habitat degradation than alternative arrangements where the mooring lines do not interact with the seabed.

There is the potential for altering biogenic (living) habitats, thereby affecting marine organisms, such as via direct removal of macrophytes or reef forming bivalves (due to scour or moorings sweeping through and clearing an area), generation of turbidity and potential toxic effects from drilling muds to install foundations/moorings, modifying connectivity between habitats (Miller et al., 2013), colonisation by biofouling organisms or invasive species (Macleod et al., 2016), attraction of mobile organisms, localised increased detrital litter fall (Wilding, 2014) and local marine fauna biomass increase (Alexander et al., 2016). The magnitude of these effects will grow with the size of the WEC – with some devices able to be scaled to quite significant sizes (Jin et al., 2022).

Where this biomass increase is of undesirable species this can create negative outcomes, but there is also the potential for the WECs to act as artificial reefs, or fish attracting devices, potentially enhancing local biodiversity (Copping et al., 2021; Hemery et al., 2021; Martinez et al., 2021). This could in theory create secondary issues if it also attracted predators and increased their displacement or chance of collision. The artificial reef effect has already been observed around MRE foundations, but less so around mooring anchors typical of WECs (Taormina et al., 2018). It is worth noting that ecological succession on artificial structures (whether of native or invasive species), such as a WEC, can take many years to evolve and stabilise (Copping and Hemery, 2020).

Despite previous prototype deployments, research is ongoing for understanding the long-term effects WECs may have on marine habitats and species assemblages (Copping and Hemery, 2020). Fish studies for other MRE device types indicate that density and distribution are influenced by factors such as time of day, current speed, and water depth, while diving seabirds and marine mammals show preferences for specific environmental conditions (e.g. water depths and current speeds) when foraging (Scherelis et al., 2020).

Studies of benthos and seafloor habitat indicate no significant changes due to WECs in most cases, unless there is physical abrasion or scour due to the mooring or due to the changed physical energy states (Marine Solutions, 2023). More research and monitoring specific to WECs, especially as larger arrays are deployed, will be required for increased certainty in terms of assurance that habitat effects are understood and mitigated.

Classic spatial environmental impact assessments (e.g. GIS-based analyses of overlap of habitat distribution and downstream WEC footprint of changed oceanographic conditions) help identify potential habitat changes (Copping and Hemery, 2020). Machine learning methods for image processing are also opening powerful means of considering sediment profile imagery systems and benthic habitat maps at potential deployment sites (Revelas et al., 2020), helping provide a solid data-base foundation for habitat assessments.

Numerical models are also being used to investigate MRE-species interactions (Buenau et al., 2022) and species distribution for potential MRE deployment sites to assess habitat use and connectivity within and among project sites – to look at the implications of any habitat loss (Baker et al., 2020), and also whether devices can act as entry points for invasive species (Hemery et al., 2021).

Global reviews undertaken over the past decade, as part of periodic reports on the State of the Science of the environmental effects of MRE development, indicate that as long as wave energy projects are appropriately sited, potential changes in habitat caused by MRE devices are likely to pose a low risk (Copping and Hemery, 2020). Whether this applies to arrays of considerable size is yet to be determined (Hasselman et al., 2023).

Pollution

WECs have the potential to generate marine pollution during installation, operation and decommissioning phases. There is a minor risk of chemical leaks from hydraulic fluids or antifouling coatings, as modern designs minimise this risk (Bald et al., 2010), though consideration to catastrophic device failure to contain contamination sources requires assessment. During installation, drilling muds or other fluids may be used that could also be released to the receiving marine environment. Similarly, toxins from antifouling coatings may be released into the surrounding environment over time. Low toxicity products can be considered in the MRE device design to reduce the contamination risk.

There is also the potential for devices to concentrate pollution through the capture of floating debris (ORJIP Ocean Energy, 2022), such as lost fishing nets. This is a small risk in Australian waters where free-floating marine debris is typically relatively scarce (although 'ghost nets' have been considered an important problem and the subject of considerable attention in some areas, e.g., the Gulf of Carpentaria; Oxenham, 2021).

A potentially greater risk is presented by debris created from catastrophic failure of the WEC mooring and detachment of the device from the seabed, or if WEC devices are not appropriately disposed of during decommissioning. This is a realised concern in Australia, as Oceanlinx had a prototype WEC break free of its moorings in 2010, sinking off Port Kembla's eastern breakwater, as well as the GreenWAVE prototype device sinking while being towed to site in 2014. In both instances the structures remained in place for 5-6 years before removal, creating both environmental and local social concerns. Successful deployments (e.g., Wave Swell Energy – UniWave200 King Island Project in Tasmania) found the dynamic environment best suited to energy generation can cause significant challenges during the deployment process (Wave Swell Energy, 2022).

6.1.3. Conclusion, key concerns, and future directions

A recent survey of Australian regulators and advisors showed that they were less familiar with wave energy than wind energy, and primarily concerned about effects of MRE on underwater noise, avoidance/displacement of animals, and benthic habitat (ORE-Environmental, 2022). Concerns about socio-economic impacts and cumulative effects of multiple environmental effects of deployment are expected to grow as the sector transitions from individual deployments to multiple arrays.

Hemer et al. (2018a) noted that understanding of the potential environmental impacts of ocean energy deployments is based on limited knowledge, particularly at a community or ecosystem level. This continues to be the case. Beyond demonstration deployments, WECs will need to be deployed as multiple arrays (Manasseh et al., 2018). To date, arrays of MRE have been small scale and short-term such that there is little understanding of implications of arrays and potential cumulative effects (Hemer et al., 2018b; Hasselman et al., 2023; Fulton et al., in review).

Continued use of adaptive management approaches will help allow for ongoing learning of adverse environmental impacts and appropriate management and mitigation.

Developing policy frameworks and environmental assessments for MRE remains a priority area for research and funding support (Hemer et al., 2018a), although lessons can be learnt from overseas, with the Tethys Knowledge Hub (https://tethys.pnnl.gov/) a useful source of information on relevant policy and assessment methods from jurisdictions across the globe. If governments commit to the development of a coordinated strategic environmental research plan, similar to that produced by ORJIP Ocean Energy in the UK (Aquatera Ltd., 2016), this can de-risk the consenting process and facilitate the sustainable development of the MRE sector.

6.2. Planning for Wave Energy Developments

6.2.1. Introduction

Site selection for wave energy developments involves examining place suitability to align technology with environmental conditions, as well as economic and societal factors.

For sustainable and economically successful developments, developers and policy-makers alike must assess potential influences on existing activities such as recreational and commercial fishing, shipping, and tourism, as well as on marine ecosystems and neighbouring communities. Developers will also undertake engagement with various regulatory bodies to ensure compliance, whilst for both developers and policy-makers, stakeholder engagement across interest groups is required to build consensus and address community concerns.

This section outlines existing planning legislation and regulatory frameworks in Australia relating to wave energy developments, provides an example of a successful wave energy planning application in Australian waters, and outlines methods for optimising planning processes to enhance project outcomes for developers, policy-makers, and the broader community.

6.2.2. Jurisdictions and Regulations

Wave energy projects, both singular and in arrays of devices may cross multiple jurisdictions in Australian waters due to Australia's territorial jurisdictional maritime zones.

Approval pathways can be challenging as they can simultaneously involve local, State, and Commonwealth jurisdictions all within a single project development.

For example, a large array may have elements more than 3 nautical miles (NM) from shore, in Commonwealth waters, have elements and subsea transmission hubs within 3 NM of the coast (under State or Territory control) and have power lines that cross the foreshore to grid connections/distribution hubs on shore in the coastal fringe (usually under Local Government control). Each of these bodies has developed their own management processes and has differing sets of constraints and pathways for development applications. Within these jurisdictions, two main modes of planning for industries and activities are prevalent: sector specific, and cross-sectional planning frameworks. As applicable Commonwealth, State, Territory and Local Council legislation varies across jurisdictions, proponents will need to seek all required approvals and licences before any offshore infrastructure activities can occur.

6.2.3. Commonwealth Acts and Bodies

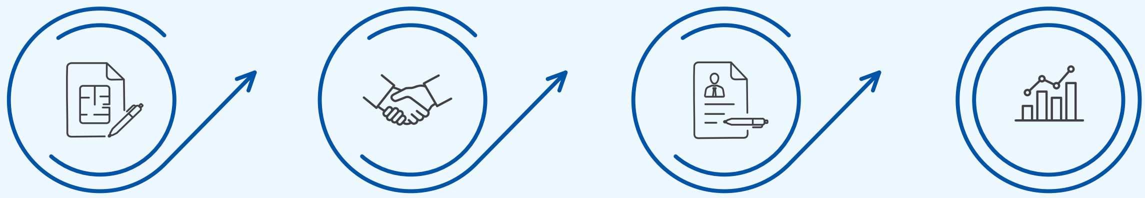
The Australian Government has created a legal framework for offshore infrastructure projects including wave energy devices when located more than 3 NM from shore in Commonwealth-managed waters. These projects are covered by regulatory acts including the **Offshore Electricity Infrastructure Act 2021** (OEI Act) and the **Environment Protection and Biodiversity Conservation Act 1999** (EPBC Act).

Five key Commonwealth agencies manage the licensing requirements and regulation of these activities in Commonwealth waters, including:

- The **Department of Industry, Science, Energy and Resources** (DISER) supports the Minister for Energy in identifying and declaring project areas.
- The **Offshore Infrastructure Registrar** advises the Minister responsible for the OEI Act and handles licensing.
- The **Offshore Infrastructure Regulator** assesses management plans and ensures compliance after approval.
- The **Department of Climate Change, Energy, the Environment and Water** (DCCEEW) Environmental Approvals Division (EAD) implements the EPBC Act, assesses proposals, and supports the Minister for the Environment with authorisation and compliance.
- The **Director of National Parks** (DNP) manages Australian Marine Park (AMP) values, oversees authorisation for activities impacting AMP values, and ensures compliance after approval.

Before any offshore infrastructure project can proceed in Commonwealth waters, it must comply with the OEI Act and all relevant environmental requirements. Licences issued under the OEI Act are separate from approvals under the EPBC Act and any other State, Territory or Local Government requirements, and approval under one Act does not guarantee approval under another. Primary approval pathways for three types of offshore projects under the OEI act have been clearly defined: commercial **projects, transmission infrastructure projects, and research and development projects** (NOPSEMA, 2022).

Given the early to mid-stage Commercial Readiness Level (CRL) of wave energy devices, the following framework for **Research and Development** projects has been highlighted in this work as most suitable for the current stage of Australian wave energy activities.



Step 1: Submission of Licence Application:

Research and demonstration activities need a research and demonstration licence under the OEI Act, as well as EPBC Act approvals, and DNP and other relevant Commonwealth and State/Territory approvals as applicable. **These licences can only be granted within already-declared areas.** The licence area applied for must be continuous and entirely within the Commonwealth declared offshore area, however they can overlap with other licences as long as the activities do not interfere with those of the other licence holders.

Step 2: Research and Demonstration Licence Granted:

For a 10-year term, with feasibility activities referred if necessary to DNP assessment, and authorisation and decision making under the EPBC Act if required.

Step 3: Management Plan Approval:

(2-3 months) where the proponents should submit management plans to the Regulator for assessment and approval, required for the construction, installation, operation, maintenance and decommissioning processes.

Conduct Research and Demonstration Activities:

Following approval, the project developers are able to conduct research and demonstration activities, with multi-agency compliance and enforcement throughout the project's life that is led by the **Offshore Infrastructure Regulator**, who oversee work health and safety, infrastructure integrity, and environmental management. If commercial project activities are planned to follow, proponents will need to seek a feasibility licence as a pre-requisite to a commercial licence (NOPSEMA, 2022).

In addition to the key Acts discussed above, other relevant Commonwealth Acts of possible relevance are given in Appendix E. Further, there are a number of international agreements which the Australian government has entered into which may guide planning or decision making in the marine environment – these are listed in Appendix F.

6.2.4. Commonwealth 2020 EPBC Act review

Currently, the Australian Government is reviewing and reforming the national environmental laws to better protect, restore and manage Australia's environment and heritage. This reform is based on an independent review of the EPBC Act (Samuel, 2020). The resultant "Nature Positive Plan: better for the environment, better for business" (DCCEEW, 2022) outlines the government's priorities, including creating National Environmental Standards and establishing an independent agency called Environmental Protection Australia (EPA). However, until new legislation is passed, for all current developments the EPBC Act 1999 continues to be in force. The Australian Government has also committed to developing a Sustainable Ocean Plan as a commitment to the High Level Panel for a Sustainable Ocean Economy, which is aimed for release in 2025 (DCCEEW, 2024).

6.2.5. State, territory and local government Acts and Regulations

Each of the States and Territories that comprise Australia have their own regulatory processes for both on and offshore developments up to 3 NM from the coastline.

Additionally, Local Councils in some regions may control both onshore and nearshore development approvals. Given the federated nature of Australia's jurisdiction, a complete summary of each State or Territory's acts and regulations is beyond the scope of this review. However, to exemplify the number and breadth of key legislation, plans, guidance documents, assessments and agreements that may guide or impact planning and decision making for wave energy projects, the State of Victoria alone has 26 State Acts, 9 Regulations, 28 Policies, Strategies and Assessments, 19 Regional Plans and Strategies, and 2 local management planning policies that may apply in addition to the Commonwealth Acts, Regulations and International Agreements outlined in the previous section (DEECA, 2023).

6.2.6. Approved Australian wave energy developments

No known wave energy projects have been approved in Commonwealth Waters under the OEI Act 2021. However, approval for wave energy projects has previously occurred, for example consent of the Carnegie CETO 6 Garden Island, Western Australia project that was approved under the EPBC Act in 2016 for the construction, operation and decommissioning of an array of three wave energy converters in Commonwealth waters. The project gained environmental approval after assessment from State EPA and Commonwealth.

Deployment of wave energy devices both singly and in small arrays have occurred in a number of State and Local Government regulated waters around Australia, with interest in deploying in these close-to-shore regions, rather than offshore in Commonwealth Waters, a direct result of the early to mid-scale Technology Readiness Level (TRL) and Commercial Readiness Level (CRL) of wave energy devices. The small-scale and demonstration projects are generally better located closer to shore for ease of access and due to the more benign environmental conditions than more exposed offshore sites.

To inform and support future planning applications by developers and development of supportive regulatory policy and processes, a case study for a wave energy device deployed in Tasmania, Australia is outlined.

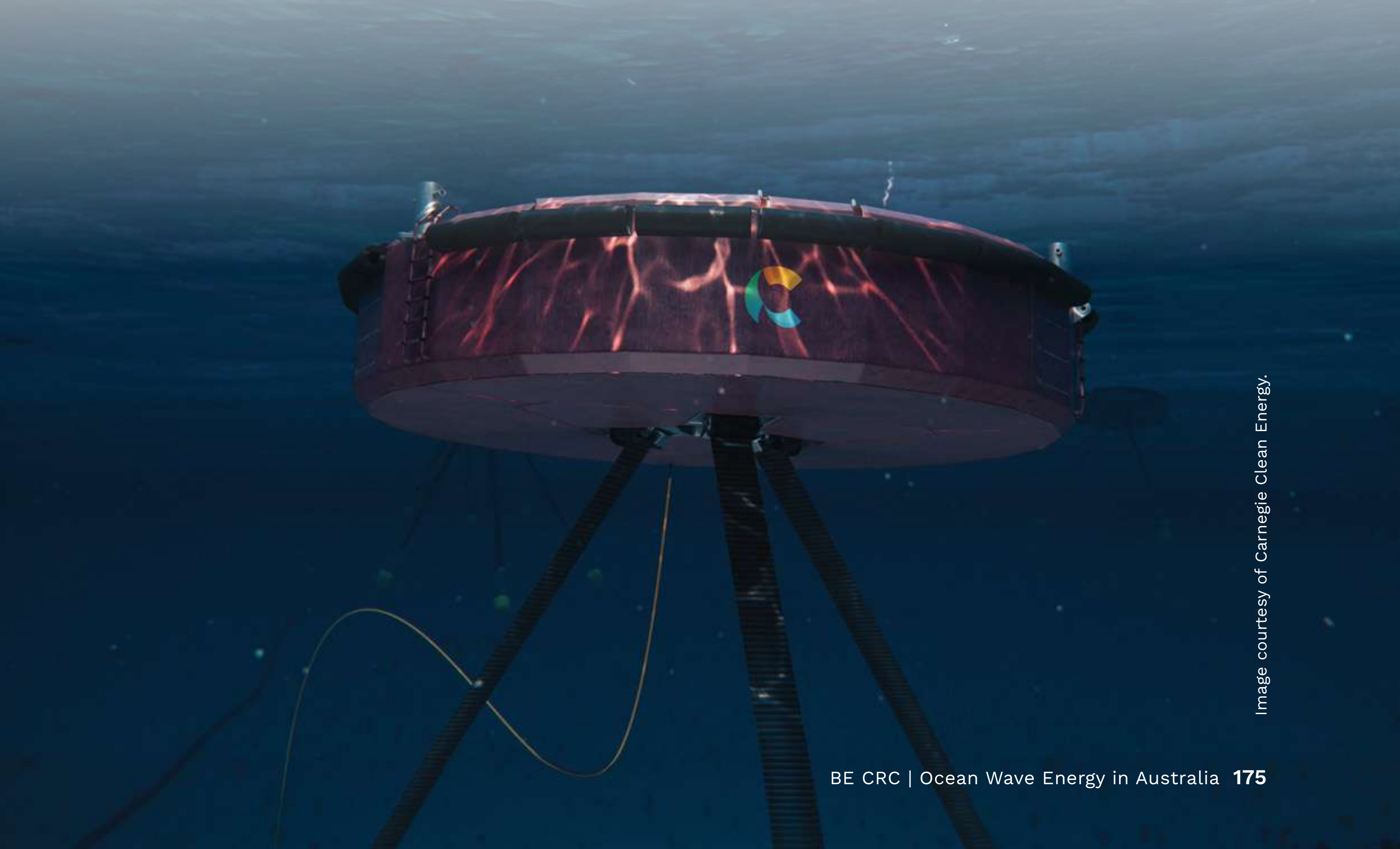


Image courtesy of Carnegie Clean Energy.

6.2.7. Case study: Wave Swell Energy at King Island, Tasmania

Wave Swell Energy (WSE), an Australian-based wave energy company, completed a more than two-year trial deployment of a single 200kW wave energy converter at King Island, Tasmania, Australia during the period 2021-2023. The gravity structure oscillating water column (OWC) WEC was sited in about 6 meters of water, with electricity delivered to the shore by a subsea cable connected to King Island's 11 kV distribution system onshore. The WEC was located on Crown Land, with two parcels of land hosting the cable and transformer kiosk owned by the King Island Ports Corporation.

For planning and development approval the project progressed through the following stages:

- To enable access to the seabed required for the OWC device, WSE submitted an application of intent to Crown Lands in Hobart, Tasmania, which was granted under the Land Use Planning and Approvals Act (1993), Tasmania Section 52(1B) Crown Lease;
- To obtain access to the two land parcels for cabling, consent from the local Port Authority of Tasmania (TasPorts) to proceed with the development was applied for and granted;
- A standard Development Application was then submitted to King Island Council and approved. This application covered the following aspects:
    - The King Island Interim Planning Scheme 2013, which covered three planning zones, "Environmental Management" for the Crown Land area including the OWC, "Port and Marine" for the parcel encompassing the port, and "General Industrial" for the parcel hosting the transformer kiosk. In particular, permitting for the "Environmental Management Zone" under Section 29.3.2 of the King Island Interim Planning Scheme, had to ensure that the device was not located in an area of significant ecological, scientific, cultural or aesthetic value;
    - Water and Waterways Code: to meet performance criteria to assist protection and conservation of a water body, watercourse, wetland, or coastal shoreline;
    - Ensure consistency with the Tasmanian Coastal Works Manual 2011 for managing coastal land issues;
    - Marine Environment Impact Assessments against the Natural Values Atlas (NVA) and the Environmental Protection and Biodiversity Conservation (EPBC) Protected Matters Search Tool (PMST) were conducted;
    - Environmental Protection Authority Tasmania, which indicated there was no reason to call the project in for environmental assessment;
    - Aboriginal Heritage Act (1975), with advice from Aboriginal Heritage Tasmania, that as long as an Unanticipated Discovery Procedure was implemented during construction, no further assessment was required;
    - Examination of the Australian National Shipwreck Database, to ensure that no wrecks, aircraft, or other maritime cultural heritage were located on site;
    - Noise performance assessments against State legislation, including the Environmental Management and Pollution Control Act 1994, the Environmental Management and Pollution Control (Miscellaneous Noise) Regulations 2016, and Environment Protection Policy (Noise) 2009;
    - Living Marine Resources Act 1995 for biosecurity purposes; and,
    - Stakeholder and community consultation was undertaken, involving 17 stakeholder contacts, two community consultation sessions, as well as newspaper articles, advertisements and radio discussions. Surveys related to the consultation sessions were also posted after the sessions to gain further feedback (King Island Council, 2019).

Approval was granted for this deployment in July 2019, and the WSE unidirectional OWC device was successfully deployed on site at King Island in 2021 for more than two years, and successfully operated as planned for more than a year.

Moreover, during the project, a noise monitoring assessment was performed by the environmental consultant, Ecopulse, and subsequent to the completion of the project, an environmental impact assessment was performed by Marine Solutions Tasmania Pty Ltd. The noise monitoring assessment concluded that *"A peak sound pressure of 64.3dB was recorded at the highest turbine speed, which is equivalent to a little louder than normal conversation, and a little softer than a dishwasher or washing machine".* The environmental impact assessment concluded *"Overall, with respect to the parameters tested in the survey, the UniWave does not appear to have had any noticeable effects on the receiving environment during its operational phase."*

Image courtesy of Wave Swell Energy.

6.2.8. Optimisation of planning processes for wave energy

Optimising the regulatory and planning process for wave energy devices, in a way that facilitates development while protecting biodiversity, functioning ecosystems, existing and future uses and local communities is a key aspiration to ensure the development of strategies and processes to enable the maximisation of the low-carbon energy generation whilst ensuring their sustainability. In Australian waters, given the complexity of navigating the jurisdiction between Commonwealth, State and Local regions, project developers require certainty and continuity of regulation to minimise project risk and maximise security of the returns, delivered by clearly focused policies. To enable effective governance, tools such as zoning plans, management plans, permitting, licensing, Traditional Owner agreements, regulatory compliance power, and policies are commonly used (Clark et al., 2021).

Effective State, Territory and Local Government policy is critical for wave energy developments given the technology is often based near-shore, and usually requires connections and supporting infrastructure in near and onshore regions. Of the States and Territories, Victoria's recent policy development is a good example of a clearly formulated management plan of ocean estate, with the development and implementation of a Marine Spatial Plan (DEECA, 2023). Federally the Commonwealth Government's development of the OEI and associated Acts, and the subsequent announcement and declaration of offshore areas in Commonwealth waters, along with the development of guidance documentation under the OEI (OIR, 2024) gives certainty to developers and community. However, the current emphasis is on the development of guidance documents for offshore wind development. This is understandable given the high TRL and CRL of offshore wind on a global scale, compared to the pre-commercial status of wave energy at present.

Further streamlining of regulatory approval processes, including environmental impact assessment methodologies and the development of nationally uniform electrical grid connection requirements would be beneficial to reduce compliance and integration costs. Further research into the environmental influence of marine energy converters, particularly on the environmental effects of marine energy (see Chapter 6.1), may also help to increase understanding, and so manage and retire risks whilst also allaying community concerns (OES, 2024).

Given the complexity of the jurisdictional space in Australia waters, mechanisms for combined governance, such as the Great Barrier Reef Intergovernmental Agreement 2009 which covers both State and Commonwealth waters, may also benefit the expansion of wave energy, although these processes are complex and unlikely in the short term.

Marine Spatial Planning

Recent policy development in marine estates has focused on the opportunities that more integrated and holistic planning processes may offer, such as Marine Spatial Plans (MSP), which may be beneficial where individual sector decision-making processes are deemed inadequate.

> ***"Marine Spatial Planning (MSP) is a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process.***
>
> ***MSP is not an end in itself but a practical way to create and establish a more rational use of marine space and the interactions among its uses, to balance demands for development with the need to protect the environment, and to deliver social and economic outcomes in an open and planned way."***
>
> **(https://www.ioc.unesco.org/en/marine-spatial-planning).**

The expansion of wave energy in Australia will most likely benefit from a more mature MSP process.

This will allow the determination of the most suitable space for WEC deployments whilst accounting for other existing and emerging ocean users. This will also improve overall participation in ocean governance.

The use of MSP can enhance site identification to maximise space efficiency and energy generation, balance demand with environmental protection, enable the assessment of cumulative impacts and conflicts with other users, and engage stakeholders, community and First Nations in marine planning and management.

Currently, MSPs has been implemented at the State legislative level in Victoria, with the development of the Marine and Coastal Policy 2020, however its use is not widespread in Australia. To enable evidence-based policies, decision making tools are utilised to assist in formulating relevant legislation and frameworks, including primarily GIS-based planning and Multi-Criteria Decision Assessment (MCDA) methodologies that can identify potential sites and examine current and future spatial social and environmental constraints (Brigg et al., 2021; Flocard et al., 2016).

Not all marine areas may require MSP-based management processes, as other established approaches may be adequate to meet needs. Sector based regulation (fisheries, oil/gas exploration and production, maritime transport, biodiversity protection) supported by environmental impact assessments and/or marine protected area planning may be more suitable. Where MSP is warranted (in areas of high use and multiple sectors) then the challenges for MSP includes managing the costs and time involved in planning and data acquisition, addressing limitations within current legislation, and coordinating activities across the three different jurisdictional levels that exist in Australia.

Current research on the application of MSP-based planning principles in Australia is underway, with research lead by the Blue Economy CRC amongst others (BECRC, 2024).

Image courtesy of Carnegie Clean Energy.

6.2.9. Conclusion

Wave energy developments in Australia may implicate federal, State and Local Government laws, bodies and regulations, with a myriad of relevant acts to navigate, including heritage protection, maritime safety, biosecurity, environmental protection, transport and more.

This makes wave energy projects as emerging technologies particularly vulnerable in a complex regulatory system, and complicated approval pathways.

Streamlining and optimising regulatory and planning processes, including across jurisdictions, to facilitate development while protecting key values is desirable. Clear policies can give certainty and direction to WEC developers. Integrated planning processes, such as MSP, can accommodate multiple users and stakeholders alongside environmental objectives, and may be preferable to sector-based regulation.

6.3. Wave Energy Ethics and Social Licence

6.3.1. Introduction

Ethical values and moral principles refer to types of acts or qualities of outcomes that are morally important. They alert us to things—like justice and fairness—that should be done.

Ethical values and principles are relevant to practitioners and policy-makers because they can:

- **guide** operations to better achieve benefits while avoiding wrongdoing;
- **inform** government policy, law and regulation;
- **help justify and explain** decisions and actions;
- **shape expectations**, ensuring that government, industry and community have shared standards; and,
- **assist in assessments** of policies and operations, gauging whether they achieved socially desirable outcomes.

Ethics plays an important role in wave energy, because the positive reasons for investing in wave energy development are based in ethics: Renewable energy helps mitigate carbon emissions, allow countries to reduce their impact on global warming, and the harms and injustices climate change engenders. At the same time, setting an ethical goal to establish renewable energy pathways might contribute to a strong social expectation that wave energy will be done responsibly and fairly.

Building a national consensus for coastal adaptation, supported by ethical action, will facilitate the combination of short term ethical 'urgencies' with the long-term planning required to tackle climatic/anthropogenic pressures (Sánchez-Arcilla et al., 2021).

As a new technology, wave energy faces several issues shared with a broad range of renewable energy developments and technologies. These include controversy as to:

- whether the project is genuinely of benefit to locals;
- impacts on community identity and its relationship to place, including Indigenous peoples;
- impacts on local ecosystems, and industries;
- concerns over coastal conflicts and the need for marine spatial planning;
- where, when and how community consultation will occur;
- political campaigns reinforcing artificial conflicts which polarise community members into opposing eco-sides: conservation versus renewables; and,
- disputes over the energy produced, its efficiency, its greenness, its carbon accounts and the precedents that such a development sets.

Australia's energy pathway, incorporating offshore renewable energy, must involve diverse stakeholders within a dynamic, ethical engagement which supports a shared coastal sustainability dialogue.

The energy transition is an opportunity to do things differently, and to do things better.

Ocean renewables are a part of this promising process. Governments and industry have both identified the central role of community in the decision-making process for a successful development project. Some ocean renewable examples are already established industries, with communities an afterthought in the process. However, more recent developments have embraced and acted upon participatory decision-making models. These models go beyond 'one-way' flows of information to communities being genuinely consulted and actively involved.

6.3.2. Seven Blue Economy Ethical Principles

Seven Blue Economy ethical principles (building on, Cooper et al. 2023; Breakey 2022; Croft et al. 2024) are relevant for wave power.

ENVIRONMENTAL SUSTAINABILITY	Wave energy activities should protect, restore and regenerate sustainability, biodiversity, and ecosystem function. This value includes responding to climate change, whether through mitigating carbon emissions, or by positively contributing to renewable energy goals.
STAKEHOLDER PARTICIPATION	Community knowledge and engagement should play a role in wave energy decision-making.
FAIRNESS	Opportunities, risks, impacts, burdens, and benefits should be fairly distributed across stakeholders, and procedural justice made transparent to all stakeholders.
HARM PREVENTION	Human rights and animal welfare should be protected and respected.
BENEFICENCE	Wave energy developments should deliver good outcomes and have good impacts, including with respect to safety, energy, prosperity, health and wellbeing, and employment.
INTEGRITY	Government and industry parties involved in wave energy development, operation and regulation must demonstrate their trustworthiness and be accountable for what they do.
PLACE ATTACHMENT	Wave energy activities should respect the bio-cultural relationship of place.

In Principle VII, place '...is not just a GPS location' (Bossi, 2023), but encompasses the relationship people share with that place. It is inclusive of identity creation, community wellbeing, aesthetic values, spiritual connections and local understandings and knowledges of place, environment and ecology. Place attachment can be an important but unpredictable factor in delivering legitimacy (Bossi, 2023; McLachlan, 2009). For example, the use of Australia-led technology might create feelings of pride, or worries about untested technologies in pristine waters.

People's local understanding of their place—for example as a place of unspoilt beauty, or as a powerhouse of energy or industry—can impact profoundly on their reaction to a new technology.

These principles are intrinsic and distinct sources of ethical value, meaning it might be possible to succeed on one dimension—such as delivering good outcomes—but fail on another, such as failing to achieve distributive fairness. At the same time, the principles can inter-relate, where living up to one principle (like environmental sustainability) contributes to achieving another principle (such as fairness).

Wave energy may encourage knowledge gains

There can be important goods that deliver benefits across many Ethical Principles. For example, **knowledge benefits** can come in the form of improving existing knowledge of different wave technology systems and their impacts; improved awareness of ecologies (such as bird or whale migration routes); and incorporating local and First Nations knowledges. Those knowledges in turn can help better manage community expectations, inform local decision-making and participation activities, and better deliver projects that are well-suited to a local ecosystem. For example, knowledge gains from Australian wave energy projects might help create much-needed renewable energy solutions for our Pacific neighbours.

Wave energy may require ethical trade-offs

Careful decision-making often requires an informed **trade-off** between different principles, where an attempt must be made, based on the best available evidence, to achieve an important ethical goal, while at the same time doing whatever possible to mitigate the resulting impact on another valued goal. In wave energy projects, as occurs in offshore wind, it may be that even within a single principle, trade-offs need to be made.

For example, 'blue vs blue' conflicts arise between a climate focus on renewable energy and the ecological desire to protect local ocean ecosystems. Whilst both contribute to environmental sustainability in different ways, conflicting ethical priorities and politicisation have allowed blue-on-blue conflicts to polarise communities. As McLachlan (2009) shows in the context of the Wave Hub in Cornwall, UK, different communities can have different symbolic representations of place and technology that impact on their receptiveness to new local renewable energy developments.

A successful wave energy industry in Australia requires navigating complex negotiations between and within all stakeholder groups

Ocean renewable energies require **complex negotiations** between stakeholders with particular factors to be ethically overcome. Appropriateness for power generation and distribution, environmental checks, and economic feasibility all have strong dedicated roles at different points in the process (see Chapter 6.2). This can leave communities feeling their concerns are neglected, and that decisions are a foregone conclusion, in particular for new technologies located within coastal uncertainties.

Geo-ecological and economic data alone, perhaps supported by government policy aims but lacking in the complex data of the human relationships in and to that place—or simply without local community support and/or involvement—can result in poor outcomes.

Image courtesy of Carnegie Clean Energy.

6.3.3. Stakeholder groups: Ethical Risks and Opportunities

Table 6.1 applies the seven Ethical Principles to relevant subject areas and/or stakeholder groups, showing the key ethical promises and risks presented by wave energy development.

Ethical risks refer to the possibility of wrongdoing occurring, or inappropriate outcomes happening. An example of an ethical risk would be that appropriate climate/carbon accounting for full disclosure reports across lifecycle on all elements of wave energy developments is not done, and therefore it turns out that carbon benefits are inappropriately communicated/asserted (the principle of Integrity applied to the Wider Community).

Table 6.1. Key ethical promises and risks in wave energy development.

Promises / Risks	Subject	Ethical Principle
Renewable energy as a response to global temperature rises	Global population Environment	Beneficence Sustainability
Community compensation and benefit agreements through a centralised fund, or ownership model	Local community	Beneficence Fairness Stakeholder participation Integrity
Jobs creation & indirect (supply chain/tourism) benefits for communities	Local or wider community	Beneficence Fairness
Direct investment and project funding (paying for infrastructure improvements)	Local community	Beneficence Fairness
Knowledge benefits: Educational and scientific research programs; technological and environmental learning	Local community	Beneficence Sustainability Stakeholder participation
Habitat development	Environment	Beneficence Harm prevention
Co-location opportunities, leveraging existing infrastructure	Global population Environment	Beneficence Sustainability
Impact on locals' sense of place Cultural, traditional and recreational values	Local community	Place attachment
Full and transparent accounting and disclosure of all environmental reports	Wider community	Integrity
Appropriate engagement with relevant stakeholders and local communities	Local community	Participation Place attachment Integrity
Development of appropriate regulatory settings	Local or wider community Developers	Sustainability Integrity
Impact on local economies: tourism, port facilities, commercial and recreational fisheries	Local community	Fairness Harm prevention
Ecosystem disturbances – marine life cycles and habitat loss	Environment	Harm prevention Sustainability
Interaction risks with animals, e.g. sea mammals Noise pollution or electromagnetic effects (impacting animal behaviour)	Local fauna	Harm prevention Sustainability
Catastrophic device failure or improper decommissioning creating major, lasting debris	Environment, local population	Harm prevention Sustainability

6.3.4. What is SLO?

In its broadest sense, the term Social Licence to Operate (SLO) refers to (often *local*) community acceptance of industry operations. The term was originally coined to describe an area of risk for multinational extraction industries when their activities were resisted by local communities.

SLO is increasingly used in an explicitly moral way, implying that industry operations should have community acceptance (Cooney, 2017). On this view, whether the operations are acceptable (an ethical question) depends on whether the operations are accepted by key communities (a descriptive question).

Social sentiment exists on a continuum (see Figure 6.2). SLO is considered lost when communities no longer tolerate the operations (Breakey et al., 2024). However, industries typically aspire to higher levels of community support beyond mere tolerance to ensure their social licence is strong and resilient over time. This requires legitimacy, credibility and trust. Industry must build and maintain these qualities over time with stakeholders and communities (see Figure 6.3).

SLO can be a valuable driver of ethical behaviour and mechanism for holding developers accountable to stakeholders. However, the concept is ambiguous, and can also be used in 'ethics washing' by industry, or employed rhetorically by activists to attack industry (Breakey, 2023).

Figure 6.2. Social Licence to Operate and the continuum of community sentiment.

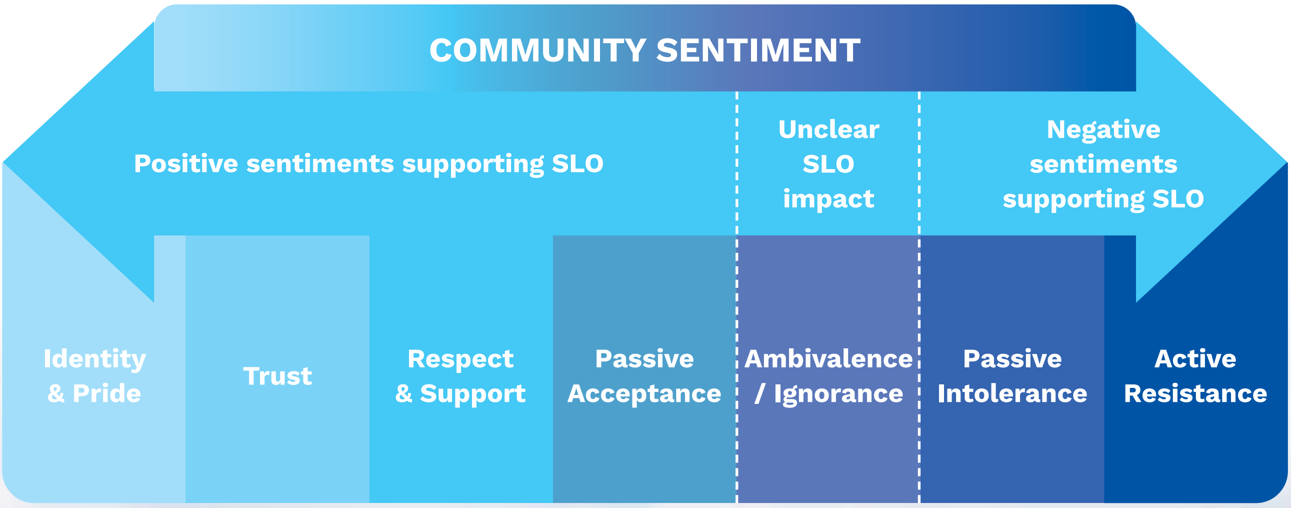
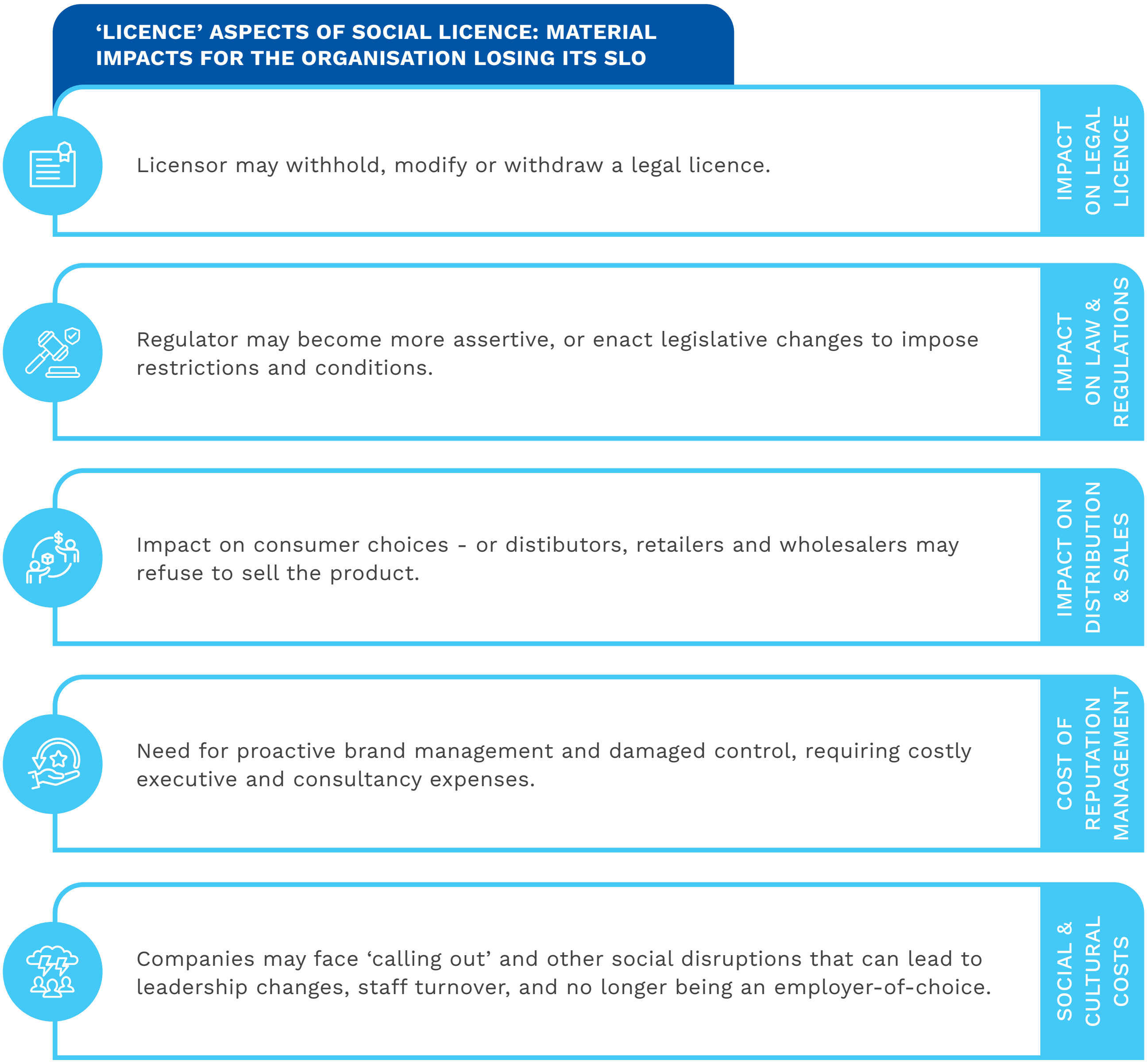


Figure 6.3. Licence aspects of social licence.



SLO in energy transition

It is unsurprising that some industries (e.g. extractive) have pursued the narrowest reading of SLO, focused only on avoiding damaging community resistance. However, in the case of renewables, and in particular ocean renewables, SLO has been used as a means to open up the discourse and invite concerns that may be relevant and valuable to the discussion.

In the context of the energy transition, the challenge for social licence is particularly heightened due to the complexity and significant investment required for renewable energy projects. These projects often involve sophisticated technology and large-scale infrastructure, which can make it challenging for communities to feel involved in the design or to feel a sense of ownership over the project. This has been evident in the offshore wind development in Australia, where, despite overall support for offshore wind energy, some communities have felt excluded from the decision-making process (Spencer-Cotton, 2024).

Moore (2013) and others argue that this energy transition will not only uproot and redesign energy systems, but all resource systems. The energy transition provides opportunities to 'do things right' and the most opportune time is to intervene in the initial decision-making process.

> ***"Once technological systems gain momentum, they become difficult to change. It is, therefore, crucial to confront social inequities and injustices from the project's outset. This requires both articulating these dimensions with input from publics and effectively integrating them into the design."***
>
> **(Moore 2013, 182.)**

In this sense, and unlike established industries, the SLO is not something sought after the event, but rather, built into the very developmental process of the industry itself. For wave energy, this means the SLO is not an exterior observer passing judgement on an untouchable system, or an afterthought to be bolted on, but rather transforms into an active participant of the development itself.

Bossi (2023, 2024) argues that SLO should not be seen as a transactional box-ticking exercise, but more a cultural practice in which stakeholders engage in meaningful dialogues and build relationships with local communities (where local communities are inclusive of First Nations Title Owners, family groups and traditional custodians—see Chapter 6.4 below). For Moore (2013) and others (Klain, 2015; Bossi, 2024; etc.), this opportunity for change begins at site selection.

Wave energy has the potential to go beyond simple risk mitigation and to view social licence as an opportunity for exploring deeper community relationships and mutual benefits.

6.3.5. Public consultation and community engagement

Even with community support for renewables and specifically wave energy, policymakers and developers ought not take initial siting processes for granted (Stelmach et al., 2023). As experience has shown for offshore wind, broad appeal does not guarantee a smooth siting process in a local context. The role of place attachment to coastal areas must be taken seriously. Public consultation and community engagement is key to ensuring social acceptance.

Different levels of community engagement

Different levels of community consultation are possible. The International Association for Public Participation (IAP2, 2018) uses the following illustrative continuum (adapted here for the context of wave energy development):

Inform:

Ensure the community is provided with trustworthy knowledge to understand the development, the technology, and any issues it raises.

Consult:

Obtain feedback from the community on their knowledge, ideas and concerns for the development.

Involve:

Work with the community to ensure their concerns are considered as key decisions on zoning, placement and development are made.

Collaborate:

Involve the community in decision making about zoning, placement and/or development.

Empower:

Place final decision-making in the hands of the community.

In the context of wave development, the first three levels are moral non-negotiables. Community—especially local community—must be appropriately *informed*, *consulted* to hear their concerns, and *involved* so that their concerns are genuinely considered. In some cases, it may be appropriate for the community to also have direct and active involvement in the decision-making process (in line with *collaborate* and *empower*).

An overarching plan for community engagement

The first priority for community engagement is for the relevant party or parties to craft a plan that explains when the key decisions will be made, what factors (legal, operational, environmental, economic, social) will need to be incorporated into each decision, what communities will need to be engaged for the purposes of making that decision, and what level of engagement is necessary (informing, consulting or involving).

The plan must also clearly explain whose role it is to engage with the community at each point, as engagement activities might be spread across different layers of government, industry as a whole, or specific developers. Without a strategic plan, and without clear allocations of responsibility, it is possible that decisions being made at any given point will not be informed by appropriate consultation activities. Community engagement might fall through the cracks, or only occur after the key decisions have been made (creating the sense that the development is a 'done deal').

Equally, unless the plan is appropriately communicated to all stakeholders, confusion may abound, creating unnecessary controversies, or confusing overlaps as different parties act independently.

There is no hard and fast rule on when and how much community engagement is required. However, greater engagement will be more likely to be required when:

1. There are close-by communities (towns and neighbours) or other stakeholders (e.g. fishers) that will be impacted visually or through noise, or have their activities impacted, by the wave project.
2. There is a possibility of significant impact on local ecologies or wildlife.
3. The project is large and/or commercial in nature, with corollary greater and more widespread impacts.
4. The development is likely to remain for a considerable period of years (e.g. a twelve-month deployment is less significant than a ten-year deployment).

Developers or researchers will be expected to know the status of these criteria given the requirements of the approvals process (see Chapter 6.2). In other words, a small research and development experiment over the course of one year with little expected ecological impact in a largely out-of-the-way place might only require an expedited process involving *Informing* locals, and *Consultation* for their concerns (Level 2), with processes for *Involving* (that is, ensuring consideration of concerns) only necessary if significant unexpected concerns emerge.

The community engagement required ought therefore to be appropriate to the place, proximity and impacts on community and the environment.

Community participation should be early and timely

The timing of public consultations and community engagement is important. Ineffective or inappropriate time lapses can risk acts of reactive resistance or even accusations of bribery during negotiations down the track. Early engagement is preferred from knowledge vacuums, especially with respect to new technologies that are not well-known to local communities.

Informing, consulting and involving communities often requires building relationships rather than a linear and uni-directional dissemination of knowledge. With the inclusion of communities in the decision making process, the consultation and engagement process should be a dynamic one, building relationships, ongoing dialogues and active participation. This can be challenging, especially if there are multiple layers of Government (national, State, local) as well as private sector bodies that need to play a role in engaging communities.

The active voice of community

Managing expectations and accurately communicating the process to communities especially by governments is crucial: local communities must have a voice, but that does not necessarily mean they have a 'veto'. But in so saying, communities must feel heard and that they are not simply a transactional means to an end. Their concerns, and perspectives and knowledges, need not only be listened to, but considered and also included within the decision-making process.

To enable informed and inclusive decision-making process as early as site selection, Government consultation with community typically needs to begin a considerable time (usually at least a year) before zone declarations. Governments should invite community into the discussions to help build relationships and help negotiate the development of wave energy from the beginning. From here, community, as an active participatory stakeholder within the project is engaged by both government and industry throughout the development and decision-making process of the project, from site selection to design, the development of community benefit schemes and ongoing processes.

Building relationships with transparent communications

As with all stakeholder negotiation, particularly those that are involving new energy systems within coastal waters, the early and ongoing community participation does not guarantee conflict-free processes. As noted above, an individual or group's acceptance or rejection of wave energy developments are contingent upon how they perceive the technology and the place, and what they symbolise to the individual or group.

It is important for decision-makers to resist simply outsourcing public consultation to separate bodies or consultancies. While experts in public participation can have much to offer private sector and public sector organisations, there are ethical risks when participation activities become overly standardised, and occur at arms-length from decision-makers themselves (Barry and Legacy, 2023). Rather it is important for government and industry bodies to build relationships with communities and local industries. There is a focus on the importance of getting this right, and not presuming that communities will be supportive, nor assuming that communities will also just be resistant either.

6.3.6. Start soon, start small, build knowledge and trust

With new technology, **opportunities for research and learning, knowledge building and sharing need to be centred in the policy-making process.** This means the speed and scale of the development may need to side more with caution than ambition. Without any wave developments in Australian waters, a cautious development that decreases knowledge gaps in place along the way benefits the global renewable energy narrative by curbing ambition for the greater good of the ecosystem and in building community trust. This need for learning also provides reason to diversify the approach to the development of renewable ocean energies and in the technologies required. It may be that **a multiplicity of companies and technologies** would best sustain the diversity of development to ensure a best fit technology and approach to the various ecosystems along the Australian coastline and along our changing ocean.

Alongside this approach must be a strong role for research and monitoring to discover an overall package of approaches that works in the Australian context. Trustworthy, independent, accessible research is crucial, as the level of trust in information brokers can vary between different stakeholder groups. Industry and technical experts can be identified as the most trustworthy information brokers by some sources, and as the least trustworthy by others (Conway et al., 2010).

The same reasons for proceeding carefully also press in favour of starting early and beginning the process of knowledge acquisition about wave energy in general, and applications in Australian waters specifically, as soon as possible. Putting off development to a later point—when there might be greater urgency for renewable development—will make it harder to proceed in an informed and circumspect manner at that point.

These same procedures apply to each step in the development of wave energy—initial testing on independent or isolated devices, later testing on larger arrays, and—in due course—ongoing research and monitoring of commercial scale developments. In each step, trustworthy monitoring and ongoing research on environmental impacts (see Chapter 6.1) and socio-cultural impacts are required, as are ongoing discussions and knowledge-sharing with local communities.

6.3.7. Dynamic management

As part of the engagement and consultation process, it is important to uphold **integrity** between the stakeholder relationships and systems created, reviewed and revised. It is important that **transparency** is maintained through **distributive and procedural justice.** A lacking in this area has caused failures in ocean renewable projects as recently as 2023 (Vasconcellos Oliveira, 2023).

Environmental concerns

As a new technology, a considerable amount of revisions toward better practice can be expected especially within a dynamic environment – tides, weather, climate change, ecosystems, migrating species, etc (Bossi, 2024). It is also expected that unlike wind energy which focusses on visual amenity, it is more likely that environmental concerns will be of the greatest concern for local communities. *Environment* concerns feed into ethics and social acceptance—as impact on marine animals and ecologies will be a major source of ethical concern. Within this, *Management* is both a factor in ethical appraisal (are management processes legitimate? Independent?) and is also a way of implementing ethical values (for example, use of Marine Spatial Planning to deliver fair distributions of ocean space amongst users and stakeholders—see Chapter 6.2). Within biocultural ethics—a moral philosophy that focuses on the relationship between particular cultures and their local environments (Rozzi, 2013)—it is important to explicitly consider the kinship world view and customs of First Nations people. *Cultural licence to operate* is a particular part of ethics that requires special attention, as discussed in the following section (Chapter 6.4).

Adaptive strategies and processes

With so much coastal uncertainty and diversity within and between stakeholder groups which are themselves in a dynamic relationship, it is important to develop equally adaptive strategies and process to manage people, and data which continue to best support and best fit our changing environment. In a dynamic system, it is important to maintain transparency, share knowledge respectfully and maintain open access data reporting so that necessary adaptation can be made in a timely and ethical manner.

It is necessary to build relationships both between and within stakeholder groups; to open up and continue direct and indirect dialogues with stakeholder groups so that energy transitions continue to maintain relevance and fit for purpose outcomes in their environments through this adaptation process.

Marine Spatial Planning (MSP) can be a useful device for managing multiple and oftentimes competing stakeholders and users in an increasingly congested space (see Chapter 6.2). To keep up with a changing and congested ocean, already under pressure by climate change, MSP can be a dynamic tool in an adaptation pathway facilitating ethical negotiations with all its stakeholders.

Community encompasses a wide-reaching stakeholder group

As residents, local business owners, industry employees, members of government, custodians and stewards of coastal environments, local community is an important stakeholder within the entire process. This comes with its own challenges, namely the diversity of community positions, mapping those, and then also developing a fair representation of that, not by surveys and representatives, but rather by establishing a means by which community is fairly represented and seated at the table.

6.3.8. Conclusion

Navigating ethical and SLO concerns can be complex and challenging. Yet ethics and community acceptance are not mere obstacles to overcome, or boxes to be ticked. Indeed, the driving motivation for wave energy is itself an ethical one: for clean renewable energy that helps Australia contribute effectively to global climate change mitigation.

To be done well, ethics and social acceptance require attention at the earliest stages of planning. It is far easier to build ethics strategically into the process, than to retrofit responsive therapies later—and far easier to begin community engagement and relationship building early and proactively, than to resuscitate social licence after trust has been lost. So too, ethics is never 'set and forget'. Ongoing attention is necessary to address the dynamic quality of the ongoing relationship between coastal ecosystems, new technologies, and human communities.

6.4. Cultural Licence to Operate

6.4.1. Introduction

Indigenous people have lived in Australia for millennia, developing strong connections to important places and significant knowledge of land, water, coasts and marine scapes. From an Indigenous perspective, the customary territory is understood to be continuous and to hold submerged offshore landscapes of significance (McIntyre-Tamwoy et al., 2013; Kearney et al., 2023; Veth et al., 2020).

The wave energy sector will potentially introduce a new regime of occupation of customary territories, of seas and coastlines, unseen beyond the European colonisation and dispossession processes experienced by Indigenous Peoples (Kerr et al., 2015).

Wave energy proposals present benefits and risks that will impact Indigenous customary practices and culture, requiring collective decision-making to consider sacred and inter-generational obligations and responsibilities while balancing potential short and long-term development opportunities (Gibson & Bradshaw, 2018; Lieu et al., 2019). Understanding the impacts of wave energy projects requires early deliberative consultation and dialogue to engage meaningfully with the types of stakes that individuals and collectives have in a wave energy proposal.

For Indigenous peoples, the on-going and increasing restrictions of access to important places and land and marine scapes have and will continue to decrease the cultural knowledge base of the population and the baseline information that is critical to make informed decisions about development projects on their lands and seas (McIntyre-Tamwoy et al., 2013; Bennett et al., 2021; Kerr et al., 2015; Lalancette, 2017; Cisneros-Montemayor et al., 2019, 2022; Krupa et al., 2015; O'Faircheallaigh, 2013; Owen & Kemp, 2013). Through mechanisms such as native title, marine use and tenure agreements and partnerships with the private sector Indigenous people are increasing their interests, albeit it marginal, in the marine resource management and economy sectors (see Lyons et al., 2023 for more information).

6.4.2. Enabling Conditions for Cultural Licence to Operate

Below are some principles that will assist businesses and Government to cultivate the conditions for cultural licence to operate (also referred to as cultural partnership pathway by Hunter et al., 2024) beginning with Indigenous Peoples as rights holders.

Indigenous Peoples as rights holders not stakeholders

Indigenous Peoples, as the first occupants of territories and estates, hold historic rights, interests and values that relate to their ancestral lands and waters. From this perspective Indigenous Peoples understand their position as different to and existing prior to stakeholders.

Four key principles to be considered when investing with Indigenous Peoples beyond stakeholder approaches in Blue Economy projects are, Indigenous People:

- bring particular economic, conservation and socio-cultural knowledge and goals that are unique to their relationship to their ancestral lands. Indigenous perspectives and knowledge can easily be lost under project capacity and operating and resource pressures affording more influential community groups greater input (Ruckstuhl et al., 2014; Newton et al., 2020; DeKoninck, 2007).
- have a custodial relationship and responsibility to their customary territories and to neighbouring groups and future generations that require appropriate and meaningful engagement beyond stakeholder approaches (DeKoninck, 2007; Jackson et al., 2012; Poyser et al., 2021).
- bring a unique perspective to partnerships based on their existing governance, responsibilities and inter-generational obligations (Ruckstuhl et al., 2014; DeKoninck, 2007; Poyser et al., 2021).
- sustain unique governance and customary responsibilities that situates their interests and rights beyond consultation – to participation in decision-making and iterative negotiations in determining acceptable risks that affect their relationship to their ancestral lands and waters (Ruckstuhl et al., 2014; Escott et al., 2015; Jackson et al., 2012).

Cultural Licence to Operate: a focus on partnership pathways

Cultural licence to operate attends to rights holders and includes important components such as legal and historic rights, territories, local protocols and practices, cultural governance and relationships with and of place and people where projects are based. Indigenous Peoples seek to engage with industry as long-term decision-making partners in commercial ventures that can also generate opportunities for Indigenous enterprise alongside those of non-Indigenous interests. Indigenous partnerships entail the explicit intent of having authority to assess and manage impacts, evaluate management options, negotiate and agree on fair terms for benefit sharing and to limit costs (Ruckstuhl et al., 2014; Fusco et al., 2022; O’Faircheallaigh, 2018; Hunter et al., 2024).

The partnership approach places emphasis on relationships and meaningful consultation, negotiation and dialogue between Indigenous groups with industry and Government as part of the ongoing use of resources and impacts on Indigenous values

(O'Faircheallaigh, 2017; Boyd & Lorefice, 2018; Poyser et al., 2021; Gibson & Bradshaw 2018). Indigenous values under a development context relate to (Jolly & Thompson-Fawcett, 2021; Wyatt, 2016):

- ways that non-negotiables need to influence cultural licence to operate in each group's circumstances;
- respect for Indigenous knowledge and capacity to ensure authority in decision-making processes;
- the use of Indigenous frameworks to conceptualise, assess and interpret impacts, and evaluate options;
- processes for continual learning and mutual adaptation that improve the overall project outcomes; and,
- outcomes and benefits as defined by communities.

Consequently, a cultural licence to operate is negotiated and earned by working at place specifically with First Nations through a group specific partnership pathway (Hunter et al., 2024).

Free, Prior and Informed Consent

The ongoing neglect of Indigenous Peoples' rights to, and laws relating to, their land and water resources has seen Indigenous Peoples continued advocacy for companies and governments to adopt the language of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) and its principles of Free Prior and Informed Consent (FPIC) for any development proposal on Indigenous territories (Mitchell et al., 2019; Curran, 2019). While the UNDRIP is not legally binding in Australia, it has supported and is utilised by Indigenous Peoples to demand that companies negotiate any developments on their ancestral territories (Gibson & Bradshaw 2018; Curran, 2019). Insisting on FPIC is based on the premise that Indigenous Peoples are able to determine whether development occurs on their lands, the form it takes, if acquiesced, and the opportunity for its continual review and re-negotiation with changing operating conditions and inter-generational values (Gibson & Bradshaw, 2018).

6.4.3. Frameworks for understanding and achieving Cultural Licence to Operate

Wyatt (2016) presents a framework which has been developed with particular attention to Indigenous experiences in the natural resource industry and provides broad characteristics of the elements to obtain and maintain cultural licence to operate. The framework can be applied to a variety of contexts and a range of partnership agreements in which Indigenous groups are engaged in negotiations to pursue their particular objectives and develop their capacity and practice for resource development agreements.

The framework consists of two main components called Path elements and Collaborative arrangements. Path elements contribute to obtaining and maintaining cultural licence to operate and are: (i) effects on socio-economic infrastructure (employment, training, business development, revenue sharing, social services etc); (ii) effects on biophysical infrastructure and the environment; (iii) effective engagement processes and governance; (iv) relationship building and trust; and (v) respecting and exercising rights. The five collaborative arrangements in Wyatt's framework are: (1) Impact and Benefit Agreements (IBAs); (2) Co-management; (3) Consultation processes; (4) Government-issued tenures, rights and licences; and (5) Economic partnerships/Contractual arrangements. Wyatt (2016) shows that no one arrangement type delivers significant contributions across all path elements but that multiple arrangements can be mobilised to do so (Table 6.2). The types of arrangements that contribute most effectively to cultural licence to operate vary with the context, capacity and interests of the Indigenous group and the proponent.

Table 6.2. Pathways to obtaining cultural licence to operate, adapted from Wyatt (2016). Cultural licence to operate outcomes can be obtained through contributions of each type of collaborative arrangement. The efficacy of each arrangement in enabling each element of cultural licence to operate is identified on a scale of 'weak' to 'significant'.

	Examples of collaborative arrangements				
Path elements	**Negotiated impact benefit agreements**	**Co-management**	**Consultation processes**	**Government tenure**	**Economic partnerships**
Effects on socio-economic infrastructure	Medium-significant	Weak	Weak-medium	Medium	Significant
Effects on biophysical resilience	Medium-significant	Medium-significant	Medium-significant	Medium	Weak-medium
Effective engagement processes	Weak-significant	Significant	Weak-significant	Weak	Weak-medium
Relationship building	Medium-significant	Medium-significant	Weak-significant	Medium	Weak-medium
Respecting, protecting and exercising rights	Uncertain	Medium-significant	Medium	Weak	Weak

Hunter et al. (2024) also emphasise that, in the context of cultural licence to operate and the Blue Economy, consent/approval/permission/licence is a not a one-off greenlight or endorsement. Instead, these processes require solid foundations to establish and maintain, and do not exist in perpetuity so can be withdrawn. Hunter et al. (2024) identify seven pillars that support cultural partnership pathways in the Blue Economy, between First Nations and industry, and with co-benefits as the central element. These pillars are: (1) Mutuality Principles (in business ethics); (2) Integrity (partnering with disclosure and within the right authorising environment); (3) Acceptability (checking for underlying limitations); (4) Co-benefits; (5) Agreement (on 'goal posts'), (6) Risk & Impact (partnering by wisely stretching boundaries); and (7) Implementation & Evaluation.

6.4.4. Conclusion

Australia's Indigenous Peoples are rights holders as offshore and submerged landscapes, and access to them, can be culturally important. Any development on Indigenous territories should be done with 'Free Prior and Informed Consent' (FPIC). Different collaborative arrangements are capable of yielding desirable outcomes that contribute to gaining and maintaining a Cultural Licence to Operate.

6.5. Case study: South-West Victoria

The south-west Victoria region was introduced as a case study in Chapter 3, where its enormous wave energy resource was discussed, and revisited in Chapter 4 with respect to coastal protection. Here, we touch on some of the relevant economic, social, environmental and cultural factors.

6.5.1. Local economy, infrastructure, and past projects

> **South-west Victoria has outstanding maritime, industrial and electricity infrastructure.**

South-west Victoria enjoys high-voltage, high-capacity electricity-transmission infrastructure; this services the Portland aluminium smelter, which in 2023 drew on average about 7% of the state's electric power (Alcoa Corporation, 2023; DCCEEW, 2024). An industrial workforce is associated with the smelter and the port of Portland, the only deep-sea mainland port between Melbourne and Adelaide. Furthermore, licences have recently been granted for offshore-wind prospecting off the SW Victorian coast, and natural gas from the offshore Otway Basin has been piped to a plant at Port Campbell since 2006, with further offshore gas deposits in the region continuing to be exploited. Onshore, several major wind farms are well established in the region; wind farms with a combined capacity over 1 GW presently operate in Moyne Shire alone. These economic factors taken together suggest that there is the industrial and human capacity in the region to support a wave-energy industry. Furthermore, there may be potential for economic synergies with offshore-wind infrastructure, particularly undersea cabling.

> **Significant wave-energy proposals have already been attracted to south-west Victoria.**

The combination of excellent resource and economic factors has led to wave-energy proposals and trials in south-west Victoria (Manasseh et al., 2017). In 2014 a proposal to build a 62.5 MW wave farm off Portland was awarded AUD66 million by the Australian Renewable Energy Agency, contingent on raising over AUD100 million in further funding. It was to be based on the floating heaving-buoy WEC already demonstrated by US company Ocean Power Technologies. However, the finding of sufficient finance was elusive, and the project never commenced (Parkinson, 2014). In 2015, an Australian-developed WEC designed by BioPower Systems Pty Ltd was installed for a trial off Port Fairy. During the actual installation, the power cable already laid on the seabed suffered unrepairable damage. This logistic setback was unrelated to the company's technology, but nonetheless consumed its remaining finances, precluding useful operation.

6.5.2. Local environmental and cultural factors

South-west Victoria hosts some of Australia's most popular natural attractions, biodiversity hotspots, and World-Heritage human history.

The coast is renowned for its natural beauty, ecosystem assets and globally recognised cultural significance. Outstanding scenery begins less than three hours from Melbourne, attracting some of Australia's largest tourist numbers. The coast includes habitats for endangered species such as the hooded plover and southern right whale (Watson et al., 2021), as well as seabed-based ecosystems such as kelp forests (Young et al., 2023) and economically significant shellfish resources (Mayfield et al., 2014). These attributes may imply that WEC designs that are entirely submerged may be preferable in some locations, and that construction works may require substantial constraints to prevent seabed disturbances and underwater noise.

The short-finned eel grows to adulthood in inland waters feeding into the ocean in south-west Victoria, migrating approximately three thousand kilometers to breed in the Coral Sea, whence juveniles return to inland waters.

The life-cycle of this edible fish was integrated into an extensive aquaculture industry with eel products traded far afield. Aquaculture was supported by the engineering of extensive permanent earth and stone structures, some dated to 6,600 years ago (McNiven et al., 2012), and part of the Budj Bim Cultural Landscape accorded UNESCO World Heritage status in 2019. The traditional eel-aquaculture industry is now being revitalised. Habitation of the area predates the sea-level rise at the end of the last ice age. Concomitantly, offshore as well as coastal landforms are prominent in local culture. These factors imply that appropriate consultation with Traditional Owners should place any WEC development and operation in a context beneficial to all stakeholders.

International case studies and the current community debates over offshore wind developments in Australia both suggest that appropriate community consultation and in some cases participation would be required to determine the socio-cultural fit with local communities and their activities. Impacts on ecosystems and local industry have been of greatest concern for local communities of offshore wave energy developments (aesthetic values typically will be only minimally impacted in WEC contexts). In such cases, community engagement and relationship-building can be crucial in negotiating a mutually beneficial fit between the community's values and decisions about the technology, location, and operations of the WEC. So too, social acceptability will require transparency in the sharing of ongoing environment assessments, and accountability throughout the development and governance processes.

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Chapter 3 Appendices

Appendix A – Australian Wave Energy Atlas methodology and validation

A first step, when considering a new renewable energy source, is to determine the resource potential. To this end, a comprehensive national wave energy resource assessment was funded by the Australian Renewable Energy Agency (ARENA) and led by CSIRO. The Australian Wave Energy Atlas (AWavEA) project was undertaken to provide the emerging wave energy industry with relevant information to support reconnaissance, feasibility and design-scale applications [Hemer et al., 2017a] [Hemer et al., 2018].

The AWavEA project wave energy assessment was based on the analysis of a global wave model simulation, with focus on the wave climate around the Australian coastline.

A wave hindcast is a wave model simulation over a historic time period that has been forced by atmospheric winds to provide a spatially and temporally continuous depiction of the wave field and corresponding wave climate over past decades. In the AWavEA project, a multi-decadal wave model hindcast that had previously been developed for the Australian and Pacific region was validated against available wave buoy and satellite data around the Australian coastline. This was to ensure its suitability for assessing the wave energy resource compared with other similar products. A detailed analysis of the wave energy resource was then undertaken.

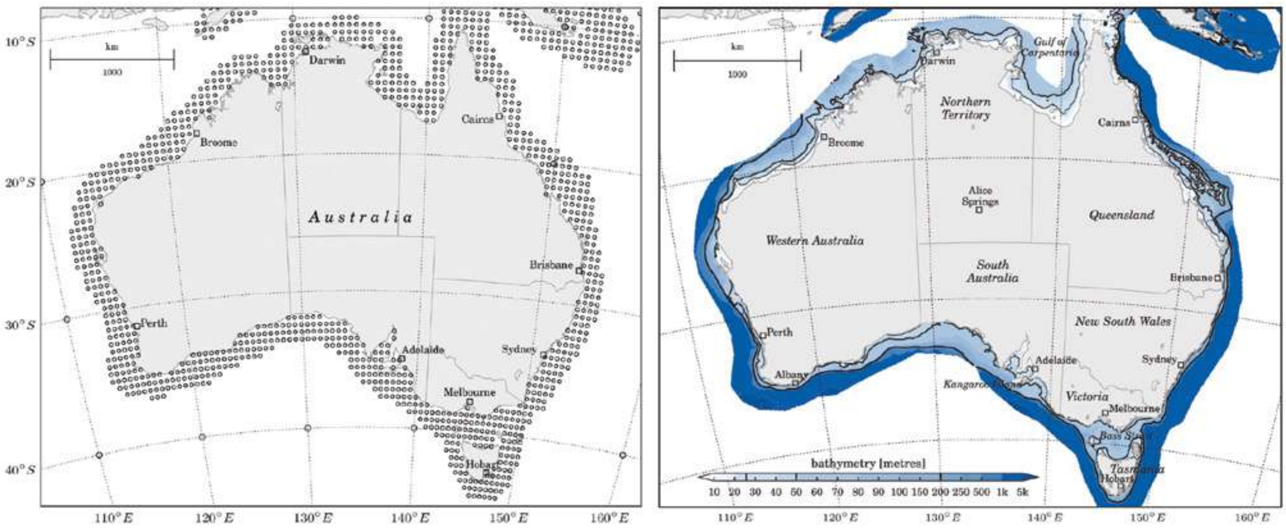
The global wave model simulation was undertaken using the WAVEWATCH III™ model (v4.08,) on a global model grid at 0.4° x 0.4° resolution with two nested grids of 10' (~18 km) and 4' (~7 km) around the Australian coast. The use of nested grids was to allow two-way transfer of information between the different grids and more detailed information on the highest resolution grids that surround the Australian coastline (Figure 3.11 left panel).

Note that the numerical model does not simulate individual waves (i.e. individual wave crests and wave troughs) but describes the evolution and propagation of wave energy. The simulated wave conditions, at a given grid location and typically predicted with an hourly temporal resolution, are referred to as a sea-state.

The digital bathymetric dataset DBDB2v3 (https://cmr.earthdata.nasa.gov/search/concepts/C1214614815-SCIOPS.html), which is a map of water depths above the ocean floor (Figure 3.11 right panel), with resolution of 2' is used in the model. Blocking of wave energy by sub-grid-scale obstacles such as small islands is parameterised using the high-resolution shoreline database GSHHS [Wessel and Smith, 1996],[Chawla and Tolman, 2008]. The analysis of the Australian wave energy resource was based on the 4' nested (aus_4m) grid surrounding the Australian continent. The wave climate simulations were forced by wind fields from the Climate Forecast System Reanalysis (CFSR) dataset [Saha et al., 2010] and its extension Climate Forecast System Version 2 (CFS2) [Saha et al., 2014], produced by the US National Centers for Environmental Prediction (NCEP).

These reanalyses provide hourly global surface winds at 0.3° spatial resolution from 1979-2010 and 0.2° resolution from 2011 onwards.

Figure 3.11: The wave hindcast output points available from the global resolution grid at 10° increments and from the higher resolution grid around the Australian coast at 0.5° increments (left) and the bathymetry used in the model, including 25 m, 50 m and 200 m depth contours (right). Source [Hemer et al., 2017a; Hemer et al., 2017b].



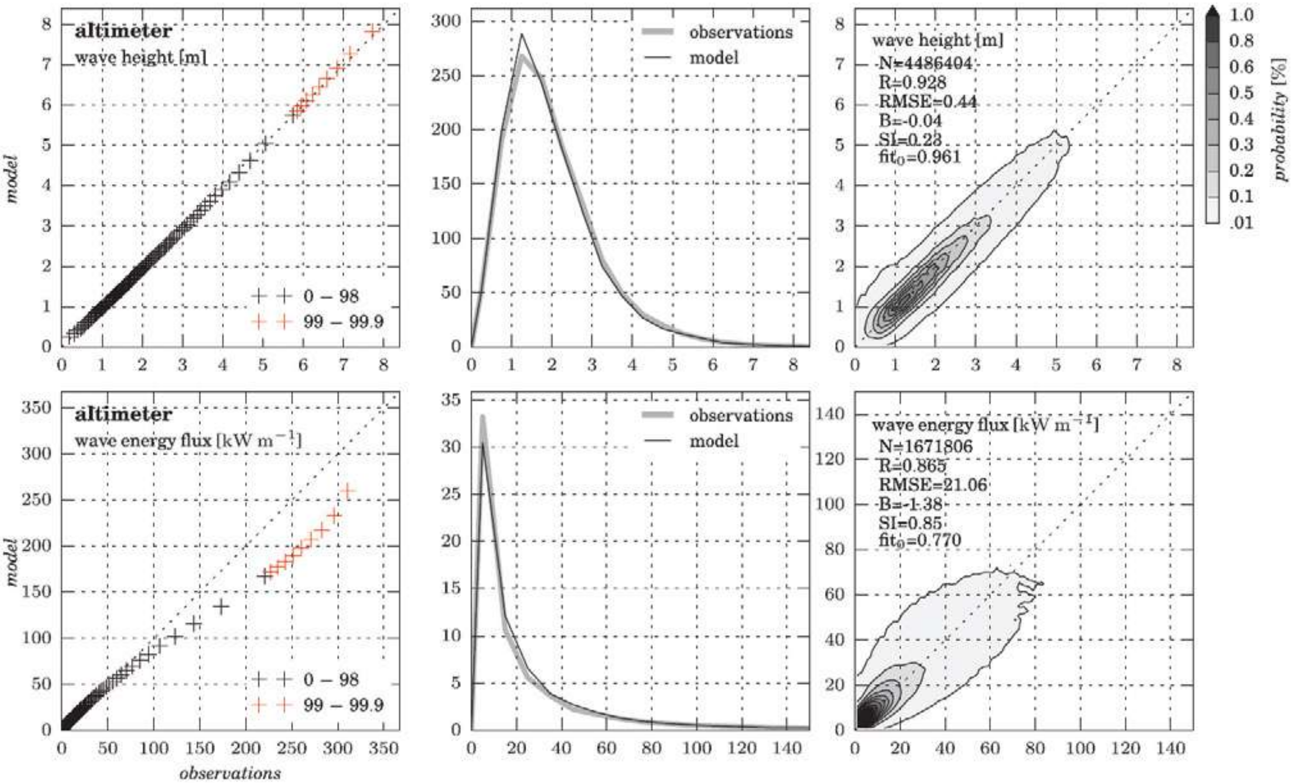
The wave hindcast was assessed in terms of its skill to reproduce significant wave height (Hs), wave period and omnidirectional wave power or wave energy flux (CgE). The assessment metrics included bias (B), root-mean-square error (RMSE), Pierson's correlation coefficient (R) and scatter index (SI). Observational datasets were assembled from available wave buoy data and satellite altimeter derived wave fields. The satellite data was assembled from multiple satellite altimeter missions in operation since 1985 to 2012. The simulated wave data was interpolated in space and time across a 150 km band around Australia to coincide with the available observational data.

The model displayed a high correlation with satellite observations with a small negative bias indicating a slight underestimation of values by the model. This tendency is illustrated in Figure 3.12, which shows quantile-quantile plots (left), probability distribution plots (middle) and scatter plots (right) for significant wave height (top) and wave energy flux (bottom). The model and observations generally displayed good agreement up to about the 90th percentile after which the model values are somewhat smaller than the altimeter estimates.

The statistics representing the overall skill of the hindcast compared to satellite observations are provided in the right-hand panels of Figure 3.12. For Hs, these show that the overall correlation is R=0.928, the RMSE is on average 0.44 m. There is a small negative bias (B = -0.04 m) indicating that the model slightly underestimates the satellite values. The wave energy flux exhibits larger scatter compared to Hs and this leads to a lower correlation of R=0.865 and an RMSE of about 21 kW/m.

In summary, apart from the extremes, the modelled wave conditions agree with the satellite observations.

Figure 3.12: Comparison of modelled significant wave height (Hs in units of m, top panels) and wave energy flux (CgE in units of kW/m, bottom panels) relative to observations from altimeters. Legend in the far-right panels shows the goodness of fit by means of number of co-locations (N), correlation coefficient (R), root-mean-square error (RMSE), bias (B), scatter index (SI) and least-square fit through origin (fit0). Source [Hemer et al., 2017a; Hemer et al., 2017b]

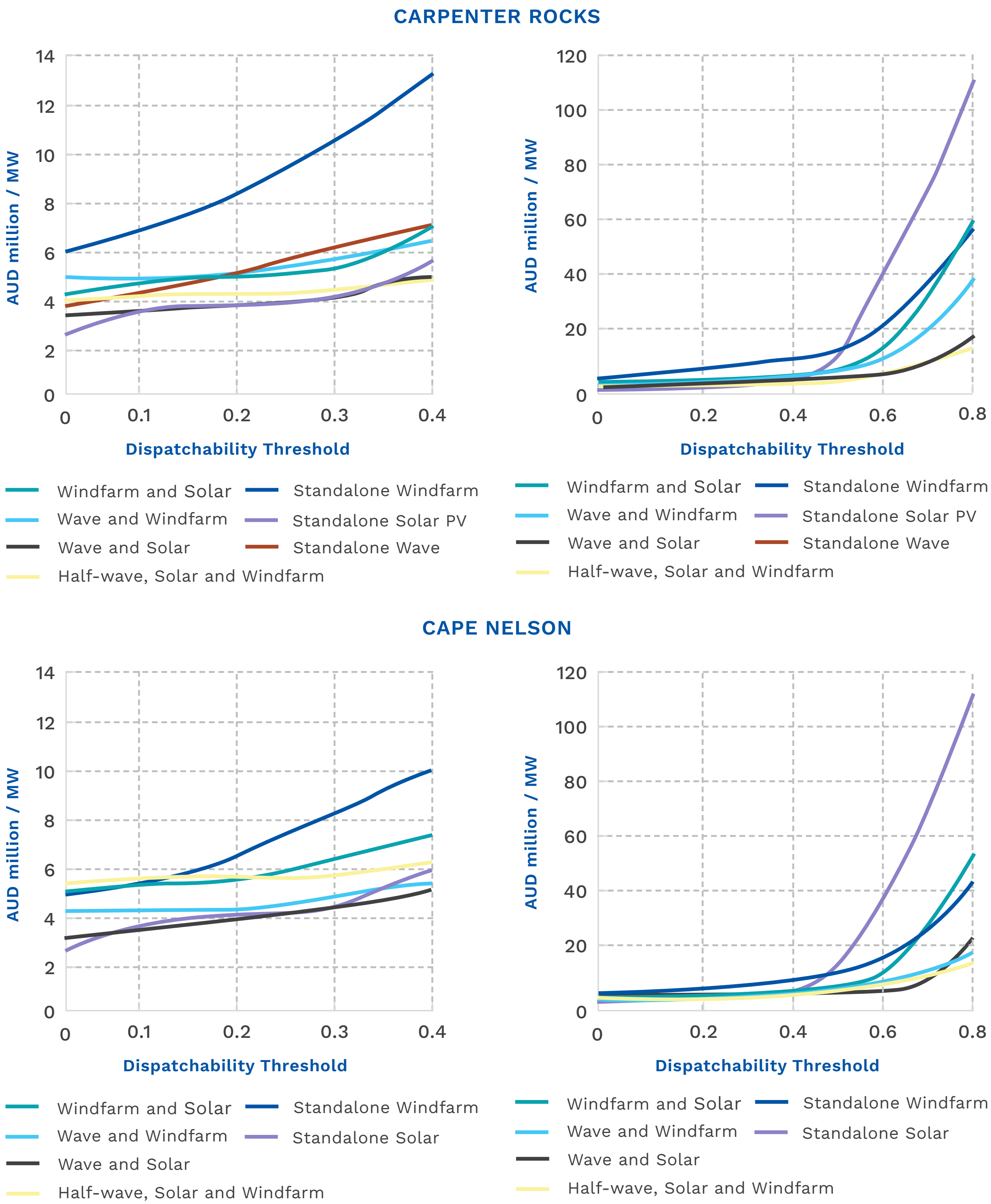


For the validation against buoy data, the average model Hs across all locations agreed well with observations (correlation 0.860) with an overall bias of 0.08 m and root-mean-square error of 0.38 m. For wave energy, the overall model bias was 4.3 kW/m and root-mean-square error was 12.9 kW/m. Differences between model and buoys can be attributed to the proximity of buoys to the coastline and associated water depths which are poorly resolved by the model resolution. There are also negative biases in Hs in the north due to known biases in the CFSR winds in the equatorial region together with likely poor resolution of extreme winds associated with tropical cyclones. Other regions with larger errors include over the Great Barrier Reef where, again, resolution of bathymetry over the reefs is likely a contributor (see the bathymetry map in Figure 3.12 right panel).

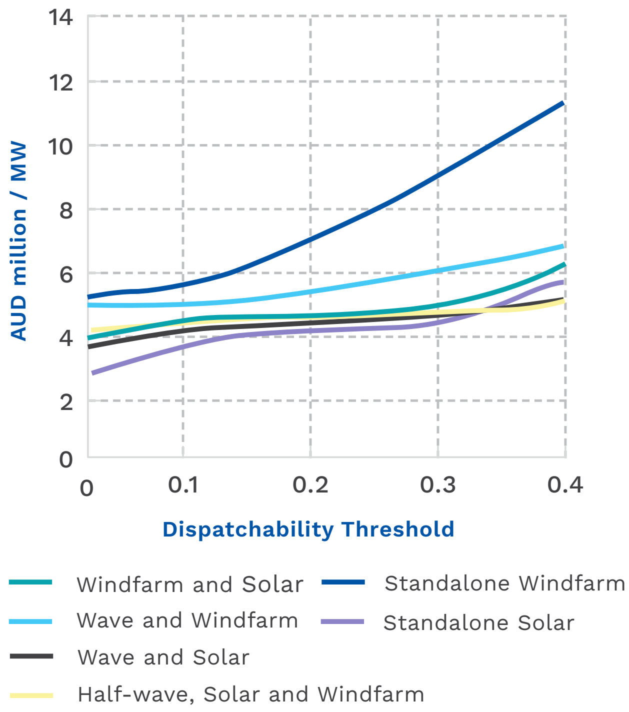
Chapter 4 Appendices

Appendix B – Dispatchability cost analysis for three sites along the south coast of Australia

Figure 4A-1: Dispatchability cost analysis for three sites along the south coast of Australia.



WARRNAMBOOL
(lower significant wave heights and stronger wind resource)



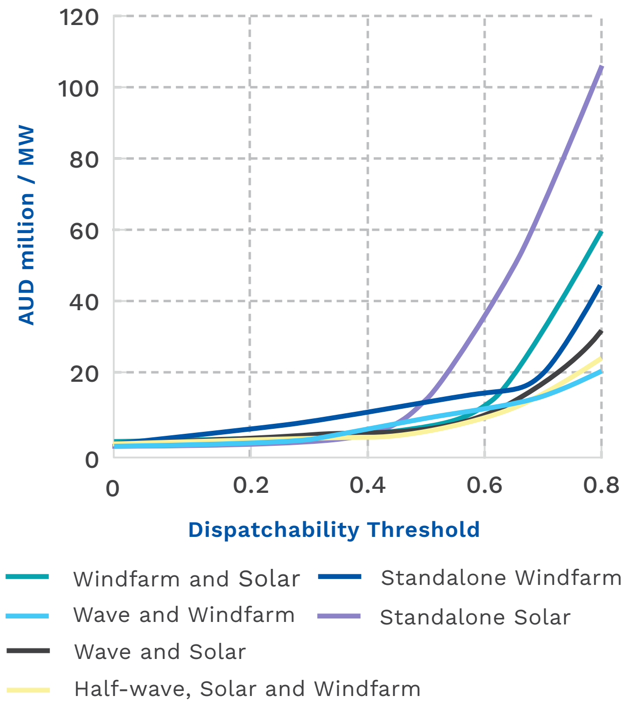
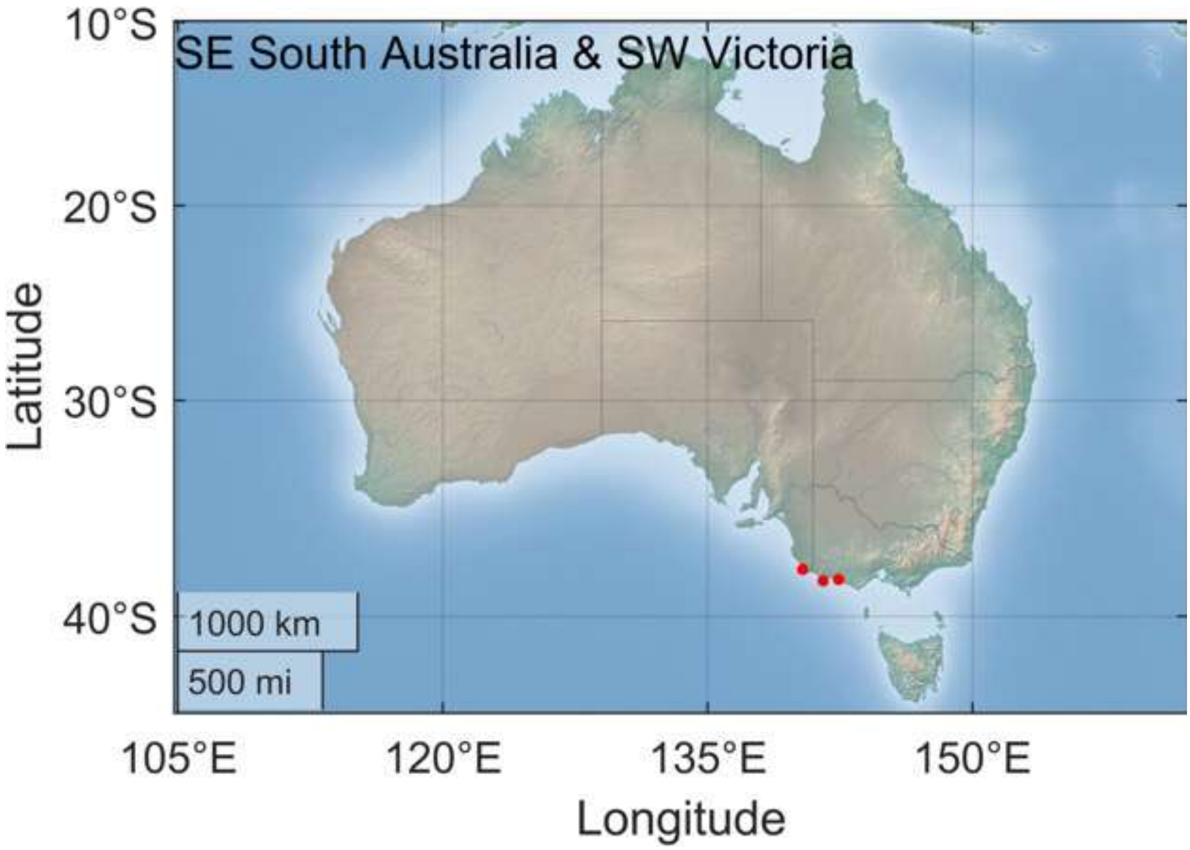
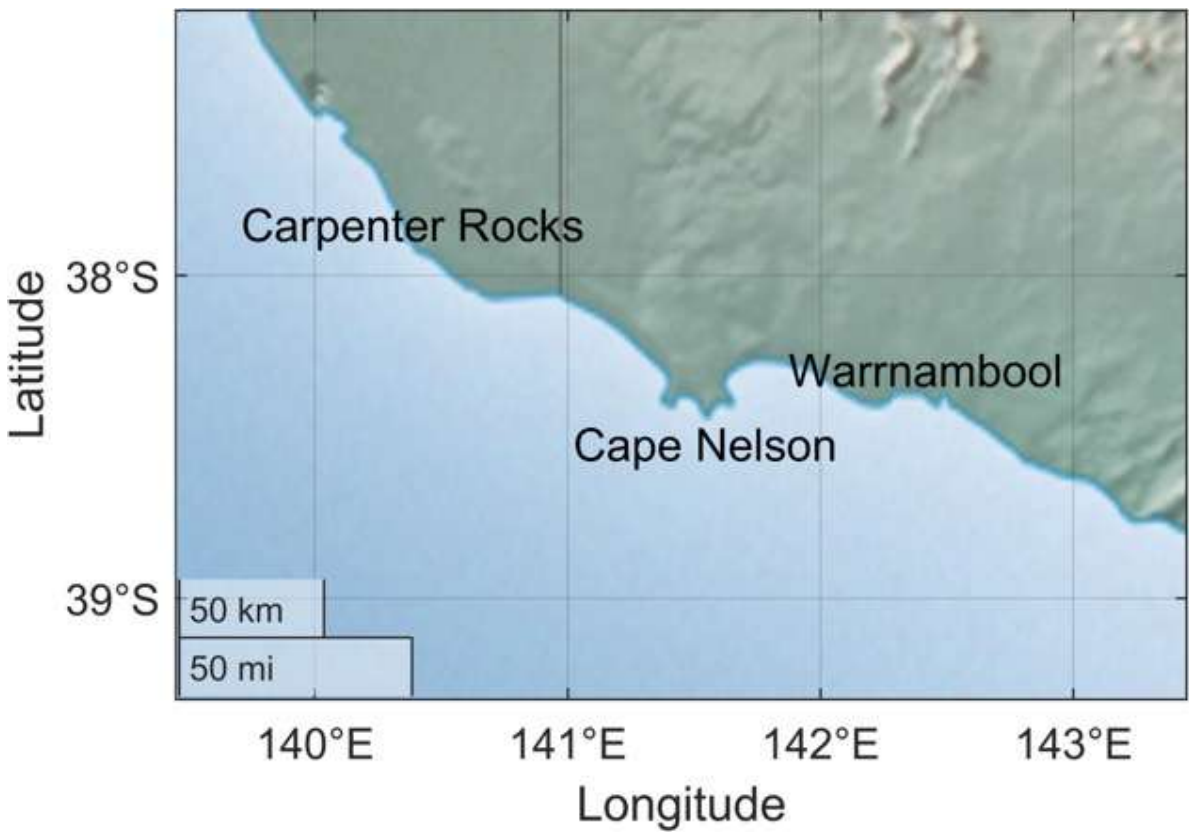


Figure 4A-2: Locations of the three sites considered along the south coast of Australia.





Appendix C – Figures in terms of rated power

Figures and tables referencing rated power are included here to acknowledge that rated power is usually used as a reference for CapEx estimates. Their inclusion here allows comparisons with studies that use rated power. However, this report does not recommend using rated power as a reference to report the CapEx required for dispatchable power systems that use intermittent resources such as wave, wind or solar energy. Rated power values are generally somewhat arbitrary; they also report a CapEx that is deceptively low because it does not account for the system's capacity factor. The alternative used in this report is average power. The examples given in the report use power that has been averaged over a 24-hour day.

Figure 4B-1: CAPEX estimates per MW rated power for standalone renewable energy resources to achieve from 0 to 0.7 dispatchability.

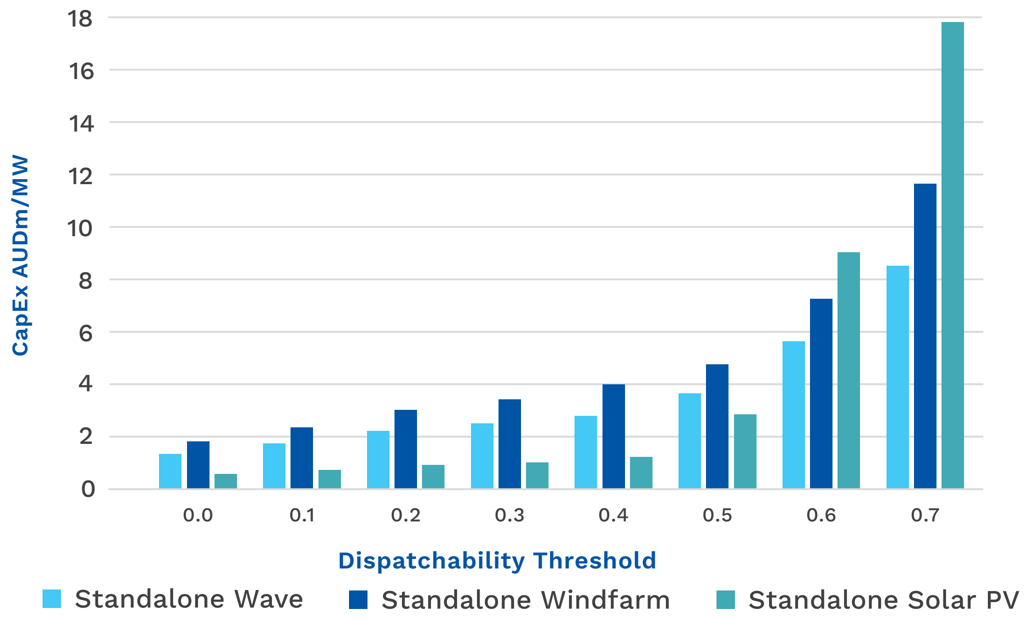
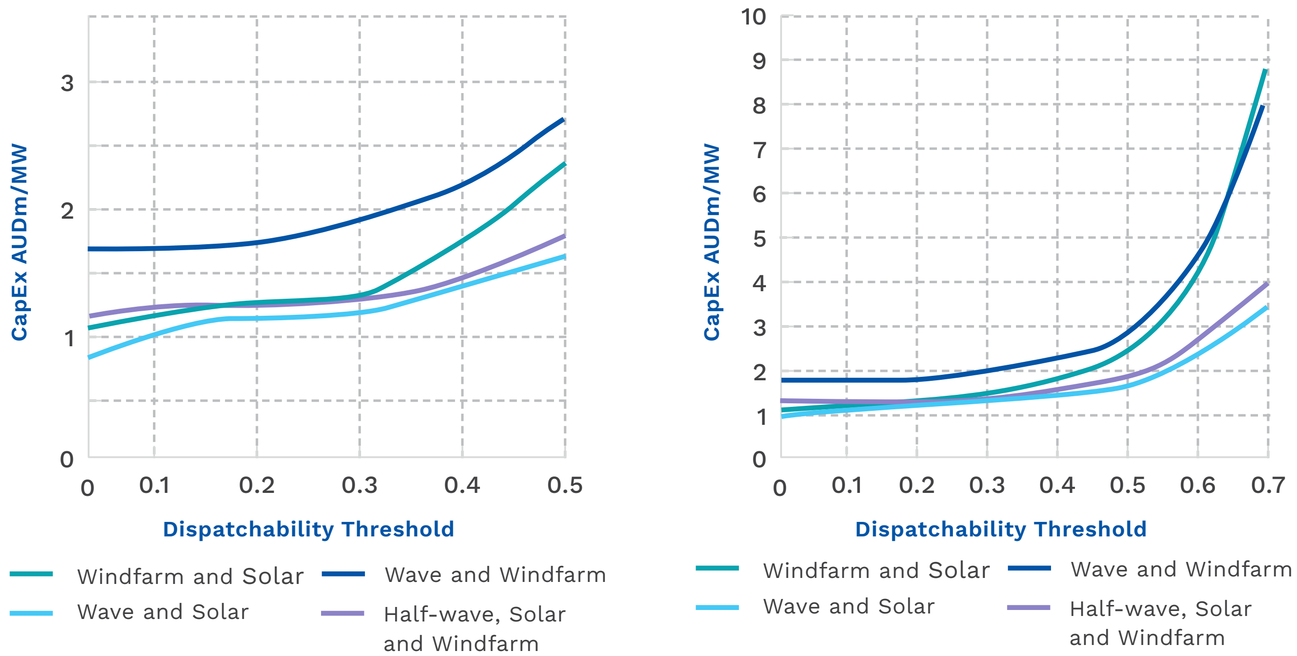


Figure 4B-2: CAPEX 2050 estimates per MW rated power for a range of hybrid renewable energy resources to achieve 0.1 to 0.7 dispatchability. Location Carpenter Rocks. This figure shown allows comparison with systems that use rated power as the reference for their CapEx estimates.



Appendix D – Interfacing wave energy with the National Electricity Market

AEMO and the AEMC have recently released an update to the National Electricity Rules. This allows a hybrid power plant system to be registered as an Integrated Resource Provider (IRP) (Figure 4C- 1). Such a system may include intermittent solar arrays and wind farms, and potentially wave energy farms), together with energy storage. Registration as an IRP provides access to Aggregated Dispatch Conformance bidding. AEMO describes levels of reliable electricity generation in terms of the availability of electricity supply from scheduled and semi-scheduled generators. There are generally far fewer bid opportunities for semi scheduled generators. The following outlines the meaning of the key terms in the figure.

It is important to distinguish between the terms *'Plant Availability'* used by AEMO and the traditional concept of electrical power availability. Electrical power availability is the percentage of time a generator is available. AEMO define Plant Availability as *"The active power capability of a generating unit (in MW), based on the availability of its electrical power conversion process and assuming no fuel supply limitations on the energy available for input to that electrical power conversion process."* A dispatch target is defined here as the minimum of:

Maximum Planned (Plant) Availability offered for the period

AND

Unconstrained Intermittent Generation Forecast (UIGF) from five minutes to two years ahead.

A scheduled generator or group of generators is characterised as:

- having a capacity greater than 30 MW,
- capable of continuous supply at rated capacity assuming no fuel limitations.

A semi-scheduled generator is characterised as:

- An intermittent generator such as solar or wind,
- Required to curtail power delivery for levels above the target level,
- Allowed to generate below the target level dependent on the resource (wind/solar) availability. However, there may be costs associated with such generation.

The commercial value of wave, solar and wind hybrid dispatchability, in this context, would be the enhanced ability to maximise UIGF which otherwise could be a limiting factor in bidding. An ambitious target might be to design a renewable system that met scheduled generator requirements.

In future, the following issues should be clarified with AEMO:

- The commercial value of complementarity may be lost in the current processes for evaluating individual unit UIGFs in a hybrid facility. To include complementarity, it may be necessary to evaluate combined unit UIGFs at the connection point (AEMO 2024).
- Wave energy forecasts are not included in the NEM, what is required for such forecasts to be acceptable?

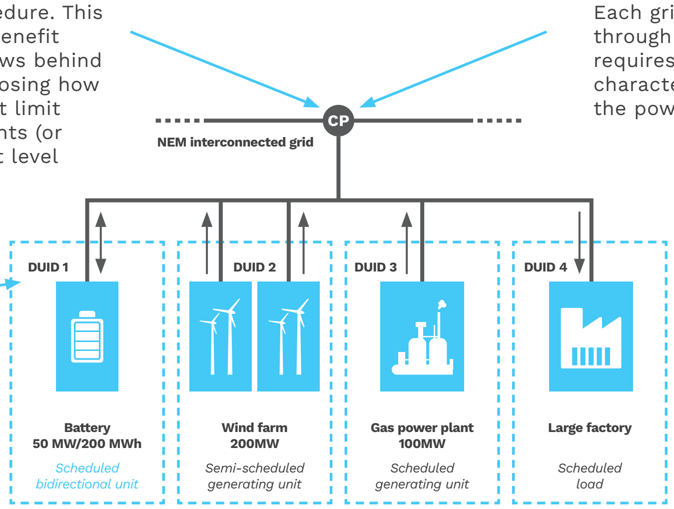
Figure 4C-1: Example of a hybrid facility that might be registered as an integrated resource provider © Australian Electricity Market Commission (AEMC, 2021), Source: National Electricity Amendment (Integrating Energy Storage Systems into the NEM) Rule 2021.

The AER would measure **compliance with dispatch** at the connection point or at unit level, as determined by an AEMO power system operating procedure. This will allow hybrid systems to benefit from self managing energy flows behind the connection point and choosing how to meet dispatch. This will not limit AEMO's ability to set constraints (or instruct/direct etc) at the unit level where appropriate.

A participant seeking to set up a hybrid facility would **register** as an IRP.

Performance standards would be set at the unit level but would be measured at the connection point. Each grid-scale unit would connect through Chapter 5 of the NER, which requires information on the technical characteristics of the unit that impact the power system.

Single DUID for integrated resource units. This is a change from the two DUIDs that currently exist for grid scale batteries. The participant would have 20 price bid bands (10 for load and 10 for generation).



Classifications and scheduling would be at the unit level for both the energy and ancillary service markets. AEMO would send dispatch instructions to each unit.

This diagram is an examples of a potential hybrid facility. A hybrid facility could vary in the number and type of units behind its connection point.

Chapter 6 Appendices

Appendix E – Additional relevant acts for wave energy project developments

Alongside the key OEI and EPBC Acts, additional Commonwealth approval requirements depend on the location and nature of the proposed activities, with key Acts outlined in Table A - 1.1 (NOPSEMA, 2022).

Table A - 1.1: Relevant Acts for Wave Energy Projects in Australian Commonwealth Waters

Act	Purpose
Aboriginal and Torres Strait Islander Heritage Protection Act 1984	To protect areas and objects that are of particular significance to Aboriginal and Torres Strait Islander people.
Australian Maritime Safety Authority Act 1990	To promote maritime safety, protect the marine environment from pollution from ships and other environmental damage caused by shipping.
Biosecurity Act 2015	To manage biosecurity risks to protect the economy, environment, and community from pests and diseases.
Control of Naval Waters Act 1918	Limits usage of waters near Defence installations and lands.
Coastal Waters (State Powers) Act 1980, Coastal Waters (Northern Territory Powers) Act 1980	Outlines the limits of the waters adjacent to each of the Australian States and of the Northern Territory.
Environmental Protection (Sea Dumping) Act 1981	Regulates the loading and dumping of waste at sea and the creation of artificial reefs in Australian water.
Fisheries Management Act 1991	Governs the management and conservation of fisheries resources within Australian waters.
Great Barrier Reef Marine Park Act 1975	Legislation specific to the Great Barrier Marine Park and surrounds.
Lands Acquisition Act 1989	Commonwealth acquisitions and disposals of interests in relation to land.
Maritime Transport and Offshore Facilities Security Act 2003	Security of maritime transport and offshore facilities against potential security threats and terrorist activities.
Offshore Petroleum and Greenhouse Gas Storage Act 2006	Framework for the exploration and recovery of petroleum and greenhouse gas activities in Commonwealth waters.
Native Title Act 1993	Recognizes and protects the rights and interests of Aboriginal and Torres Strait Islander peoples in land and waters based on their traditional laws and customs.
Seas and Submerged Lands Act 1973	The domestic legal framework for Australia to declare its international offshore maritime zones.
Underwater Cultural Heritage Act 2018	Ensures that underwater cultural inheritance is protected for future generations.
Underwater Cultural Heritage (Consequential and Transitional Provisions) Act 2018	Protection of Australia's shipwrecks, and has broadened protection to sunken aircraft and other types of underwater cultural heritage including Australia's Aboriginal and Torres Strait Islander Underwater Cultural Heritage in Commonwealth waters.
Work Health and Safety Act 2011	Secure the health and safety of workers and workplaces through the elimination or minimisation of risk.

Appendix F – Key international agreements

The Australian government has entered into a number of international agreements that may guide or impact planning and decision-making in the marine environment. These need to be considered in developing plans and are outlined in Table B - 1.1 (NOPSEMA, 2022).

Table B - 1.1: International Agreements Applicable to Wave Energy Developments

International Agreements	Purpose
Agreement on the Conservation of Albatrosses and Petrels 2004 (ACAP)	To conserve albatrosses and petrels by coordinating international efforts to mitigate threats to these seabirds.
China-Australian Migratory Bird Agreement (CAMBA) 1988	To protect migratory birds and their environment between the two countries.
Convention on the Conservation of Migratory Species of Wild Animals 1983 (CMS) (Bonn Convention)	A global platform for the conservation and sustainable use of migratory animals and their habitats.
Convention on Wetlands of International Importance especially as Waterfowl Habitat 1971 (Ramsar Convention)	To halt the worldwide loss of wetlands and to conserve, through wise use and management, those that remain.
East Asian-Australasian Flyway Partnership	Flyway-wide framework to conserve migratory waterbirds and their habitat.
International Convention for the Control and Management of Ships' Ballast Water and Sediments 2004	Help prevent the spread of potentially harmful aquatic organisms and pathogens in ships' ballast water.
International Whaling Commission (IWC) 1946	Protection and conservation of cetaceans (whales, dolphins and porpoises).
Japan-Australia Migratory Bird Agreement (JAMBA) 1981	Measures for the management and protection of migratory birds, birds in danger of extinction.
Republic of Korea-Australia Migratory Bird Agreement (ROKAMBA) 1986	Prevent harm to these birds and their environment through the prohibition of the taking or trading of listed birds and their eggs, the control of invasive species and other measures.
United Nations Convention on Biological Diversity (CBD)	Conservation of biodiversity, sustainable use of components, fair and equitable sharing of benefits.
World Heritage Convention 1972	Nature conservation and the preservation and security of cultural properties.

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