WSE UniWave
technical and financial feasibility

July 2024

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Contents

Disclaimer and acknowledgment

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1. Project description and overview

The King Island UniWave200 project comprised the design, construction, deployment, operation, and decommissioning of a 200kW wave energy converter (WEC) (see Figure 1), utilising Wave Swell Energy's (WSE) proprietary technology in the ocean adjacent to Grassy Harbour on the south-eastern side of King Island. The term of operation of the WEC was nominated at 12 months, however, with the agreement of ARENA, the WEC was operational for over 14 months. The project culminated in the decommissioning, removal, and subsequent recycling of the WEC to satisfy ARENA's requirements.

The specific objectives of the project were to:

1. Successfully design, construct, deploy, instal, and operate the WEC at the deployment site. See section 2.1
2. Demonstrate the technical feasibility and structural integrity of the UniWave200 through 12 months of operations in real ocean conditions, including confirmation of the conversion efficiency predicted for given wave heights and periods and, thereby, validating the models entailed in the various stages of the technology's power conversion process. See sections 2.2, 2.3 and 2.5.
3. Provide data to enable the optimisation of the WSE electrical control system, the purpose of which was to efficiently convert the mechanical energy of the turbine shaft into electricity, minimising energy wastage, and maximising output. This electrical process incorporated a short-term storage facility, utilising state-of-the-art supercapacitors, to provide a smoother delivery of electrical energy to the grid. See section 2.3.
4. Provide a tangible demonstration of WSE's unidirectional OWC technology's ability to produce useable electrical energy capable of being integrated with and consumed in a remote island grid. See section 2.6.
5. Provide data, information, and experience related to the day-to-day and long-term operation and maintenance of the WSE WEC. See section 2.1.

Each of these specific objectives were achieved. Detail of the results, achievements, and attainment of these objectives is set out in Section 2 of this report.

The project also led to coordination and collaboration, in Australia and globally, between the research community, government, and the ocean energy industry through knowledge sharing activities. WSE collaborated extensively throughout the project with both the University of Tasmania's Australian Maritime College (AMC) and the US Department of Energy (DOE), both of which were provided full access to project data. These collaborations resulted in the performance of the technology being independently assessed and validated.

Construction, assembly, operation, and decommissioning of UniWave200 in Australia was a critical investment in building local capacity, skills and a supply chain to address future demand for the technology, both domestically and globally.

Figure 1 UniWave200 in operation

2. Results and achievements

2.1. Project lifecycle

WSE, along with its partners, developed, designed, built, installed, operated, and then decommissioned its 200kW wave energy converter, dubbed UniWave200, over a 5-year period. This enabled WSE to learn, gain experience, and refine the full project lifecycle.

As the business moves to commercialise its technology, ultimately a significant increase in installed capacity is required to refine the technology. This will result in driving down the capital costs and levelized cost of energy (LCOE). 'Learning by doing' is a well-established and understood process that is critical to this commercialisation endeavour.

The UniWave200 demonstration project has established a baseline from which WSE will further refine its systems, processes, and capability, including:

- Project development – resource assessment, permitting, environmental assessment, stakeholder consultation
- Engineering – Lessons learnt and practical experience to feed back into future designs
- Construction – Methodologies, systems integration, modularisation to streamline timelines
- Installation – Marine operations, planning, weather windows and downtime
- Commissioning – Importance of plug and play, minimising time in the field and offshore
- Opeation – Proven autonomous control and optimisation as the starting point
- Maintenance – 27 months of in situ upkeep and data to feed back into future designs
- Decommissioning – Recycling, working with weather windows, remediation

2.2. Survivability

The UniWave200 was in situ at King Island for over two years and experienced extreme sea states, the challenges of remoteness, and cold and wet winter months. Given the harsh environmental conditions that are experienced by wave energy converters, exhibiting survival in the inclement conditions of the southern oceans were critical to building confidence in the future success and commercialisation of the technology. King Island provided the perfect location to thoroughly test the UniWave200 structure. On several occasions the maximum sea states for the water depth at the site were observed. The structure stayed in position without moving at all for the 27 months it was on site. Furthermore, no structural damage was sustained, as was evident through visual inspections. WSE also established the robustness and mobility of the technology when, after 27 months in situ, UniWave200 was refloated, towed two kilometres, and resettled in a new location for the purposes of decommissioning, demolition and recycling.

Figure 2 UniWave200 being pounded by large waves

2.3. System efficiency

An important goal of the project was to maximise the amount of energy in the waves that was exported into the grid for each given wave condition. Most of this optimisation process was realised via the turbine. A constant speed algorithm was initially utilised, resulting in wave to grid efficiencies of approximately 35% in sea states above 1m. Over time, various iterations of a variable speed control algorithm were developed that improved that efficiency to almost 50% (Figure 3)

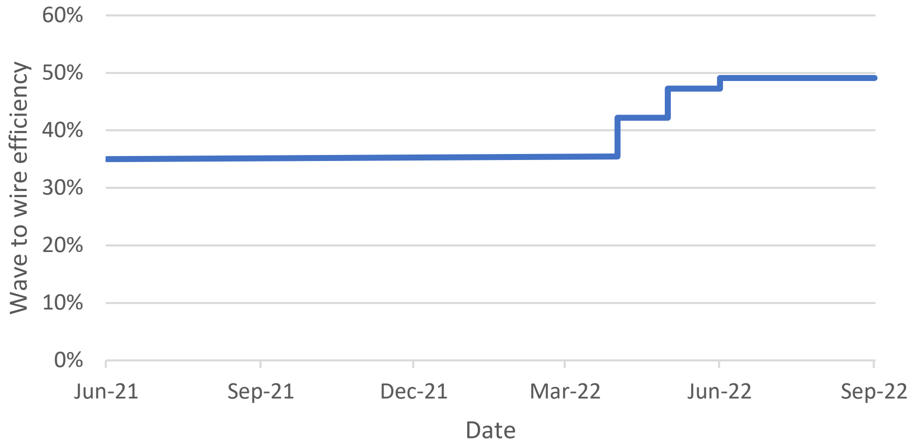

Figure 3 Turbine control efficiency over time

As can be seen in Figure 4, the wave to wire efficiency in sea states above 1m are consistently around 50%. These more efficient sea states are of greater interest for commercial installations, which will have higher average incident energy levels with significant wave heights regularly above 1m. Further details on the full system efficiency can be found in (see appendix 6.1)

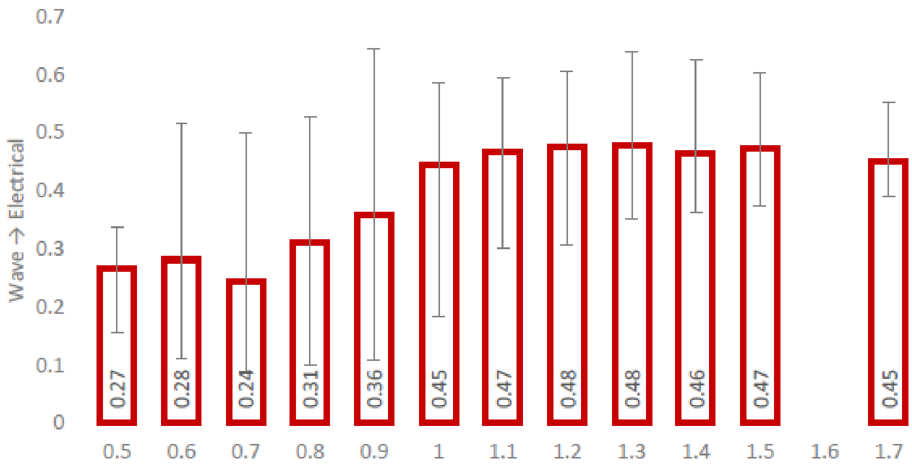

Figure 4 UniWave200 conversion efficiencies

2.4. Availability

The first six months of operation were spent experimenting in order to optimise various aspects of the control system, with the goal being to achieve reliable and fully autonomous operation in line with the project's functional description. As mentioned earlier, optimising the turbine control to maximise power output for each wave condition was a core aim during this period.

Examples of other control features include automated stop and start based on sea state limits, remote communications and operation, export power profile to match Hydro Tasmania requirements, and pressure relief control during larger sea states. The focus throughout the subsequent period until decommissioning was on maximising the uptime and, therefore, availability. Throughout this 6-month period, the average availability was 80%, meaning the unit was in an operational state and able to produce power whenever there was sufficient energy in the waves for 80% of this time period.

2.5. Model testing validation

A 1:16 scale model of the UniWave200 device was tested in the Australian Maritime College (AMC) model test basin in January 2022. A range of conditions and environmental parameters were tested to mimic those experienced at King Island. AMC is a global leader in testing ocean energy technologies. AMC adopts the recommended procedures by the International Towing Tank Conference (ITTC). A key aim of these documents is to provide guidelines on "best practice" when performing any form of physical experiment. The ITTC have also developed specific guidelines, such as - 7.5-02-07-03.7 Wave Energy Converter Model Test Experiments

There was excellent alignment when comparing the average between model-scale testing and full-scale deployment (Figure 5). This authoritatively demonstrates that model experiments can be used to predict the pneumatic power output of an OWC. Since there is a large range of wave to pneumatic efficiency observed at full-scale, it means that predictions from experimental data will yield better accuracy by also varying the wavemaker's irregular wave parameters, such as random seeding and using different values for 'gamma' parameter. (see appendix 6.1)

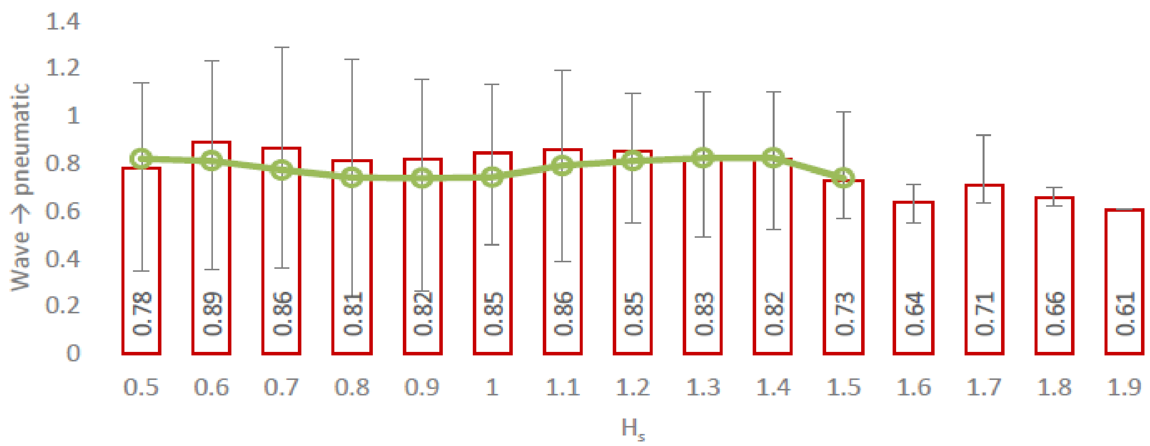

Figure 5 Full scale vs model pneumatic power comparison

Good agreement, within 10%, was observed between predicted and model power when using more energetic time series waves

2.6. Grid connection

As shown in the following excerpt from the accompanying confirmation letter from Hydro Tasmania, UniWave200 commenced exporting energy into the grid on King Island on 18 June 2021:

"Please be advised that, subsequent to Wave Swell Energy Ltd (WSE) having commenced the provision of electrical energy into Hydro Tasmania's electrical network on King Island from its 200kW wave energy generator at Grassy Harbour on 18 June 2021, Hydro Tasmania acknowledges that date as the Commissioning Date, as described in the contract titled Connection and Power Purchase Agreement dated 5 June 2019 between the two parties (Agreement)."

Prior to connection, WSE was required to meet an extensive set of requirements, as detailed in the PPA and connection agreement with Hydro Tasmania. This included*:*

- Compliance with all safety laws, regulations, and good practice
- Agreed operational requirements
- Power quality
- Earthing
- Electromagnetic interference
- Protection
- Islanding

2.7. TRL level

The WSE technology, as demonstrated via the UniWave200 unit, has attained a technology readiness level of TRL 9.

The ARENA TRL standards define TRL 9 in the following way - "Actual system proven through successful operations: Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place".

All these technology requirements have been attained as part of the UniWave200 demonstration at King Island, with independent third-party documentation (AMC, US DOE) validating the thorough and successful demonstration and testing of the technology in a real ocean operational environment.

The integration of the hardware and software systems resulted in a smooth delivery of electrical energy to the grid that met all the requirements of Hydro Tasmania for commercial power. The 14-month demonstration of the unit not only provided successful operating experience for WSE, but also facilitated the compilation of detailed documentation and engineering support to sustain future versions of the technology in subsequent projects.

2.8. Environmental and noise assessment

Marine Solutions Tasmania Pty Ltd (see appendix 6.3). conducted an environmental survey in Grassy Harbour, King Island, on the 19th of December 2022, to facilitate an Environmental Impact Assessment (EIA) of the UniWave200 installation. The objective of the EIA was to determine if the deployment and operation of the UniWave200 had any detectable impact on the ocean, seafloor, and ecology of the immediately surrounding area.

The assessment concluded there were no detectable environmental impacts of the installation beyond the obvious expected impacts of the physical structure itself (i.e. footprint on seabed, structure for substrate for colonising algae). Overall, with respect to the parameters tested in the survey, the report stated "the UniWave200 does not appear to have had any noticeable effects on the receiving environment during its operational phase".

A noise study was also undertaken in collaboration with Ecopulse Pty Ltd (see appendix 6.4). For receptors at the nearest accessible point on the beach (50m from the WEC), the highest recorded sound level was 64.3dB, which is a little louder than normal conversation, and a little softer than a washing machine.

2.9. Building capacity in Australia

During the project, WSE worked with over 125 companies and countless individuals on all aspects of the project, including R&D, engineering, project planning, construction, deployment, O&M, and decommissioning. The experience, learning, and skills gained by these organisations and individuals has greatly enhanced the capacity of the Australian workforce to build future versions of the WSE technology in order to meet demand, both domestically and globally.

2.10. Collaboration with research

As part of the UniWave200 project, WSE collaborated directly with both the Australian Maritime College (AMC - a division of the University of Tasmania) and the US Department of Energy (DOE). AMC were provided with full access to all performance and operational data from the project, and subsequently independently analysed the performance of the WEC, validating the conversion efficiency across the full range of wave conditions experienced and providing reports documenting this analysis. The DOE, through its Pacific Northwest National Laboratory (PNNL), independently analysed and assessed the efficiency data.

In addition, the DOE subsequently requested permission to write an independent peer reviewed paper to be published in an international renewable energy journal. This paper is currently in the process of final review for publication in the globally renowned Institute of Electrical and Electronic Engineers Transactions on Renewable Energy journal.

3. LCOE and Financial Analysis

(see appendix 6.2)

The experience in constructing the UniWave200 WEC, and the subsequent results emanating from the project at Grassy, allow for a calculation of both the energy production of larger units at more energetic sites and the capex and O&M costs of such WECs. These calculations then allow for the LCOE of these larger commercial projects to be determined.

The construction experience gleaned from the UniWave200 experience suggests a follow-on WEC with a 1 MW capacity would involve a capex of roughly $14 million. Using an O&M “percentage of capex” of 3.02% (as used for marine renewable technologies by both the IEA and CSIRO, representing an estimate of the sum of the fixed and variable O&M costs), along with an annual energy production for such a unit in a typical southern Australian wave climate of 3 GWh (based on the performance results of the UniWave200), with a 25 year project life and a 5.99% discount rate (as used by the CSIRO for marine renewable projects, see appendix 6.2), allows for an appropriate LCOE calculator to be applied, in this case, the following definition (in italics) used by the CSIRO’s Energy Division (see appendix 6.2).

The levelised cost of electricity (LCOE) is a metric commonly used to compare the cost of generating electricity between different technologies. It represents the cost only; it does not include revenue, taxes or depreciation.
The standard formula for the LCOE in $/MWh is:

$$LCOE = IDC \times \frac{r \times (1+r)^L}{(1+r)^L - 1} \times \frac{K\ x\ Capacity}{Annual\ Generation} + \frac{O\&M_{FIX}\ x\ Capacity}{Annual\ Generation} + O\&M_{VAR}$$

where r is the discount rate, L is the lifetime, K is the capital cost in $/MW, Capacity is the plant’s peak capacity in MW, Annual Generation is the plant’s output over a year in MWh, O&MFIX is the fixed operations and maintenance (O&M) cost in $/MW/year, and O&MVAR is the variable O&M cost in $/MWh.

IDC is the ‘interest during construction’ which is paid over the construction period. It is given by:

$$IDC = \sum_{i=1}^{P} \frac{1}{P} \times (1+r)^{(i-1)}$$

where P is the construction period in years and assumes the same annual payments during the construction period.

Applying these inputs lead to an LCOE of $517/MWh.

Of course, as the scale of projects increases, the cost of generating energy will decrease. The CSIRO has conducted a detailed analysis of the expected reduction in the cost of the generation of the WSE technology, based on established learning curve effects and the results from the King Island project (see appendix 6.2).

This analysis concluded that, by the time 10 MW of the WSE technology is installed on a global cumulative capacity basis, the LCOE of the WSE technology will have decreased to $251/MWh, dropping further to $129/MWh at 100 MW of installed capacity, and to $66/MWh at 1000 MW.

Furthermore, the CSIRO analysis, using its state-of-the-art GALLUM-E computer model (an integral component of its annual GenCost analysis), predicts the WSE technology can attain a 1.3% share of the global electricity market by 2050, valued at in the order of $100 billion in revenue.

4. Technical risks and mitigation

During the planning phases of the King Island project projects risks were assessed and certified through an independent third-party auditor to comply with AS 31000:2018 Risk Management Guidelines Safework Australia Safe Design of Structures Code of Practice Oct 2018. These risks were continually assessed throughout the course of the project.

The following table summarises the key risks encountered during the project and the mitigation measures either undertaken or to be undertaken in future projects

Risk	Description and Mitigation
Scour	The potential for scour of the seabed around the base of the UniWave200 structure was considered a possibility prior to deployment of the unit and actions were planned in the event that this did become an issue. As it transpired, scour did eventuate, and it was necessary for mitigation actions to be enacted. This involved the placing of rock bags around the base of the unit to ensure the stability of the sand making up the seabed in that location. This action stabilised the unit and no further scour issues ensued.
Commissioning delays	Commissioning took some time, as it was necessary to run through all the checks and systems tests. While acceptable for a demonstration project, future projects will require plug and play components with 'full system' commissioning and factory acceptance happening prior to installation.
Downtime due to unavailable autonomous and remote operations	In the early phases of the project all operations were undertaken on board. As confidence grew in the control systems, operations moved onshore using CCTV cameras and then, finally, fully autonomous operations. This caused delays in the early phases as weather restricted access to the unit and, furthermore, meant the unit was not initially operating in medium to large sea states. Given the learning and control system development, this risk can be mitigated by utilising the already developed control code.
Mechanical/Electrical failures	To avoid failures and downtime, all mechanical and electrical systems were located out of the water and protected from water ingress. Next iterations of the technology will take this to a new level, with additional protection to extend the life of the systems out even further.

5. Moving forward

5.1. Regulatory approvals

WSE undertook appropriate steps to ensure all regulatory approval pathways and timelines were addressed as part of the King Island demonstration pilot, and WSE now has a comprehensive understanding of the relevant regulatory landscape in Australia.

Given the expected global demand for WSE ‘s technology, understanding relevant regulatory approval pathways in different markets around the world is a key criterion in determining the feasibility and attractiveness of project opportunities, and WSE will undertake appropriate due diligence on a case-by-case basis.

5.2. Manufacturing potential

WSE is considering the future potential of establishing a centralised manufacturing and integration facility in Australia. As was proven with the fabrication and construction of the UniWave200 unit for the King Island pilot project, Australia has the skills and resources required to support the establishment and operation of such a facility. Doing so ensures the economic and social benefits associated with the establishment of a new manufacturing capability serving a global demand will be realised in Australia.

Key to the commercial case for establishment of such a facility will be securing of a pipeline of projects deploying WSE’s technology. This pipeline will be global in nature. Where project locations are outside of Australia, WSE anticipates civil structures will be constructed near to project locations, utilising local resource and skills, and shipping its integrated power take off (turbine, mechanical, electrical and control systems) from the manufacturing and integration facility in Australia to project sites for installation and commissioning.

WSE recently engaged representatives from the National Reconstruction Fund (NRF) with respect to support for a manufacturing and integration facility in Australia. The response from the NRF was positive and we anticipate further constructive engagement with the NRF as commercialisation of our technology progresses.

5.3. Commercialisation

Full commercialisation of WSE’s technology requires WSE to secure a pipeline of projects deploying the technology. Whilst WSE would prefer to be developing a pipeline of projects in Australia, the current lack of federal and state government policy, production targets, and financial support for wave energy technologies in Australian waters has resulted in WSE prioritising its focus on international markets.

WSE is currently working with project developer partners and stakeholders in the Pacific Islands, Maldives, Philippines and the USA on potential deployments of our technology in those countries. We anticipate the unit generation capacity for these projects will range from 250KW up to 1MW and multiple units may be deployed in one project. In each engagement it is a core requirement that the technology deployed delivers acceptable financial returns to project developers and investors and the offtake is the subject of a commercial power purchasing agreement.

We also anticipate different configurations for deployment of the technology. A unique feature of the WSE technology is its versatility. The technology was deployed in a standalone seabed based steel and concrete structure for the purposes of demonstration at King Island, however the unidirectional oscillating water column and power take off can also be deployed in floating structures and in breakwaters, seawalls and port infrastructure. In the specific case of the Maldives, and in certain locations on the west coast of the USA, the integration of WSE’s technology in a coastal structure such as a breakwater or seawall that is designed to combat coastal erosion and rising sea level is of great benefit. The addition of WSE’s technology creates a utility and revenue stream for what would otherwise be the sunk cost of the investment in structures designed for coastal protection.

In developing project opportunities, it is a core requirement the technology deployed delivers acceptable financial returns to project developers and investors and delivers contracted volumes of electricity that will be the subject of commercial power purchasing agreements.

Timelines for completion of feasibility studies, final investment decisions, and implementation vary from project to project and depend upon many factors, including regulatory permitting and approval processes. These factors will determine the timing for commercialisation of the WSE technology. Our best estimate for timing of the commercialisation of the technology is 2026/2027.

5.4. Commercial risks

Lack of public policy and financial support:
Risk: As has been the case with the emergence of solar, onshore wind, and now offshore wind technologies, in order to attract private investment and project financing for projects, public policy and financial support (capital and revenue subsidies) is required for initial projects. In the event no such support is forthcoming, it will be challenging for projects to achieve positive financial investment decisions.
Mitigation: WSE is seeking to identify projects in locations where there is public policy and financial support programmes for the introduction of wave energy and will work with project developer partners, customers and stakeholders to successfully pursue grant funding.

Protracted delays in permitting and approval processes for projects:
Risk: Delays in obtaining all permits and approvals delay the timeframes within which WSE is able to realise revenue and cashflow from project deployments.
Mitigation: WSE is seeking to identify and execute project opportunities with partners that result in optimal timing for project permitting and approvals.

Supply chain disruption:
Risk: Failings in supply chain either logistically or commercially may threaten the timing and commerciality of projects.
Mitigation: The components required to fabricate and construct civil structures within which the oscillating water column and power take-off will be integrated are commonly available. It is intended that turbine manufacture will be under the control of WSE. Other mechanical, electrical and control systems components can be acquired off-the-shelf. The tasks of fabricating, constructing, deploying, and operating units are not complex and can be undertaken by readily accessible labour skill sets.

Intellectual property breaches:
Risk: Competitors of WSE or other third parties may seek to copy WSE’s technology.
Mitigation: WSE has, since inception, undertaken all appropriate steps to comprehensively protect its unique intellectual property in key commercial markets globally.

6. Appendices

6.1. AMC Report

REPORT REFERENCE: 22/M/01(B)

WAVE SWELL ENERGY
UNIWAVE200 FULL SCALE AND 1:16 SCALE
PERFORMANCE COMPARISON
SUMMARY VERSION

11 OCTOBER, 2023

AMCS
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Document Control Sheet

AMC Search Ltd Maritime Way Newnham Tasmania 7248 Australia Tel: +61 36324 9850 Locked Bag 1400, Launceston, Tasmania, 7250, Australia www.amcsearch.com.au	Reference Number:	22/M/01 (B)
	Title:	UniWave200 Full Scale and 1:16 Scale Performance Comparison – Summary Version
	Report Author/s:	Alan Fleming Gregor Macfarlane
	Client:	Wave Swell Energy
	Client Contact:	Scott Hunter
	Client Reference:	N/A
Project Summary:	A concise summary covering the full-scale UniWave200 unit installed at Grassy and model test experimental results conducted at 1:16 scale in January 2022.	

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1	Final – Full Version	15/07/2022	DC	EH	15/07/2022
1.1	Final – Condensed Version	13/10/2022	DC	KW	13/10/2022
1.2	Final – Summary Version	11/10/2023	DC	KW	11/10/2023

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Lead Author

Name	Signature	Date
Alan Fleming		11/10/2023

Report Released By

Name	Signature	Date
Dean Cook		11/10/2023

Figure 1 UniWave200

A 1:16 scale model of the UniWave200 device (Model 21-22) was also tested in the AMC model test basin in January 2022. Experiments were conducted to replicate conditions at Grassy, to compare the pneumatic power at full and model scales. Comparison tests of a bidirectional OWC configuration with a unidirectional OWC were also conducted.

Figure 2 1:16 UniWave200 scale model

3.Key Findings

The UniWave200 OWC, deployed at the Grassy site, has demonstrated excellent hydrodynamic conversion efficiency, consistently exceeding 80% when assessed in terms of incident wave power across the chamber width. This performance underscores the system's capacity to effectively harness wave energy.

Furthermore, the investigation revealed that the average pneumatic to electrical (PTO) efficiency ranged from 50% to 67% when employing variable speed control. This adaptability enhances the system's overall efficiency and versatility in a wide variety of wave conditions.

1. Introduction

This report provides a summary of the performance of the UniWave200 unidirectional Oscillating Water Column (OWC) wave energy device deployed at King Island, including results from both the full-scale demonstration unit and corresponding model scale tests.

The unidirectional OWC is a technology patented by Wave Swell Energy (WSE) and consists of a semi- submerged chamber that encloses a water column that rises and falls under wave action, check valves to relieve air-chamber pressure, and a unidirectional air turbine for energy extraction. As the water column rises (exhalation), the air above the water is displaced from the chamber via a bank of one-way valves, permitting the water column to rise uninhibited, temporarily storing the wave energy in the water column as potential energy.

When the wave recedes, the water column falls (inhalation) and air is drawn into the chamber, resulting in the rotation of the unidirectional air turbine, with the energy subsequently being extracted via the direct-coupled electric generator. The energy extracted during inhalation has been found to be equal to or greater than the amount of energy generated using a bidirectional turbine configuration over the whole wave cycle.

The primary advantage offered by the unidirectional OWC is its ability to optimise and simplify the turbine geometry for the single directional air flow. This includes the ability to enhance the conversion efficiency by the incorporation of twist in the turbine blades.

2. Background

In 2021 WSE deployed a demonstration version of the UniWave unidirectional OWC technology, UniWave200, at Grassy Harbour, King Island (Figure 1). The unit was a gravity based OWC that consisted of a reinforced concrete structure with two pontoons to provide additional buoyancy for self-installation and decommissioning. The unit was 24m long and 13.6m wide with a chamber length of 4m and chamber width of 7m and was installed on a sandy bottom with a mean sea level (MSL) of 5.1m with a ballasted mass of 1080 tonnes. The unit was fitted with 15 bespoke rubber flap air vents and an axial flow air turbine (power take-off (PTO), with a tip diameter of 1.291m directly coupled to a 200kW synchronous electric motor. The electrical system consisted of a DC bus with supercapacitor energy storage and active front end, connected to the King Island electrical grid via a subsea cable linked to a shore kiosk with circuit breakers and a transformer. A regenerative motor drive connected the motor to the DC bus and a dump load resistor was also provided to protect the DC bus against overvoltage.

The wave-to-wire efficiency was also found to be relatively high and very consistent, typically between 45% to 48% for significant wave heights exceeding 1.0 metres. This outcome carries significant implications, as it suggests that future iterations of the UniWave technology, deployed in locations with waves exceeding 1.0 metre most of the time, could operate with even higher conversion efficiencies.

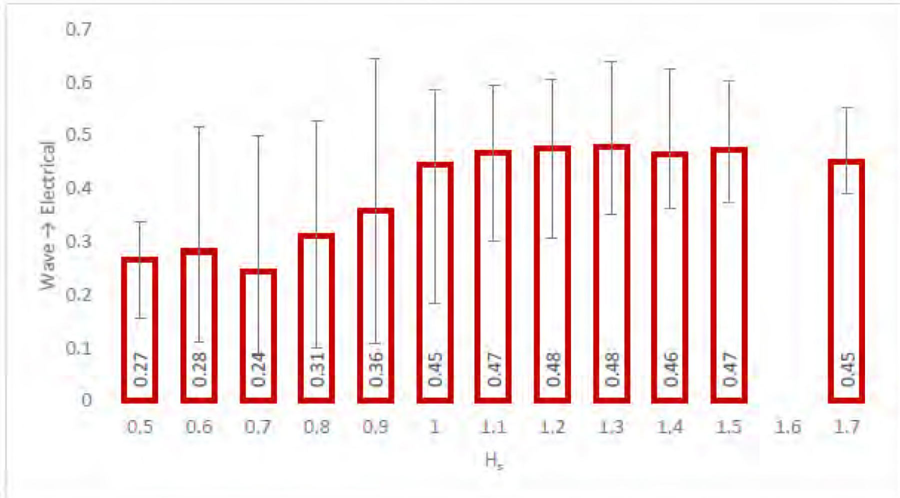

Figure 3 Wave to Electrical efficiency

The model-scale validation tests were also fruitful, demonstrating strong agreement with the full-scale results, typically within a 10% margin between predicted and modelled power outputs.

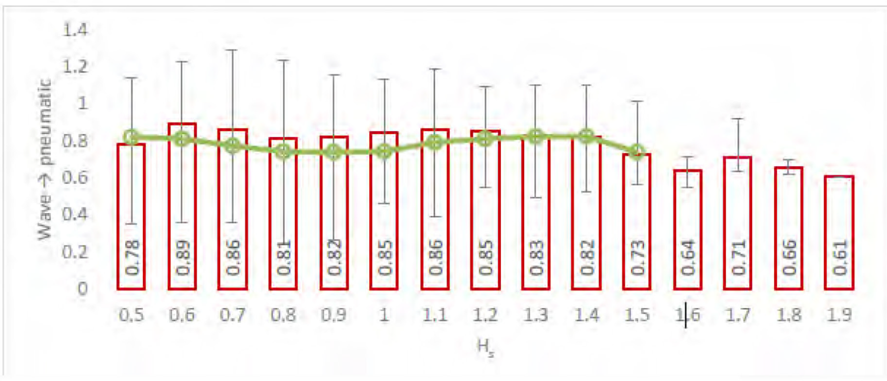

Figure 4 Full scale vs model scale pneumatic power conversion efficiency (model scale results are shown as circles)

Modelling work showcased how a unidirectional PTO configuration for the UniWave200 OWC generates greater pneumatic power compared to a bidirectional PTO in sea conditions exceeding 1.0 metre. This insight allows for more precise system optimization and energy capture strategies.

Furthermore, the study underscores the resilience and efficiency of the bespoke one-way valves, known as UniValves, used in the UniWave system. The simplicity of the system, combined with the fact there are no moving parts underwater, resulted in an impressive availability for a demonstration unit of over 80%.

Finally, the research also highlighted the superiority of the optimized variable speed turbine control algorithm over a constant speed algorithm, with turbine efficiency improvements of up to 25% observed. This advanced control strategy enhances energy conversion efficiency and aligns with the dynamic nature of wave energy generation, making it a valuable asset for future deployments.

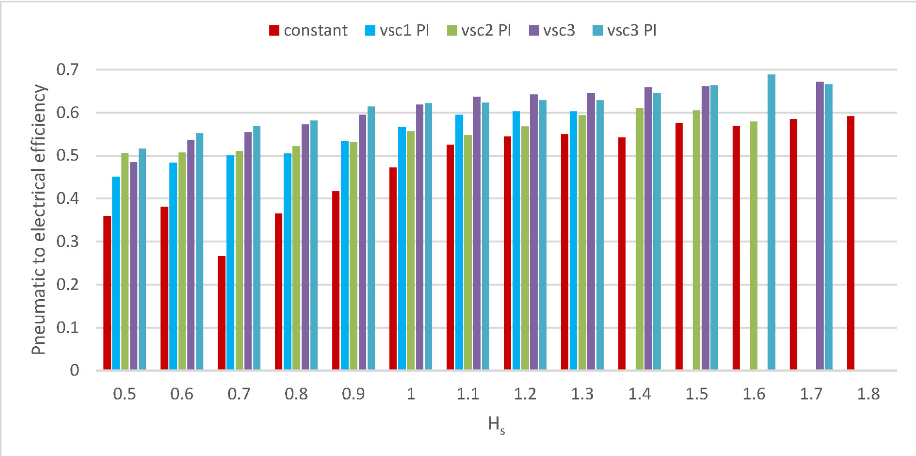

Figure 5 Average pneumatic to electrical efficiency by turbine control mode (vsc: variable speed control)

The UniWave200 operated fully autonomously, including during start up and shut down, to suit sea state limits. Remote intervention was only used to modify and advance the control system when required.

After demonstrating the effectiveness of the core technology of the PTO and unidirectional OWC through a gravity-based structure, WSE should now have confidence to replicate this achievement across diverse platform types. This core technology can be efficiently applied in near-shore arrays, integrated into coastal infrastructure, and implemented on a wide range of offshore fixed and floating structures.

6.2. CSIRO Technology Cost Projections

Australia's National
Science Agency

Wave energy cost projections

A report for Wave Swell Energy Limited

Jenny Hayward
15 October 2021

CSIRO Energy

Citation

Hayward JA (2021) Wave energy cost projections: a report for Wave Swell Energy Limited. CSIRO, Australia.

Copyright

Important disclaimer

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Figures

Tables

Executive summary

CSIRO was commissioned by Wave Swell Energy Ltd (WSE) to independently analyse the potential for capital cost and levelised cost of electricity (LCOE) reductions of its proprietary unidirectional oscillating water column (OWC) wave energy converter (WEC) technology. The analysis is based on the widely accepted concept of “learning-by-doing”.

As to be expected, individual firm learning rate data was not available for WSE’s WEC as it is a novel technology that has had limited deployment thus far. An estimated learning rate based on industry wide learning rates was used as the next best approach. It is not known how different an individual firm’s learning rate might be compared to the industry wide learning rate, which is a source of some uncertainty in the methodology. In any case, a single firm cannot deliver all learning in a technology class such as wave energy and all technologies will benefit from collective learning. The wave energy sector’s overall learning rate will, therefore, be the result of a concerted industry wide effort with support, for example, from government and the research sector.

Early stage or emerging technology classes have been found to have, on average, an industry wide learning rate (LR) of approximately 20%. However, using a bottom-up engineering approach, a more conservative LR of 18.23% was calculated for wave energy technology. Based on this LR, the capital cost was projected as a function of cumulative capacity out to 10,000 MW, and the LCOE was calculated alongside the capital cost.

At present, the WSE technology already has an LCOE that is competitive with diesel generation in remote locations. The modelling approach projected that the WSE technology can be cost competitive with offshore wind within 25 MW to 45 MW of installed capacity.

Applying an industry wide learning rate, it is projected that the WSE technology can achieve an LCOE of 0.05 $/kWh, which is equal to the current lowest cost generation of onshore wind and solar (Graham et al., 2020) if it can reach a deployment of 2,500 MW of installed capacity. This is approximately 0.35% of the installed capacity that onshore wind and solar PV have required to reach this same LCOE. As a comparison, the total global installed capacity for electricity generation was 7,484,000 MW at the end of 2019 (IEA, 2020), with wind and solar energy having reached 733,000 MW and 714,000 MW of this capacity respectively by the end of 2020 (International Renewable Energy Agency, 2021).

Using the CSIRO’s global and local learning model (GALLM-E), which compares 27 electricity generation technologies under a scenario where the world heads towards net zero emissions by 2050, it is projected that wave energy, including the WSE technology, can achieve a 1.3% share of the global electricity market in 2050 if it can sustain an 18.23% learning rate. This equates to 170,000 MW of installed capacity and is greater than the total projected contribution of biomass and geothermal generation combined. Even if the learning rate halves over time, as has been the case for wind and gas turbines, for example, it can still achieve the same market share by 2050, however, early and large scale uptake would then be delayed by approximately 10 years.

The analysis in this report is based solely on reductions in capital cost. It does not take into account potential improvements in the conversion efficiency of the technology and, thus, any increases in the capacity factor. Technology improvements and increases in capacity factor are inevitable and have been observed to lead to greater proportional reductions in LCOE than for capital cost, implying the potential for an even lower LCOE for the WSE technology than projected in this report.

1 Introduction

CSIRO was commissioned by WSE to undertake cost projections of its proprietary wave energy converter (WEC) technology. WSE provided technology cost and performance data based on the company's experience with the UniWave200 King Island project, and the remainder of the data used is either publicly available through the GenCost project (Graham et al., 2021) or from other literature sources.

The report begins by reviewing the literature on technological development, with a focus on the early development stages, given wave energy and WSE's WEC is an emerging technology. The use of learning curves and learning rates (LRs) for projecting the future cost of a technology, along with methodologies for deriving an LR for WSE's technology as a wave energy device, are explained. Section 3 describes the methodologies and assumptions used in this study to determine the WSE LR, as well as those used to undertake future cost projections and the modelling to explore the future global electricity market potential for wave energy.

The calculated capital costs and levelised cost of electricity (LCOE) are presented in Section 4, expressed in Australian dollars (AUD). A sensitivity analysis of the LCOE to the underlying assumptions is also performed, along with an analysis of what LR and cumulative capacity are required for the LCOE of WSE's technology to be equivalent to that of established electricity generation technologies (using 2020 and 2030 cost estimates). This is followed by an analysis of the global market potential of wave energy, and a final discussion on the commercial implications to conclude the report.

2 Technology Development

Technologies progress through various stages in their development cycle, from the first invention through to senescence. Emerging energy technologies are in the early stages of development, sometimes known as the “formative phase”, and are typically characterised by demonstration projects and then deployment in niche markets. The focus of Section 2 is on the stage of development appropriate for wave energy and WSE’s WEC, as it is an emerging technology.

2.1 Characteristics of the early development stages

The formative phase represents the first steps of commercialisation (Grübler et al., 1999). “Technology push” occurs in these early stages, where research and development (R&D) investments are used to support emerging technologies to improve their performance and reduce their cost, allowing these technologies to begin deployment, particularly in niche markets where performance is often more important than cost. At the same time, niche markets provide “market pull,” i.e. ongoing demand for a new technology once technology push has reduced the gap between the incumbent technology and the emerging technology. “Technology push” and “market pull” mechanisms are used to drive deployment (Santhakumar et al., 2021; Wilson, 2012; Wilson and Grübler, 2011; Neij et al., 1997).

Emerging technologies in the early stages of commercialisation have not achieved consensus in terms of size of unit capacity and will continue ‘up-scaling’. Up-scaling refers to a general increase in output capacity of a given generation unit. There are examples of up-scaling across the broad spectrum of energy technologies, from fossil fuel power stations to renewables. Up-scaling can lead to significant cost reductions, which is one factor that results in high LRs for technologies at this stage of development (Wilson, 2012; Wilson and Grübler, 2011).

A good example of the impact of up-scaling on an emerging technology is wind energy. In Denmark, wind energy began its development by building lots of small unit sizes over several years and underwent significant learning before upscaling. Other countries focussed on rapid up-scaling to achieve cost reductions, but this resulted in a lack of learning at smaller (and thus cheaper) unit sizes and consequently failed (Wilson, 2012; Wilson and Grübler, 2011).

The length of the up-scaling phase depends on the characteristics of the technology in question. The historical data shows that it starts later and takes longer for technologies that have multiple applications and require different unit sizes. Examples of this are gas turbines and photovoltaics. Technologies with clear economies of scale in unit sizes, such as steam turbines, start up-scaling earlier and have a more rapid upscaling phase. LRs can slow down at the end of the up-scaling phase (Wilson, 2012; Wilson and Grübler, 2011; Grübler et al., 1999).

2.2 Learning-by-doing

The observed principle of 'learning-by-doing' states that the capital cost of a technology reduces as cumulative production of that technology increases. Furthermore, the costs tend to reduce by an approximately constant factor for each doubling of cumulative production (Wright, 1936; Arrow, 1962; Grübler et al., 1999). This is illustrated in Figure 1, which is a log-log plot of historical energy technology costs against cumulative capacity and shows how the costs have reduced as technological uptake has increased.

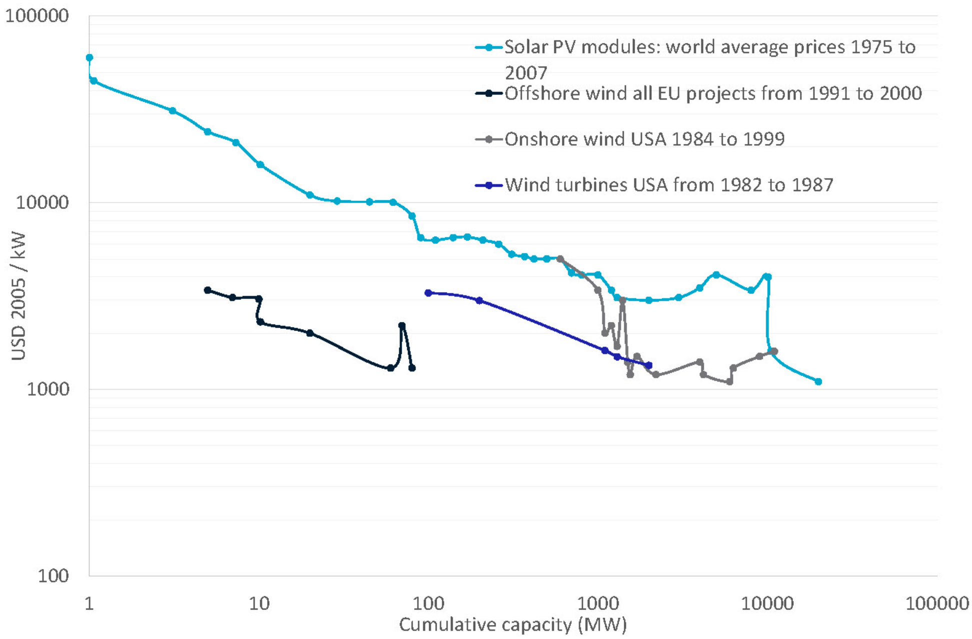

Figure 1 Historical technology costs versus deployment illustrating learning-by-doing. Source of data GEA (2012). PV=photovoltaics, EU=European Union, LR=learning rate, USA=United States of America, USD=United States Dollar. Wind turbines refer to just the component and onshore wind refers to onshore wind farms.

Learning-by-doing has been frequently applied to many technologies as it allows for the ability to create cost projections based on projections of the future uptake of a technology. Projections can be created from a transparent mathematical equation as follows:

$$IC_i = IC_0 \times \left(\frac{CC_i}{CC_0}\right)^{-b}$$

where IC_i is the investment cost of a technology at CC_i cumulative capacity at a given future point in time i, IC_0 is the investment cost at a given starting period and cumulative capacity CC_0, and b is the learning index. The learning index is related to the learning rate (LR) by LR = 100 – 2^{-b} where LR is represented as a percentage.

LRs and learning curves can be developed for an individual firm through to whole industries (Neij et al., 2003). They can be applied at the individual firm level to understand how production process costs can reduce costs through learning by doing as production increases, or to how a technology can reduce costs with uptake at a global level. Energy technology LRs that are available in the literature are generally based on a technology as a whole, such as wind turbines and the geographical scale can vary from a country to the whole world. There are very few published LRs for individual firms' technologies.

2.3 Learning rates

As discussed above, learning curves are based on historical cost and deployment data. While various wave energy devices have been deployed on a trial basis, they have all been located on the left hand side of the Grubb Curve (Figure 6) and there is insufficient historical cost and deployment data for wave energy and other new emerging technologies. In these circumstances, the LRs of analogous technologies at the same stage of development can be used. Observations of cost and deployment of energy technologies when in their early development stages, for example, photovoltaics, wind, and gas turbines, have revealed a general trend of a high LR of approximately 20% (Grübler et al., 1999). Figure 1 features technologies when they were in their early development stages, and the LRs, when calculated, are all close to 20%.

In fact, Grübler et al. (1999) observed that LRs in the range of 20% – 40 % are to be expected during the niche commercialisation phase, prior to the technology reaching a 5% market share (or approximately 1,350 TWh annually, based on 2019 global electricity production (IEA, 2020)). An LR of 20% is considered to be a good rule of thumb to use for emerging technologies (Jamasb and Köhler, 2008). Emerging technologies are situated in the first 'Early' learning stage in Figure 2.

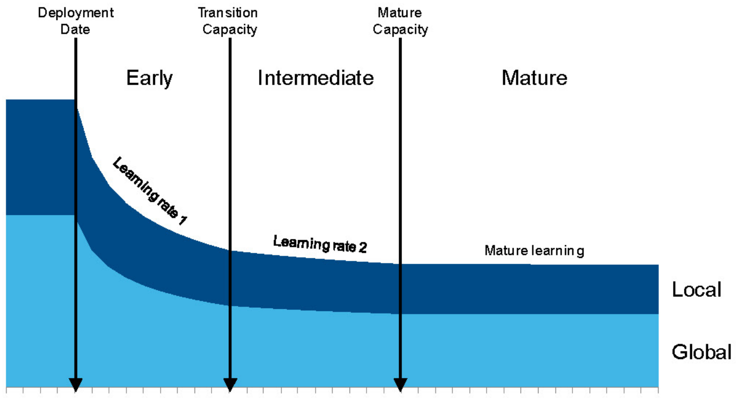

Figure 2 Schematic of changes in the LR as a technology progresses through its development stages after commercialisation

The high rate of learning observed for these early-stage technologies does not continue indefinitely. Several rates of learning can be observed for the same technology over its lifespan, and the rate depends on the stage of development of the technology. Typically, the LR reduces by approximately half as the technology matures (Grübler et al., 1999). The second LR is activated when the technology reaches the diffusion or intermediate stage, referred to as “Transition Capacity” in Figure 2. This occurs when the technology has reached approximately 5% market share (Grübler et al., 1999).

Once a technology reaches the mature stage, which corresponds to its lower LR limit, there is limited learning; however, there may be opportunities to reduce costs further by improvements related to materials etc.

Only the technology components, not labour components, have a second reduced rate of learning. Experience, particularly from the oil and gas industry, has shown that labour rates of learning tend to remain high even once the technology has become pervasive (Brett and Millheim, 1986; Schrattenholzer and McDonald, 2001).

2.3.1 Distribution of learning rates

It is instructive to examine the LR that different technologies have experienced during their evolution. One way to do this is by assembling the results of different studies that have been conducted into technology LRs. Schrattenholzer and McDonald (2001), Kahouli-Brahmi (2008) and the IEA (2008) compiled extensive lists of energy technology LRs. A histogram of the LRs is shown in Figure 3, with the LRs aggregated into bins of 4% increments.

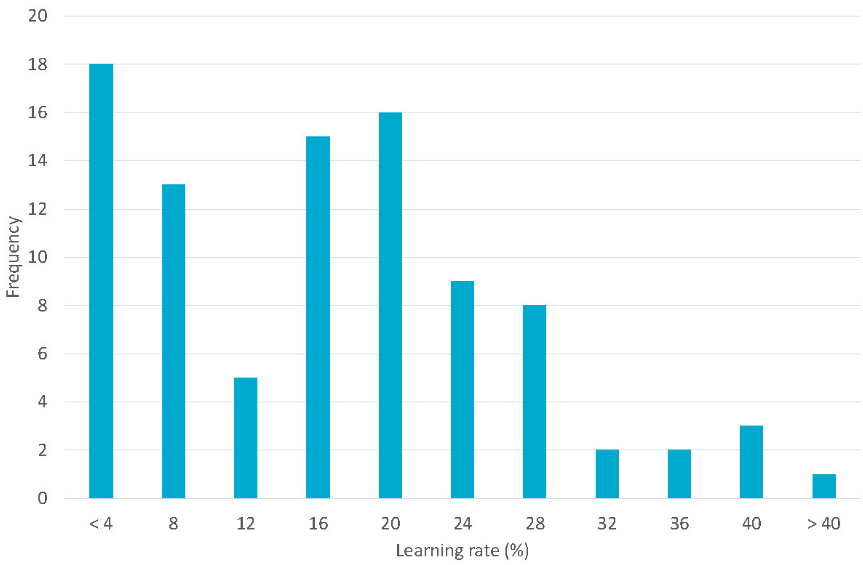

Figure 3 Histogram of 91 energy technology LRs

There are two modal values in the distribution, at 4% or less, and at 20%. The higher LRs tend to be associated with technologies in their early phases of development and are not just related to renewable technologies but also to fossil fuels. For example, an LR of 22% was calculated for gas turbines installed between 1958 and 1963. Solar PV modules exhibited a global LR of 20.2% between 1968 and 1998.

Mature technologies tend to have LRs of 4% and less. This includes combined cycle gas turbines from 1990 to 1998, and hydropower from 1975 to 1993.

The LRs of what can be considered to be early emerging technologies were extracted from the dataset, and a histogram showing the distribution of these emerging LRs is presented in Figure 4. In order to be classified as an emerging technology, the LRs needed to be calculated based on cost and cumulative capacity data from the early stages of deployment only. For wind turbines as a technology component and onshore wind farms, this meant that LRs beginning in the 1980s and ending in the 1990s were chosen. All solar PV LRs were chosen, and judgement based on CSIRO experience was used with the remaining technologies as to whether the dates were appropriate for an early-stage technology. If no dates were provided, the LR was not included.

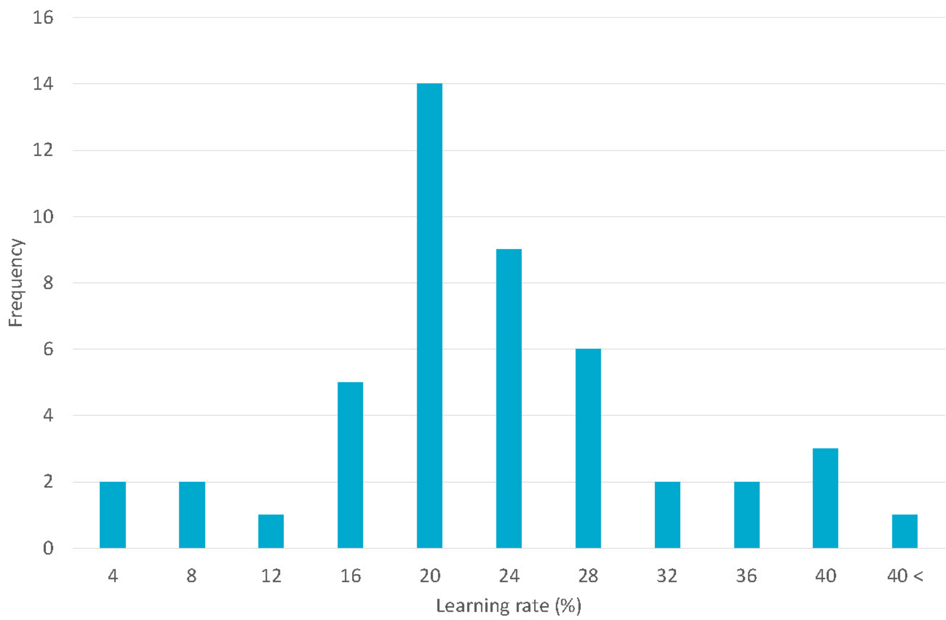

Figure 4 Histogram of 47 emerging technology LRs

Using the data presented in the histogram above, it is possible to elicit various statistical information: mean = 21.5%, median = 20%, mode = 20%. The minimum is 4%, and the maximum is 41.5%.

Additionally, based on the distribution of this LR data, 70% of all emerging LRs observed in these studies are above 18.23% (this statistic is of later relevance in Section 3.1).

2.4 Limitations of using learning curves

There are limitations in adopting the learning curve approach. The first is that it is not a law; it is based on observations. It does not include sudden technological changes, market shifts and other factors which can impact the rate of cost reduction. Cost reductions are the accumulation of several factors, not just learning by doing, which, in most cases, cannot be separated.

These other factors are well understood and include economies of scale, both in manufacturing and installation and knowledge spillovers (where learning is shared between technologies and regions). Cost overruns in the early stages of a technology's deployment can skew learning curves upwards, but they need to be included, as they are part of the process of technology development.

There are also other forms of learning which tend to be wrapped up into learning by doing, as again, they impact cost reductions. Learning-by-researching is important for emerging technologies, as it occurs during the R&D process and before commercialisation. Learning by researching is supported by R&D investments and leads to improvements in the technology and cost reductions. This also leads to a greater likelihood of technology deployment, and thus supports other aspects of learning by doing (Kahouli-Brahmi, 2008).

In addition, LRs vary depending on the time period over which they are measured, which is related to the observations made by Grübler et al., (1999). It is important that an appropriate data set is used when comparing technologies at similar stages of their commercialisation.

A good example is the offshore wind industry, where the first decade of commercialisation exhibited an LR of just over 18%, while the period 2010-19 resulted in a lower LR of about half that, partially due to extraneous market factors. This case is elaborated upon in Section 2.5.

It has been shown that at least 10-12 years or 2-3 magnitudes of cumulative output data is required to produce a stable estimate Santhakumar et al., (2021).

2.5 An emerging technology case study – offshore wind

The early stages of offshore wind's development from 1991 and into the early 2000's can provide some insight into LRs for wave energy as an emerging technology being deployed in the ocean. Junginger et al., (2004) estimated a 38% LR for the installation cost of interconnection cables and 29% for high voltage direct current (HVDC) converter stations. A 23% LR was estimated for the installation cost and, at the time, the actual construction of wind turbines had a LR of 15% to 19%. The breakdown of an offshore wind project's cost into contributions from each component as an emerging technology is shown in Table 1.

Table 1 Breakdown of offshore wind cost components during its early development phase (Junginger et al., 2004)

Component	Share of the total cost (%)
Turbine	30 - 50
Foundation	15 – 25
Internal grid and grid connection to shore	15 – 30
Installation	0 – 30
Other costs	8

Junginger et al., (2004) did not estimate a total offshore wind farm LR; however, applying a weighted average of the individual component LRs against their relative contribution to the total capital cost, suggests an overall LR of close to 20%.

As an emerging technology from 1991 to the early 2000's, offshore wind would be situated in the "Early" stage as shown in Figure 2. However, now that offshore wind is an 'intermediate' technology, its capital cost based LR has slowed. But, before this occurred, there was a period in the mid 2000's where there was a lack of wind turbine supply and increased demand which impacted the cost of both onshore and offshore wind. This increased the price of offshore wind, as can be seen in Figure 5. By including this price increase (due to market factors) in the calculation of the long-term LR of offshore wind, the apparent LR is reduced considerably.

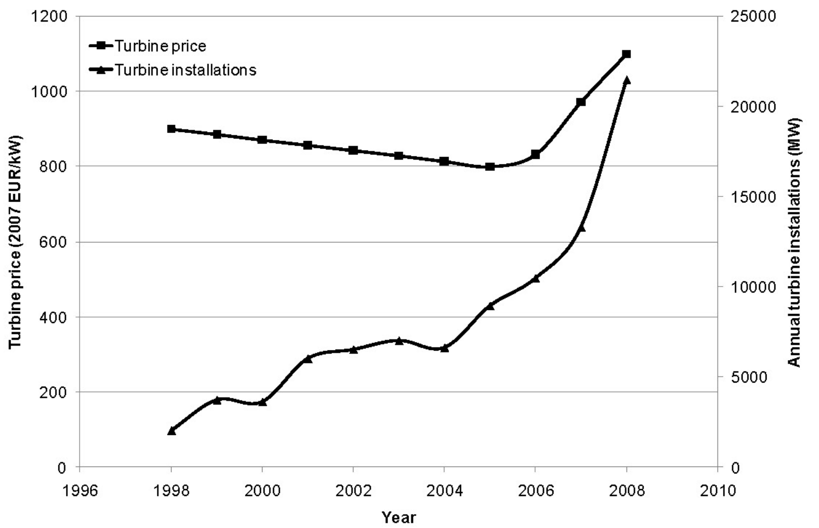

Figure 5 Wind turbine price and annual installations in IEA countries (Hayward and Graham, 2011)

Offshore wind underwent a shift in focus around the year 2010 from reducing the capital cost to reducing LCOE. Subsequent reductions in LCOE have been achieved by many factors, including moving to deeper waters, increasing farm scale, and increasing turbine blade length and hub

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height. These changes have led to increases in the capacity factor and thus reductions in the LCOE (IRENA, 2016), even while reductions in unit capital cost have been slowing. Innovations have also been occurring to reduce operations and maintenance (O&M) costs, improve control and, as the developers gain experience, they will be able to access lower cost finance. This will reduce the weighted average cost of capital (WACC)/discount rate so it does not include a risk premium and, thus, further reduce the LCOE (IRENA, 2016).

The combination of increasing turbine prices, moving to deeper waters, and the shift in focus from reducing the capital cost to reducing LCOE, has led to low long-term capital cost LRs for offshore wind of less than 5% (Santhakumar et al., 2021). IRENA calculated a capital cost learning rate for offshore wind using the last 10 years of data which is 9%, almost double the long term rate (IRENA, 2021a).

2.6 Estimating a learning rate

Wave energy, and WSE's WEC , are clearly at the early commercialisation stage and are therefore defined as emerging technologies. There are three approaches that can be taken to estimate a LR for wave energy at this stage of its development:

(1) Apply a *rule-of-thumb*. The literature that has focussed on the early formative phases of a technology's development have all shown a high LR of ~20% across a range of energy technologies. This is considered to be a rule of thumb LR. An LR of 20% has been achieved or exceeded by solar PV and both onshore and offshore wind during their formative phases and beyond.

(2) Use an LR from a similar technology at the same stage of development. Offshore wind and wave energy should have many similarities, given they share the same difficult ocean environment. LRs have been calculated for each of the components of offshore wind when it was in its early development phase (Junginger et al., 2004). These indicate a resulting composite LR for the early stage of offshore wind of 18.3% (see Figure 8).

(3) Break wave energy down into its components and estimate a LR based on a bottom-up assessment of the costs and individual LRs of each component. Santhakumar et al., (2021) suggest taking this approach for wave energy, an approach that was used by Junginger et al., (2004) to estimate the early offshore wind LRs (as per point (2) above).

The IEA (2020) quotes an ocean energy LR of 14%. It is not known what is behind this value, given there is no cost reduction data for ocean energy from which to estimate a learning rate. It may be based on a longer-term trend LR for offshore wind, which the IEA assumes is 15%. However, this longer-term trend includes the period when the supply of wind turbines could not match demand, which resulted in price increases unrelated to learning, which would artificially deflate the apparent offshore wind LR if those data points were included.

2.7 The technology learning environment

In trying to understand what may happen in the future with wave energy and WSE's technology it is useful to look at the period during which another technology was emerging and has achieved success – wind turbines in Denmark.

Wind has been deployed for centuries however it wasn't until the 1970s that the modern wind industry began to appear, which was driven by the global oil crisis. Denmark was particularly impacted by the oil crisis as oil provided 94% of its primary energy needs. Denmark decided to pursue wind energy as it has a strong wind resource and no substantial hydro or coal resources. The government directed the Danish Nuclear Laboratory (RISØ) and the Technical University of Denmark to research wind energy. At the same time, there were many amateur wind turbine developers taking advantage of the windy conditions and building their own turbines. Vestas was formed in the 1970s off the back of one of the amateur designs, which later became known as the "Danish concept" and consists of the three-blade turbine used today with fibreglass blades. Other companies started emerging as government support increased via loans and subsidies for renewable energy investment. By 1980 there were 10 turbine manufacturers however these eventually merged into either Vestas or later Siemens Gamesa. Vestas was the first company to mass produce a wind turbine and is still a world leader (Owens, 2019). Vestas did not become a world leader on its own. Vestas was supported by a whole learning environment focussed on wind energy in Denmark, with support from the government, the research community, other wind turbine developers and the public.

There have been designs for wave energy devices for many years; by 2012 there were at least 200 (CSIRO, 2012). However, only a handful of devices have been tested and trialled at sea. Some early devices had design and technical issues with hydraulic fluid, for example, or there were issues with the business itself and financing. The wave energy industry as a whole has learnt from these earlier trials and now there are fewer companies and designs and the newer designs, such as WSE's, are based on a simple point absorber or an OWC with very few moving parts. While there is less direct government support in Australia for wave energy as there was in Denmark for wind, there is a recognised global need to move the world towards net zero emissions by 2050, which will require a suite of renewable energy technologies and in particular, technologies that can provide some dispatchable power, such as wave energy. Given this imperative, further support for wave energy should be realised.

The wave energy industry as a whole is emerging and, by continuing to cooperate through sharing knowledge and with support from the research community, this will lead to cost reductions which contribute to learning-by-doing.

3 Methodology

3.1 WSE Learning rate

With only a single unit installed, WSE does not have an individual firm learning rate and there are no other examples available of individual firm learning rates in the wave energy sector. The only alternative, therefore, is to use an industry wide learning rate. The use of industry wide learning rates applied to an individual firm creates some uncertainty in the applicability of the data but is unavoidable due to data limitations.

Applying a bottom-up approach, that is a combination of Options 2 and 3 from Section 2.6, where the relevant component LRs from the offshore wind industry, highlighted in Junginger et al., (2004), are used and weighted against the relative cost of these components for the WSE technology, indicates an overall LR of 18.23%. The details of this calculation are shown in Table 2.

Table 2 Bottom-up calculation of WSE LR. Source WSE.

Component	CAPEX ($/kW)	LR (%)	Weighted LR (%)
Power take-off	2,983	19	4.07
Foundation	1,365	10	1.07
Structure	5,400	18.3	5.23
Grid connection	846	20	1.43
Installation	2,348	23	4.93
Other	989	14	1.50
Total	13,931	-	18.23

Given that all three of the methods from Section 2.6 suggest a consistent LR of 18-20% for the niche commercialisation phase of wave technology, it is considered appropriately conservative to apply the LR value derived from the bottom-up approach to the further analysis of this report, which includes using it as an industry-wide LR and for WSE as an individual firm.

As was shown in Section 2 of this report, 70% of all emerging energy technologies studied exhibited LRs higher than 18.23%. Therefore, this bottom-up LR of 18.23% was chosen for use in subsequent calculations.

3.2 Capital cost projections

In order to project capital cost reductions due to learning by doing, a projection of the future cumulative capacity of the technology needs to be determined. This can be undertaken using a model, as is described in Section 3.4, or a simple approach can also be used, which is to assume a continuous increase in cumulative capacity, up to 10,000 MW in this case. There is no need to include a time element to this type of projection as the capital cost is dependent on cumulative capacity, not time.

Capital costs of a technology do not necessarily begin to decline from the first installation. Typically, costs increase as more is understood about the technology and difficulties arise with real-world installations. Once a technology overcomes the pilot and demonstration phases, the costs may begin sustained declines. This process is illustrated by the Grubb curve as shown in Figure 6.

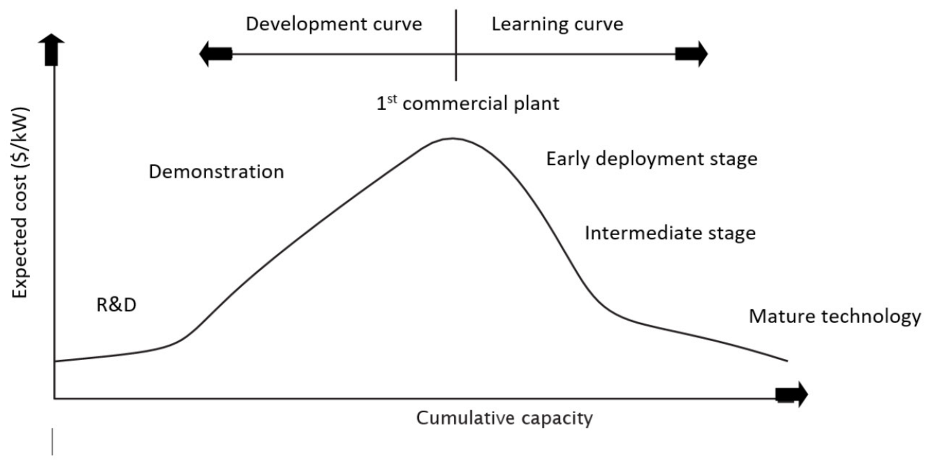

Figure 6 Stylised Grubb Curve (Smitham and Hayward, 2011)

WSE's WEC is at a technology readiness level (TRL) of 9[1] and a commercial readiness index (CRI) of 2[2], having demonstrated its technology via the construction, installation, and operation of its King Island installation in Tasmania. The King Island project has allowed WSE to understand its cost base in detail, along with requirements for installation, operation, and likely future maintenance, thereby overcoming its initial cost hurdles. WSE states that the technology is now about to enter its commercial phase, placing it at the peak of the Grubb Curve. It is expected that sustained cost reductions will occur in future deployments of this technology.

[1] TRL9 - Actual system proven through successful operations: Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

[2] CRI2 - Commercial trial: Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.

3.3 Levelised cost of electricity

The levelised cost of electricity (LCOE) is a metric commonly used to compare the cost of generating electricity between different technologies. It represents the cost only; it does not include revenue, taxes or depreciation.

The standard formula for the LCOE in \$/MWh is

$$LCOE = IDC \times \frac{r \times (1+r)^L}{(1+r)^L - 1} \times \frac{K}{8760 \times Capfac} + \frac{O\&M_{FIX}}{8760 \times Capfac} + O\&M_{VAR}$$

where r is the discount rate, L is the lifetime, K is the capital cost in \$/MW, Capfac is the plant capacity factor (as a ratio), $O\&M_{FIX}$ is the fixed operations and maintenance (O&M) cost in \$/MW/year, and $O\&M_{VAR}$ is the variable O&M cost in \$/MWh.

IDC is the interest during construction which is paid over the construction period. It is given by:

$$IDC = \sum_{i=1}^{P} \frac{1}{P} \times (1+r)^{(i-1)}$$

where P is the construction period in years. This formula assumes the same annual payments during the construction period.

The LCOE has been calculated for WSE's WEC at various levels of cumulative capacity.

To explore the sensitivity of the LCOE to each assumption, Tornado charts have been calculated. Each assumption has been varied by ±25% to examine their impact on the LCOE.

3.4 Global electricity sector potential

The use of a modelling framework with the learning curves at its core allows for the uptake of the technology to be determined at the same time as the cost reductions i.e. simultaneously.

CSIRO developed the Global and Local Learning Model – Electricity (GALLM-E), which features endogenous technology learning, using learning curves for intermediate and emerging technologies and 13 world regions with electricity demand. GALLM-E is solved as a mixed integer linear program where costs are minimised to reach a given level of electricity demand. Projected global and regional electricity demand has been sourced from the IEA (2020). For more information on GALLM-E see Graham et al. (2021) and Appendix A of this report.

Energy models include broad technology classes such as wave energy. They are unable to distinguish the contributions of individual technology providers as that would become computationally intractable and there is insufficient data to enable this. There is also the issue of technology lock-in, where such a model will tend to choose the least-cost technology to the exclusion of others. In reality, a technology may be used in a particular application for reasons besides cost, which cannot be included in a model of this type. The WSE technology fits into the broad class of wave energy technologies, which is how it has been modelled in GALLME. The assumptions presented in Table 3. All other assumptions remain the same as in the 2020-21 GenCost report (Graham et al., 2021).

Including wave energy in GALLM-E means that it is in global competition with 27 electricity generation technologies to install capacity and contribute to regional electricity generation with existing and new generation capacity. The least-cost electricity generation mix is chosen by the model, within constraints such as land and biomass availability, renewable resources, and climate policies.

A capital cost trajectory over time will be extracted from the results and used to calculate the LCOE.

3.5 Technology cost and performance assumptions

Two scenarios have been modelled using the global electricity sector model, Achievable and Conservative, with the key assumptions presented in Table 3. The Achievable scenario has a continuous 18.23% LR and the Conservative scenario begins with an 18.23% LR but it reduces to 9% as cumulative capacity increases to 20,000 MW, simulating the transition from an emerging to an intermediate technology.

The simple capital cost projection method has been applied to a single learning rate, which corresponds to the Achievable scenario. The sensitivity of the LCOE to changes in the Achievable scenario assumptions will be determined as stated in Section 3.3.

Supported capacity refers to government supported technology investments, which can start a technology's journey down the learning curve. GALLM-E has such support for all emerging technologies including carbon capture and storage, tidal energy and small modular nuclear reactors.

Table 3 Key assumptions

Assumption	Units	Achievable	Conservative	Sources
LR	%	18.23	18.23 and 9	WSE bottom-up calculation
O&M cost	% of capital cost	3.02	3.02	IEA (2020)
Initial capacity factor	%	35	35	WSE
Construction time	years	1	1	WSE
Lifetime	years	25	25	Graham et al. (2021)
Discount rate	%	5.99	5.99	Graham et al. (2021)
Supported capacity	MW	10	750	

The capital cost of the WEC is 14,000 $/kW. This was used as the current technology cost. The technology only has a single fixed percentage O&M cost. There is no variable O&M cost.

The capacity factor has been kept constant. However, it is expected to improve with deployment as more is understood about the resource and about how to improve the efficiency of converting wave energy into electrical energy. An increased capacity factor will lead to an even lower LCOE than that projected through capital cost LRs alone.

The LCOEs of the comparison technologies: solar PV, onshore wind, offshore wind and diesel generators were sourced from Graham et al., (2021). The diesel fuel price was assumed to be

1.328 $/L, which was the weekly national average wholesale price for the week beginning 15 August 2021[3]. Stationary energy diesel users can claim the diesel fuel rebate and this was not included in the calculation. However, this saving may be offset by transport costs to remote locations which is where diesel tends to be used for stationary energy. Because of this uncertainty, the calculation has been based on the price listed above.

[3] https://www.aip.com.au/sites/default/files/download-files/2021-08/Weekly%20Diesel%20Prices%20Report%20-%2015%20August%202021.pdf

4 Results

4.1 Current LCOE

As a new technology, WSE's LCOE is higher than more established forms such as coal, wind, and solar PV. However, all forms of energy production decrease over time as more capacity of that technology is installed, with the decrease in cost being most rapid in the early phase of the technology's commercialisation. The WSE technology is generally cost competitive with the diesel-based generation that is endemic in remote locations, particularly islands. These locations are logical niche markets for the WSE technology in the immediate term, as many are surrounded by an abundant wave energy resource. Figure 7 illustrates the LCOE of the current WSE 1 MW UniWave WEC with the LCOE of other forms of electricity generation.

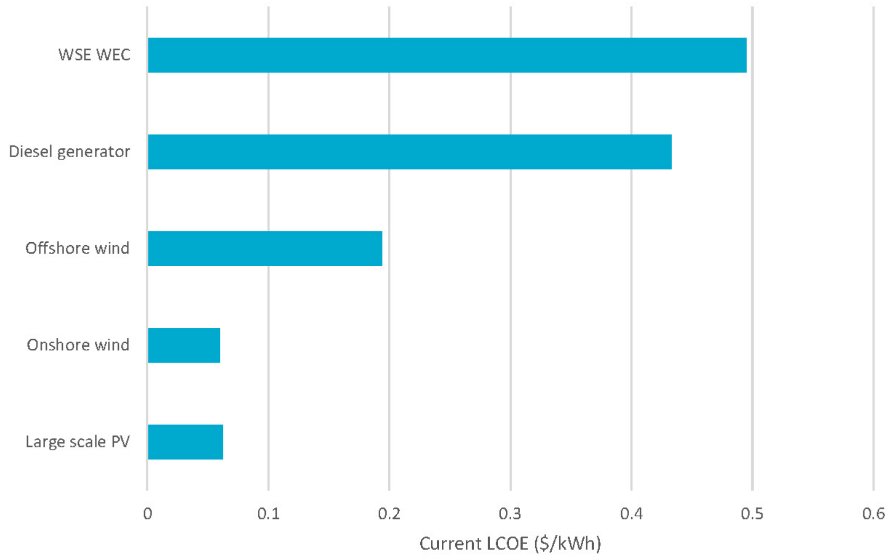

Figure 7 LCOE of WSE's WEC and other electricity generation technologies

Note, for the LCOE of WSE's WEC to break even with that of the diesel generator from Day 1, the price of diesel needs to be 1.58 $/L.

4.2 Projected capital cost and LCOE

Figure 8 shows the projected capital cost reductions of the WSE technology, using the fixed industry wide 18.23% LR defined in Section 3 that does not reduce as cumulative capacity increases, along with historical cost reductions of technologies when they were in the early learning phases. The currency units are USD 2005; therefore the WSE WEC costs were converted to USD from AUD and deflated to 2005 to be consistent with the other technology's costs.

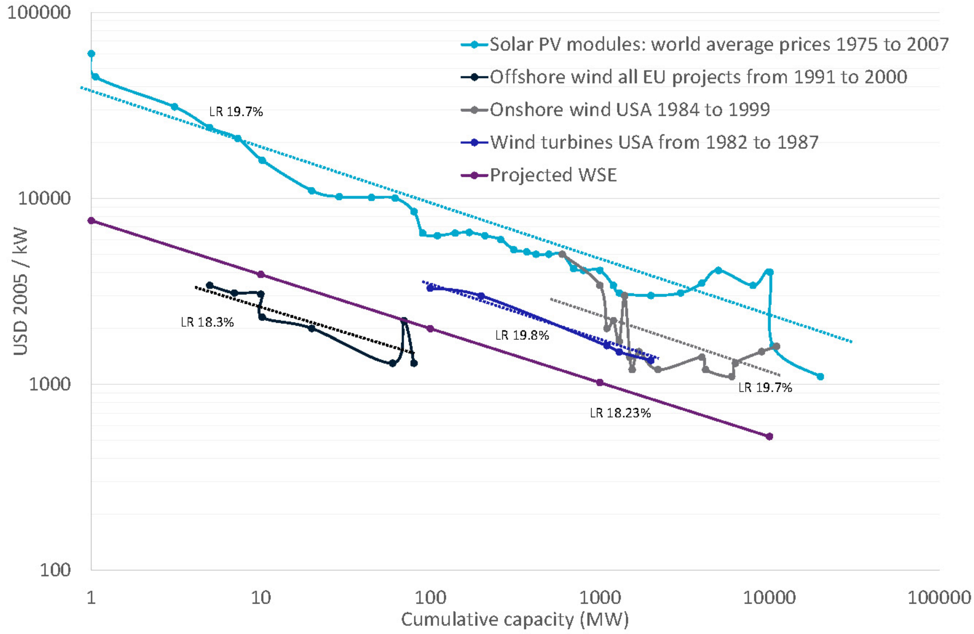

Figure 8 Projected capital cost with an increasing cumulative capacity

If WSE, as an individual firm, can achieve learning rates consistent with industry wide learning, the projected capital cost and LCOE of the WSE technology in AUD 2020 is shown in Figure 9. The present day LCOEs of large-scale PV, offshore and onshore wind, and diesel generators have been overlaid for comparison purposes. This figure illustrates at what cumulative capacity the LCOE of WSE should equal that of the current cost of various other technologies, noting that while this a comparison against the current cost of wind and solar PV, the LCOEs of these technologies will also continue to decrease with uptake. The breakeven cumulative capacities of WSE with the current LCOE of various technologies are shown in Table 4.

Table 4 Cumulative capacity at which the LCOE of WSE calculated using an 18.23% LR is equivalent to that of the current cost of other technologies

	Diesel generator	Offshore wind	Onshore wind	Large scale PV
Breakeven cumulative capacity (MW)	1.6	25.3	1422	1203

The industry wide LR of 18.23% leads to capital costs reducing to 3676 $/kW by the time 100 MW have been installed and 1022 $/kW when the cumulative capacity reaches 1000 MW. Since the O&M cost is a percentage of capital cost, it will also reduce at the same rate. The current O&M cost is 423 $/kW/annum, and this will reduce to 31 $/kW/annum when the cumulative capacity reaches 1000 MW. The associated LCOE at 1,000 MW of cumulative capacity is 0.07 $/kWh, dropping to 0.05 $/kWh by 2,500 MW.

To achieve and maintain the 18.23% LR and the associated cost reductions, the focus needs to be on actions that can increase the impact of learning-by-doing, i.e. achieve cost reductions while deploying the technology, scaling up manufacturing, and building economies of scale through deploying larger units, which will be dependent on site conditions and by deploying multiple devices into larger wave farms.

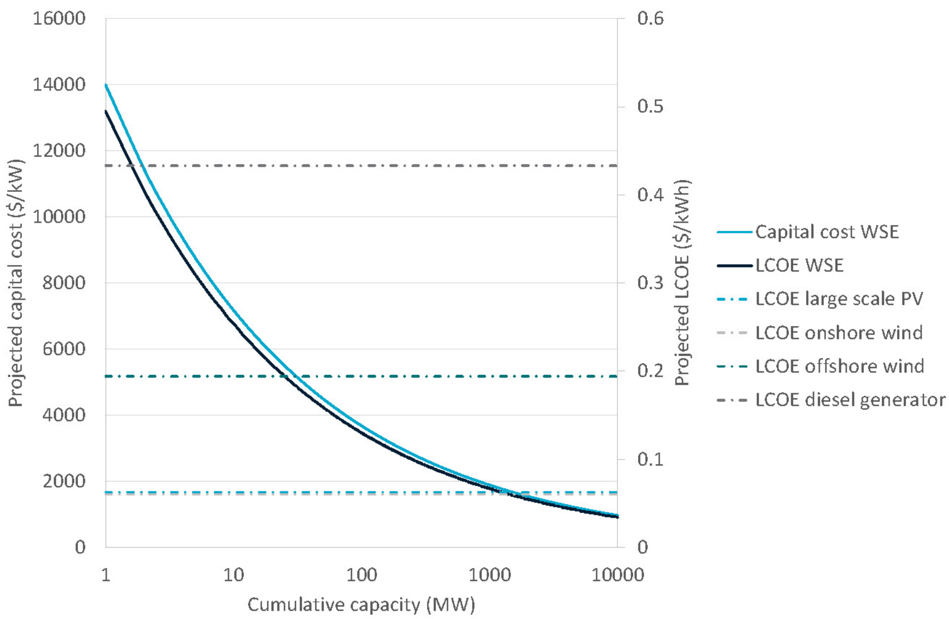

Figure 9 Projected capital cost and LCOE of WSE's WEC with increasing cumulative capacity along with the current LCOEs of various technologies

4.3 Cost parity analysis

Figure 10 and Figure 11 illustrate the amount of cumulative capacity of the WSE technology that would be required, at various LRs, in order to reach cost parity with various other technologies in

2020 and 2030 respectively. These other technologies have a range of LCOE based on the results from Graham et al., (2021).

It can be seen in both figures that the WSE technology is almost competitive with diesel generation in remote locations and is, therefore, quite insensitive to LR in that case. Other technologies, however, demonstrate variability with LR. In all cases, as is logical, a higher LR results in the WSE technology achieving cost parity at a lower cumulative capacity. As would be expected, Figure 11 shows that a higher cumulative capacity is required to match the expected lower LCOEs of these technologies in 2030. In 2030 and at a 20% LR for the WSE technology, a cumulative capacity of 32 to 35 MW and between 600 and 1,300 MW is required to compete with offshore wind and onshore wind respectively. At a 15% LR, 120 to 129 MW and 6,140 to 17,270 MW of cumulative capacity is required for WSE's LCOE to match that of offshore wind and onshore wind, respectively. As a basis for comparison, the current total global electricity generation capacity is 7,484,000 MW (IEA, 2020).

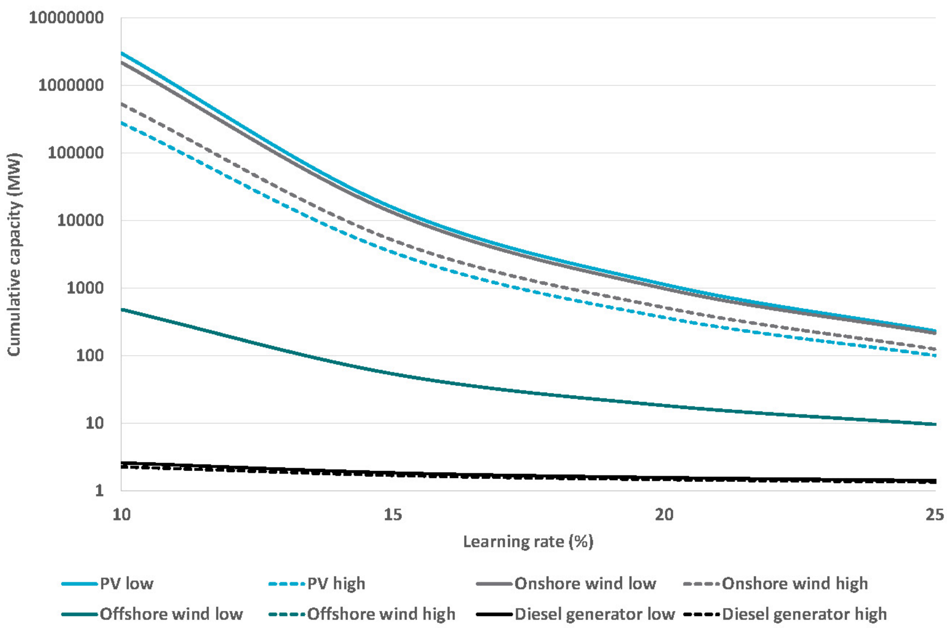

Figure 10 LR and cumulative capacity where the projected LCOE of WSE's WEC is equivalent to that of other technologies in 2020

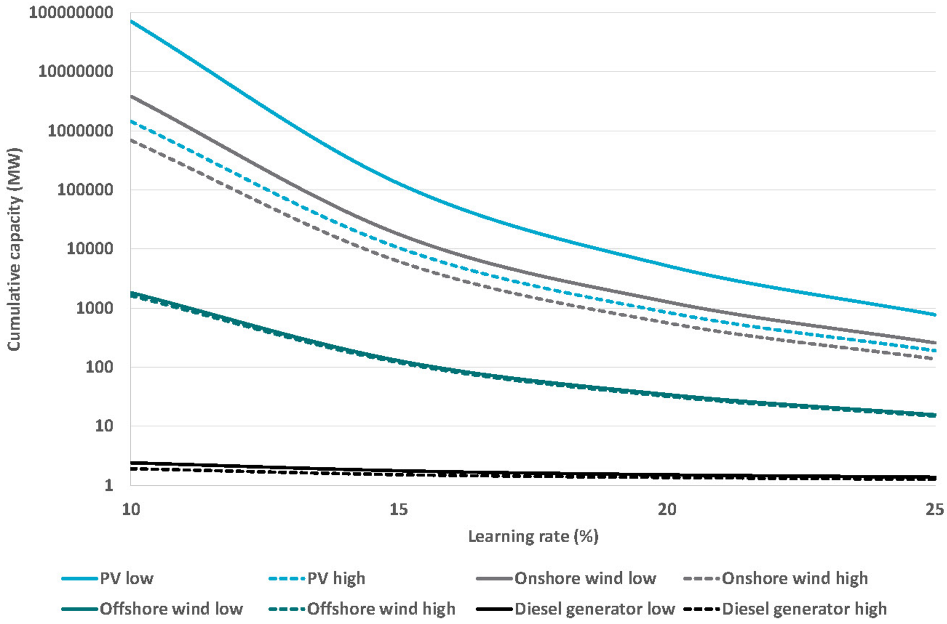

Figure 11 LR and cumulative capacity where the projected LCOE of WSE's WEC is equivalent to that of other technologies in 2030

Figure 12 and Figure 13 illustrate similar sensitivities, only now with LCOE plotted against cumulative capacity for discrete LRs across the LR range of the previous graphs, for the years 2020 and 2030 respectively. Horizontal coloured lines represent the breakeven points where the WSE technology matches the LCOE of other technologies (the very similar LCOEs for onshore wind and solar PV result in an overlay of their horizontal lines in the 2020 case).

Again, it can be seen that the WSE technology is competitive with diesel generation at a low cumulative capacity and at any LR. Other technologies, however, require more cumulative capacity for WSE to be competitive, with less capacity required when LRs are higher. For example, at 2020 LCOEs and at a LR of 15%, the WSE technology reaches parity with diesel at a cumulative capacity of 1.7 MW, with offshore wind at 54 MW, and with onshore wind and solar PV at ~7,000 MW. At a 20% LR these capacities drop to 18 MW and 700 MW for offshore wind and solar PV / onshore wind respectively. By 2030, the corresponding capacities are 125 MW and 10,000 MW at an LR of 15% for offshore and onshore wind respectively, and 34 MW and 800 MW at 20%. Interestingly, by 2030 solar PV is predicted to be at a lower cost than onshore wind as it has a higher ongoing LR.

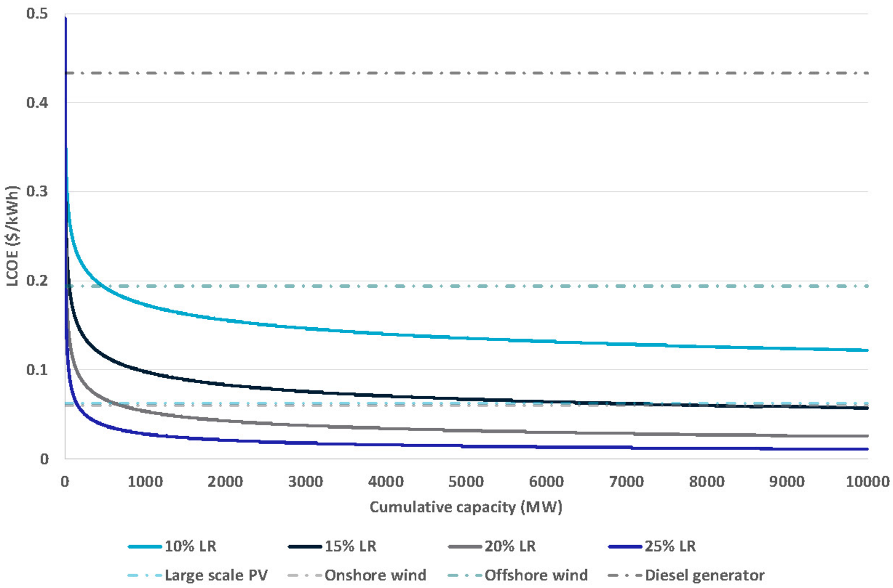

Figure 12 Projected LCOE of WSE's WEC at various LRs and as a function of cumulative capacity and the 2020 LCOE of other technologies

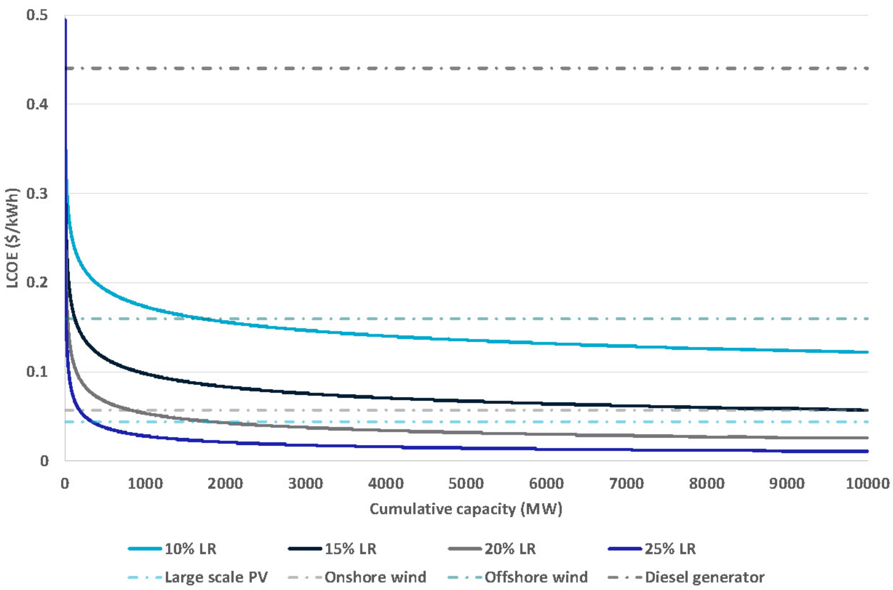

Figure 13 Projected LCOE of WSE's WEC at various LRs and as a function of cumulative capacity and the 2030 LCOE of other technologies

4.4 Sensitivity analysis

The sensitivity of the LCOE to a change of ±25% in each assumption is shown in Figure 14 at 10 MW of cumulative capacity and Figure 15 at 1,000 MW of cumulative capacity. The base value of each assumption is presented with the labels.

At 10 MW of cumulative capacity the capacity factor has the greatest influence on the LCOE, where a 25% increase in capacity factor reduces the LCOE by 20% and a 25% decrease in capacity factor increases the LCOE by 34%. While the impact of the capacity factor on LCOE is the same at 1,000 MW, the assumption with the greatest influence on LCOE at that capacity is the LR. When the LR of 18.23% is reduced by 25% to 13.67% the capital cost increases from 1,884 $/kW to 3,234 $/kW which is almost double and the LCOE increases by 70%. When the LR is increased by 25% to 22.79%, the capital cost reduces to 1,064 $/kW and the LCOE reduces by 43%.

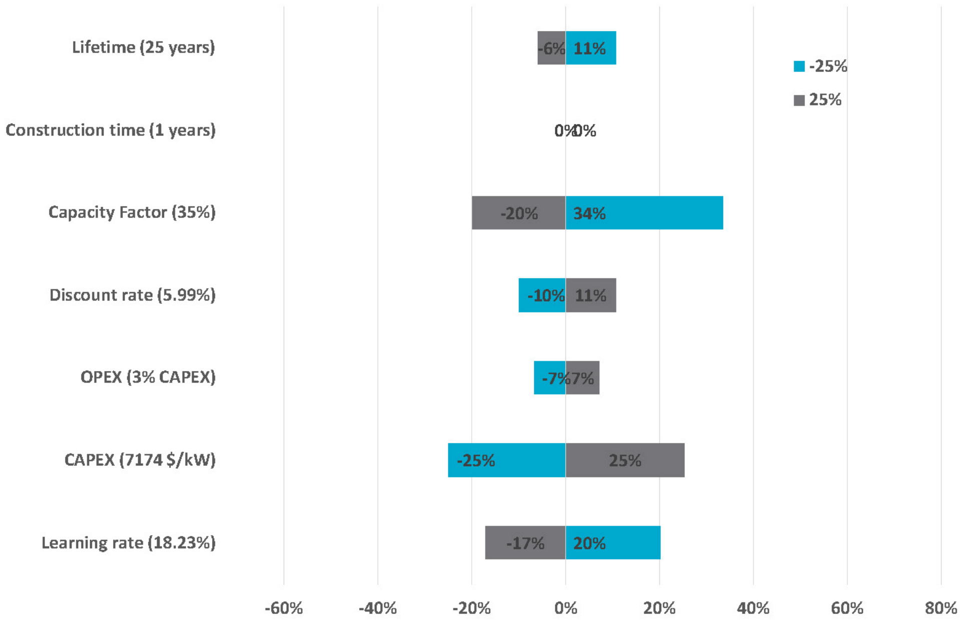

Figure 14 Projected sensitivity of the LCOE to changes in assumptions at 10 MW of cumulative capacity

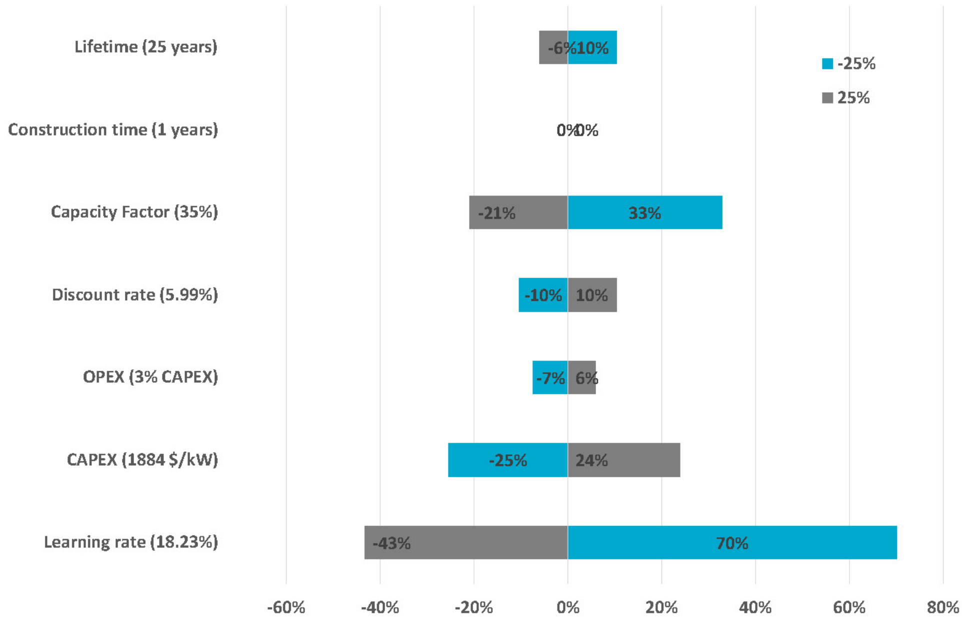

Figure 15 Projected sensitivity of the LCOE to changes in assumptions at 1000 MW of cumulative capacity

4.5 Global electricity sector results

4.5.1 Achievable scenario

The projected global electricity generation mix is shown in Figure 16. From 2021 to 2050, wave energy contributes 11,525 TWh to global electricity generation. To put this into perspective, it is slightly greater than the total contribution of biomass and geothermal generation combined. It also amounts to 718 TWh per annum by 2050, which is more than double Australia's total 2019 electricity generation of 265 TWh. The market share of wave energy in the early part of the next decade is projected to be 0.46%. By 2050, wave energy is projected to achieve a 1.3% global market share, with an LCOE of 0.03 $/kWh and an installed capacity of 170,000 MW.

It should be noted that this scenario is predicated on an immediate uptake of wave energy technology in the form of early projects. A strong "market pull", as described in Section 2.1, is required for the installed capacity of the technology to increase, leading to capital cost and LCOE reductions in line with the above analysis. The reality often experienced by many new energy technologies is that early projects are slower to develop due to caution on the part of funders and other stakeholders. If this cautious slower uptake were to occur in the early phase of the commercialisation of wave energy technology, the above estimate of market share and LCOE by early next decade might be delayed.

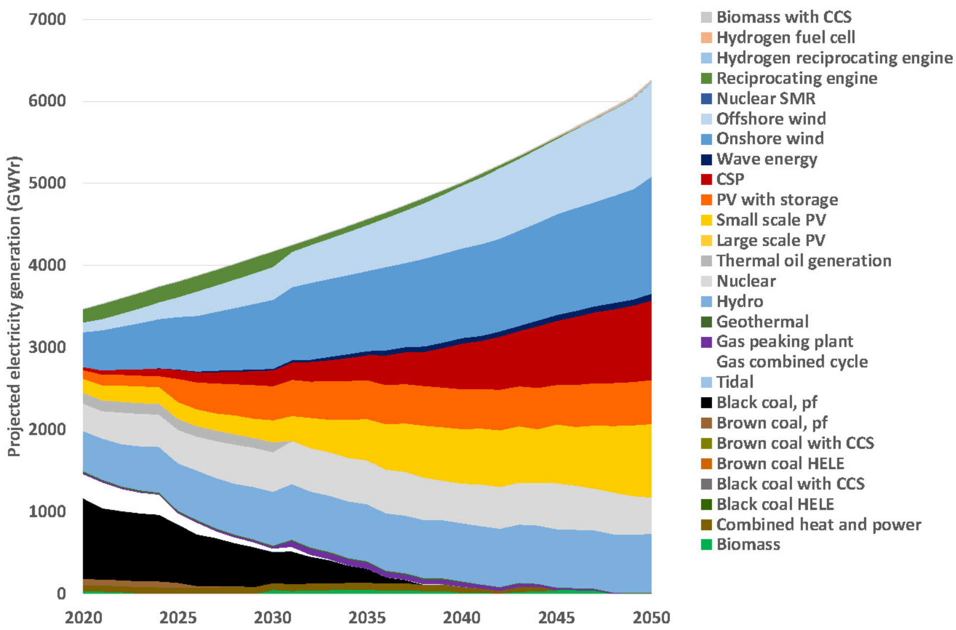

Figure 16 Projected global electricity generation under the Achievable scenario

CCS=Carbon Capture and Storage, SMR=Small Modular Reactor, CSP=Concentrating Solar Power, pf=pulverised fuel, HELE=High Efficiency Low Emission

The majority of wave energy electricity generation is projected to be in North America, which can be seen in Figure 17. Wave energy reaches a 5% market share in North America in 2033 with an installed capacity of 29 GW and an annual electricity generation of 113 TWh. From this point onwards, wave energy can be considered to be out of the early learning stage and into the intermediate stage in North America. Wave energy's 2050 market share is projected to be 8% of total generation.

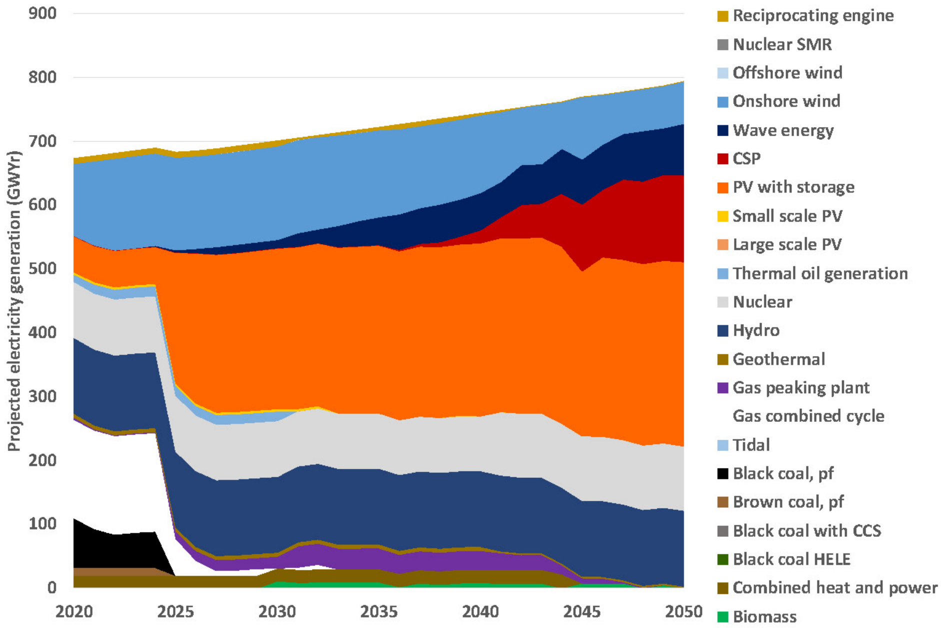

Figure 17 Projected North American electricity generation under the Achievable scenario

4.5.2 Conservative scenario

Figure 18 shows the projected global electricity generation mix under the Conservative scenario. Between 2021 and 2050, wave energy generates a total of 3,210 TWh. By 2050 wave energy is projected to generate 753 TWh per annum. This is slightly greater than under the Achievable scenario. By the early part of the next decade, the installed capacity of wave energy is projected to be 450 MW. This is lower than in the Achievable scenario, which shows the impact LR has on the uptake of wave energy. The change in LR has led to a slower deployment of wave energy, however, by 2050 the installed capacity is higher under the Conservative scenario at 180,000 MW.

As in the Achievable scenario, the greatest amount of wave energy is projected to be installed in North America, as shown in Figure 19. The total generated from 2021 to 2050 is 2,992 TWh. Wave energy reaches a 5% market share by 2046 and by 2050 wave energy's share of generation is projected to be 9%.

The reason wave energy has a 1% higher market share by 2050 under the Conservative scenario is because the installed capacity is slightly higher. This shows that even though the LR was reduced, the additional early supported capacity has led to an increase in the total installed capacity of wave energy by 2050.

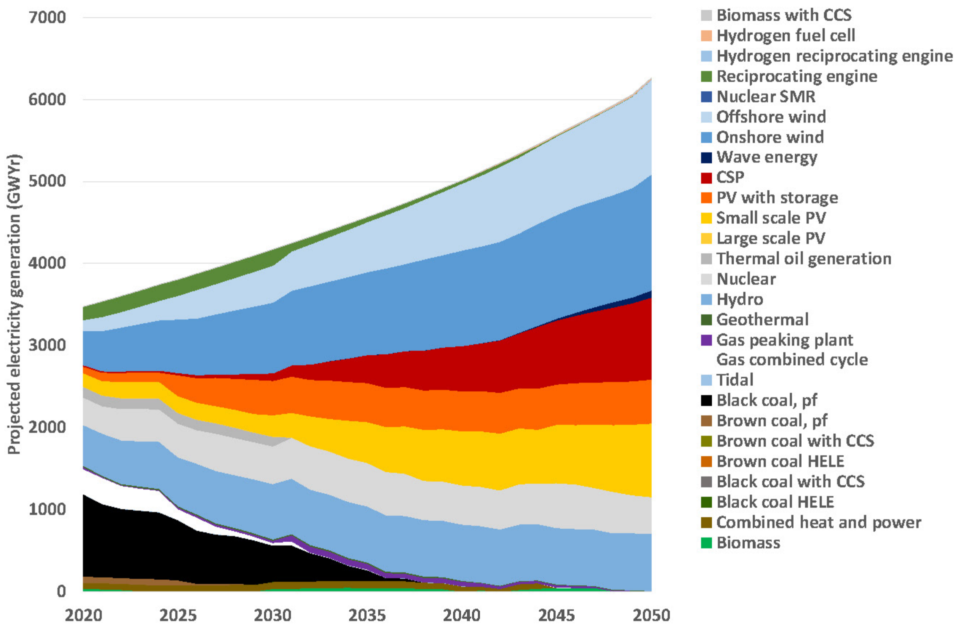

Figure 18 Projected global electricity generation under the Conservative scenario

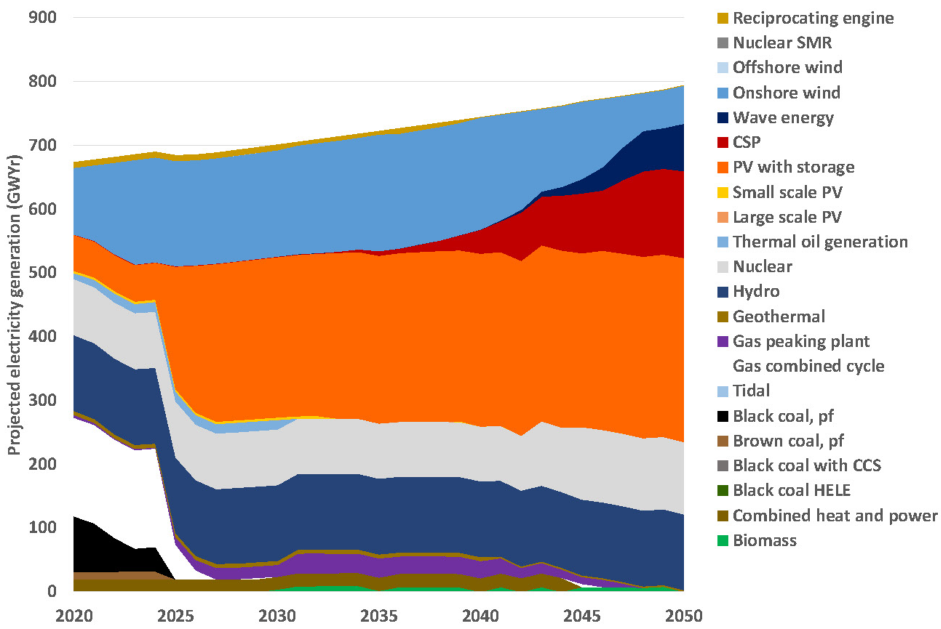

Figure 19 Projected North American electricity generation under the Conservative scenario

4.5.3 LCOE comparison

The modelled capital cost trajectories, and the LCOEs calculated based on those trajectories, and the current LCOE of other technologies, is shown in Figure 20. As can be seen, the flat sections of the graph represent an initial commercial development period, where early-stage projects are being originated, negotiated, and funded. If this phase were to be delayed for any meaningful period of time, the result would be an equivalent translation of the curves to the right on the timeline. And in fact, the Conservative scenario is slightly delayed compared to the Achievable scenario, even though it has more supported deployment. The supported deployment leads to continued, but slower, cost reductions compared to the Achievable scenario. This figure illustrates the difference the change in LR makes to the final outcome.

Therefore, the focus needs to be on maintaining that high learning rate through increased deployment, economies of scale in individual units, farms, and manufacturing. However, even if the learning rate does halve after a cumulative capacity of 20,000 MW, the LCOE of wave energy is competitive against diesel generation in remote locations by 2025 and with offshore wind before 2035.

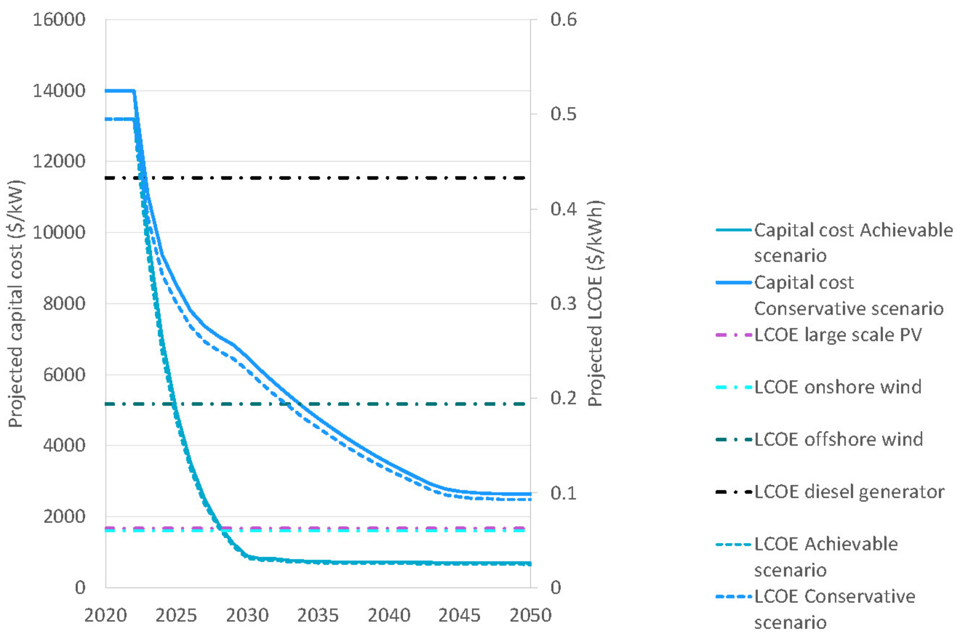

Figure 20 Projected modelled capital cost and LCOEs under the Achievable and Conservative scenarios

5 Discussion

The principle of learning-by-doing, where technological costs have been observed to reduce by a constant factor, known as the LR, as deployment increases, can be used to project future cost reductions. LRs can be calculated at the individual firm level, up to technologies deployed on a global scale. The overwhelming majority of literature LRs are for whole technologies at an industry wide national or global level.

A review of technological development, with a focus on early-stage technologies, has shown that these technologies have an industry wide LR of approximately 20% until they reach approximately 5% market share, at which stage their LR reduces. WSE's technology is currently in the commercialisation phase, which means it is an early-stage technology and thus should have a high LR. Data supporting an individual firm learning rate was not available. An industry wide 18.23% LR was determined from a bottom-up engineering-based calculation using component LRs associated with the offshore wind industry combined with WSE cost data.

The WSE technology currently has an LCOE that is already almost at parity with that of diesel generation in remote locations. This means that WSE's WEC has the potential to readily offset diesel CO_2 emissions and provide electricity at approximately the same cost to island communities that are reliant on expensive diesel, if projects have access to energetic wave resources, such as exist in many locations throughout the world.

If WSE as an individual firm can achieve an LR equivalent to the industry calculated value, the technology is projected to reach cost parity with the 2020 LCOE of offshore wind in Australia after a cumulative capacity of 25 MW and with the 2030 LCOE of offshore wind in Australia once the cumulative capacity has reached 50 MW. Relative to the global average LCOE of offshore wind, these capacities correspond to 45[4]MW and 300[5]MW.

For WSE's WEC to be competitive with solar PV and onshore wind in terms of LCOE, the technology needs to see cumulative installations of 5,543 MW and 1,658 MW by 2030 respectively, while maintaining the industry wide 18.23% LR. In order for WSE and wave energy to reach high levels of installed capacity at that LR, the wave energy sector as a whole will need to cooperate to share knowledge, and be supported through investments and research support which all contributes to cost reductions through learning by doing.

Global electricity sector modelling under the Achievable scenario has revealed that wave energy is projected to have an installed capacity of 42.6 GW by as early as 2030, given a strong early market pull. This is more than what is required to be competitive against large scale solar PV and onshore wind. The timing of these projections relies on the commercialisation of the technology commencing in the near term. A slower uptake will delay the timing. Under the Conservative

[4] Based on a global average offshore wind LCOE of 0.1150 USD 2019/kWh (IRENA, 2020)

[5] Based on a 2030 projected global average offshore wind LCOE of 0.07 USD 2018/kWh (IRENA, 2019)

scenario, which has a reduced LR, large-scale uptake of wave energy is delayed by more than 10 years. However, it reaches a similar installed capacity to the Achievable scenario by 2050.

The global installed capacity of wind and solar energy reached 733 GW and 716 GW respectively at the end of 2020 (IRENA, 2021). Solar PV modules have maintained a high LR of 25% over their 40-year commercialisation phase (Fraunhofer ISE, 2021) and, because of this, has achieved cost reductions to allow them to reach an LCOE of approximately 0.05 $/kWh in Australia (Graham et al., 2020). The capacity factor of solar PV is lower than that of wave energy, which means that wave energy can obtain an equivalently low LCOE at a higher relative capital cost and a lower cumulative capacity than solar PV.

The two largest drivers of the LCOE are the LR (and hence capital cost) and the capacity factor. The impact of the LR increases as cumulative capacity increases because a higher LR results in more significant capital cost reductions as shown by Figure 12 and Figure 13.

The capacity factor has a constant impact on the LCOE, as shown by the sensitivity analysis, where an increase of 25% results in a decrease in the LCOE of 20-21% and a 25% decrease in capacity factor results in a 33-34% increase in LCOE.

These results mean that, to achieve a high level of cost reductions in LCOE terms, the focus needs to be on maintaining the LR through learning by doing, economies of scale in manufacturing, and in installation. At the same time, sites with suitable wave energy resources need to be chosen for projects, and improvements to the technology to increase the efficiency of conversion and, thus, the capacity factor, need to continue to occur.

The analysis in this report is based solely on reductions in capital cost. It does not take into account potential improvements in the conversion efficiency of the technology and, thus, increases in the capacity factor. Technology improvements and increases in capacity factor are inevitable and will lead to an even lower LCOE than those stated in this report.

Appendix A Further information on GALLM-E

GALLM-E has been developed by CSIRO to project the capital cost and uptake of electricity generation technologies. GALLM-E is solved as a mixed integer linear program in which total costs of electricity supply are minimised to reach a given level of electricity demand over time. The model features endogenous technological learning through the use of learning curves at both the global and local scale. The learning curves are segmented into step functions and the location on each learning curve (i.e. cost vs. cumulative capacity) is determined at each time step. The learning curve solution space is non-convex, which means that there are singularities i.e. the solution space is not continuous. However, it is possible to find an optimal, least-cost solution. It also means that any change in any of the parameters that impact the learning curve, such as a change in generation capacity, will result in an entirely new solution space.

GALLM-E has 13 regions based on OECD regional definitions but also some greater resolution of countries that are Australia's main trading partners, namely Australia, Africa, China, Eastern Europe, Western Europe, Former Soviet Union, India, Japan, Latin America, the Middle East, North America, OECD Asia Pacific (without Australia and Japan) and the rest of Asia. It also features 27 electricity generation and energy storage technologies (Hayward & Graham, 2013; Graham et al., , 2021; Brinsmead et al., 2019). It runs from the year 2006 until 2100, however, results are only reported up until 2050 due to the much greater level of uncertainty in the input assumptions beyond that date.

GALLM-E includes a "penalty constraint", where in any given year, if the new installed capacity of a technology exceeds 1/3 of new demand for capacity, then the cost of that technology will increase. If it exceeds 2/3 of new demand for capacity, the cost penalty is even higher. This constraint is based on supply constraints that have been seen in the past for technologies such as wind and PV, where the price increased as demand increased. The constraint ensures that the model recognises the potential to overheat a technology supply chain, and to some extent this constraint encourages a wide variety of technologies to be deployed. However, if it needs to build more of only one technology, it is not prevented from doing so. Similarly, GALLM-E has a market constraint, where again, in any given year new capacity of a technology cannot exceed the existing installed capacity by more than 1.55 times, except for emerging technologies, where this constraint only becomes active after 3 GW of installed capacity. This constraint avoids rapid and unrealistic sudden increases in installed capacity and the value (1.55) is based on the approximate maximum historical build rates of electricity generation technologies.

GALLM-E has constraints on renewable energy resource availability in India, Japan, Asia and Western Europe, based on a review of the literature around technical limits of resources, land availability and roof space availability for rooftop solar PV (Hayward & Graham, 2017). This means these countries/regions are limited in their ability to rely solely on locally generated renewables for electricity generation and so would benefit from importing hydrogen. China (and the remaining regions in GALLM-E) have unlimited renewable resources (relative to expected electricity demand). There is a limited fossil fuel constraint, where brown coal-fired generation can only be located in a region that contains brown coal (as brown coal is not traded).

Government policies are a key driver of technology uptake in GALLM-E. The main policy lever is a carbon price, but there are country and region-specific technology incentives such as forced capacity construction or renewable energy targets.

Key exogenous data assumptions are presented in Table 5.

Table 5 Key exogenous data assumptions and their sources used in GALLM-E

Electricity demand	IEA for the equivalent scenario	(IEA, 2020)
Fossil fuel prices	IEA for the equivalent scenario	(IEA, 2020)
Biomass and uranium prices	CSIRO Australian National Outlook II	(Brinsmead et al., 2019)
Initial capital costs, operating and maintenance costs and plant fuel efficiencies	From several studies but the majority are from the GenCost project 2020	(Graham et al., 2021) (Aurecon, 2021)
Fossil fuel emission factors	Australian factors for direct and indirect emissions	(CO2CRC, 2015)
Historical installed capacities	Various sources most notably the IEA and the United Nations (UN)	(IEA, 2008) (UN, 2013) (UN, 2014)
Government policies	Various sources, majority from the IEA	(IEA, 2020)

Appendix B Brief description of the WSE technology

WSE's WEC generates electricity in a multi-stage process which provides it with ample room for improving the conversion efficiency and, hence, increasing the capacity factor[6], which improves the technology's economics:

- The energy in the incoming wave is converted into an oscillatory column of water
- The energy from the oscillatory column of water is converted into an airflow
- The airflow is converted into mechanical energy via a turbine
- The mechanical energy is then converted into usable electrical energy via various power systems

The geometry of the device is an important factor in determining its performance. The current version of the WEC is made predominantly from concrete and steel, but there are opportunities to use all manner of materials, including composites and recycled plastics that could significantly improve the manufacturing process and hence costs. The WEC can also be tethered to the seabed by various means.

[6] Capacity factor is unitless and is defined as the ratio of electricity generated over a period of time to the maximum possible output i.e. if the plant was operating at its rated capacity continuously.

Shortened forms

ABBREVIATION	MEANING
AEMO	Australian Energy Market Operator
AUD	Australian dollars
CAPEX	Capital Cost
Capfac	Capacity factor
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CO2CRC	CO2 Cooperative Research Centre
CRI	Commercial Readiness Index
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrating Solar Power
EU	European Union
EUR	Euro
GALLM-E	Global and Local Learning Model - Electricity
GEA	Global Energy Assessment
GW	Gigawatt
HELE	High Efficiency Low Emission
HVDC	High Voltage Direct Current
IDC	Interest During Construction
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISE	Institute for Solar Energy
kW	Kilowatt
kWh	Kilowatt hours
L	Litre
LA	Louisiana
LCOE	Levelised Cost of Electricity
LR	LR
MW	Megawatts
NY	New York
O&M	Operations and Maintenance
$O\&M_{FIX}$	Fixed Operations and Maintenance
$O\&M_{VAR}$	Variable Operations and Maintenance
OECD	Organisation for Economic Co-operation and Development
OPEX	Operations and Maintenance Cost

OWC	Oscillating water column
pf	Pulverised fuel
PV	Photovoltaics
R&D	Research and Development
SMR	Small Modular Reactor
TRL	Technical Readiness Level
TWh	Terrawatt hours
UK	United Kingdom
UN	United Nations
USA	United States of America
USD	United States Dollar
WACC	Weighted Average Cost of Capital
WEC	Wave Energy Converter
WSE	Wave Swell Energy

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6.3. Marine Solutions – Environmental impact assessment

Marine
SOLUTIONS
TASMANIA PTY LTD
www.marinesolutions.net.au

Environmental Impact Assessment

Wave Swell Energy Test Site

Grassy Harbour, King Island, Tasmania

prepared for

Wave Swell Energy

February 2023

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Version	Contributor/s	Date reviewed	Reviewed by	Notes
1	G. Williams	14 Feb 2023	L. Smith	-
2	G. Williams	22 Feb 2023	L. Smith	
3	G. Williams	23 Feb 2023		

Cover photo: UniWave installation (left - https://www.waveswell.com/technology/), Grassy Harbour, King Island (right - Google Earth).

Table of Figures

Executive Summary

Marine Solutions conducted an environmental survey in Grassy Harbour, King Island on the 19th of December 2022, to facilitate an Environmental Impact Assessment (EIA) of the UniWave installation. The objective of the EIA is to determine if the 2-year deployment and operation of the UniWave had any detectable impact on the ocean, seafloor and ecology of the immediately surrounding area.

A suite of environmental data was collected in surveys at the UniWave site, and at two control sites at a nearby reef and inside the Grassy Harbor marina. The environmental data collection at all three locations included underwater habitat surveys, water quality profiling and sediment analysis (contaminant and particle size). An additional bathymetric mapping of the seabed around the UniWave installation was conducted.

The bathymetric mapping revealed a gently sloping uniform seabed with no notable depressions or crests around the UniWave installation. A dive survey found that the hull of the unit had been colonized by green and brown algae. These were representative of the species in the surrounding area and expected for a benign submerged installation of this duration.

Measurements of temperature, salinity, dissolved oxygen and turbidity in the receiving environment showed a shallow, fully mixed water column with little fluctuation across sites and depths and did not appear to be influenced by the UniWave. Similarly, concentrations of heavy metals and total petroleum hydrocarbons were low in the vicinity of the installation. By comparison, there were slightly elevated levels of arsenic and nickel observed in the control site in the marina.

Sediment particle size varied across the three sites and was largely related to local habitat structure. The substrate near the UniWave installation and the marina largely consisted of fine and coarse sand whereas the substrate near the reef consisted of a mixture of very fine sand and silt along with large pieces of coarse sediment and shell grit. Particle size analysis did not show any evidence of deposition or erosion caused by the presence of the UniWave structure.

There were no detectable environmental impacts of the installation beyond the obvious expected impacts of the physical structure itself (i.e. footprint on seabed, structure for substrate for colonising algae).

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.

1 Introduction

1.1 Proposal Brief

Marine Solutions was invited by Scott Hunter from Wave Swell Energy to conduct an environmental impact assessment of the UniWave installation in the harbour adjacent to the town of Grassy, Tasmania. The UniWave was installed in January 2021 and connected to the King Island electrical grid in June 2021 (WSE, 2021). The operational phase of the project was completed in late 2022 and the unit has now been decommissioned and scheduled for removal in early 2023.

1.2 Purpose and Scope

The purpose of this report is to detail the methods and findings of a marine site survey at the UniWave installation and nearby control sites to determine if there were any detectable environmental impacts on the receiving environment in Grassy Harbour, King Island, Tasmania. The information presented in this report will provide Wave Swell Energy (WSE) with data and analysis to include in future proposals for UniWave deployments internationally. Specifically, to provide a case study to address potential concerns around environmental impacts.

The project includes the following:

- Bathymetric mapping of the seabed
- Water quality profiling for temperature, salinity, stratification, dissolved oxygen and turbidity
- Underwater habitat characterisation
- Sedimentary particle size analysis, to determine substrate composition and stability
- Sedimentary contaminants (heavy metals and Total Petroleum Hydrocarbons)

1.3 Study Area

The study area is located close to shore in Grassy Harbour, King Island (Figure 1). The region is renowned for its fishing, scuba diving and local penguin colony at Grassy Penguin Island. The UniWave was partially submerged on the seabed approximately 100 m from shore in 5.75 m of water (WSE, 2021).

Figure 1. Map showing the location of the survey sites around Grassy Harbour (base image source: Google Earth). Environmental data from west and east of the UniWave installation as indicated.

2 Local Bathymetry

2.1 Methods

Bathymetric mapping of the seabed was conducted on the 19th of December 2022 in the vicinity of the UniWave installation and surrounding area in order to characterise the seafloor and highlight any benthic features.

The study area was mapped using a CHIRP-enabled broadband sounder and Garmin EchoMAP plotter, logging GPS positions and water depth every two seconds. This information was logged at sufficient resolution, such that representative interpolations between data points could be made, to produce accurate bathymetric data of the given area to Australian hydrographic survey requirements. Depths were measured to the nearest tenth of a meter, and tidally and barometrically corrected for Chart Datum (CD) using tide charts and observations from the Bureau of Meteorology. The results were interpolated using GIS software Surfer 11.0 to create a bathymetric profile of the area (Figure 2).

2.2 Results

Seabed bathymetry across the UniWave deployment area showed a uniform increase in depth with distance from the shore (Figure 2). Depths reach approximately 9 m below chart datum at around 150 m offshore and the seabed was largely characterized by fine to coarse sand particles. At the time of the survey, there were no remarkable bathymetric features to note and no evidence of any artificial depressions or crests that would suggest any influence of the UniWave operation or interaction with local tides/currents.

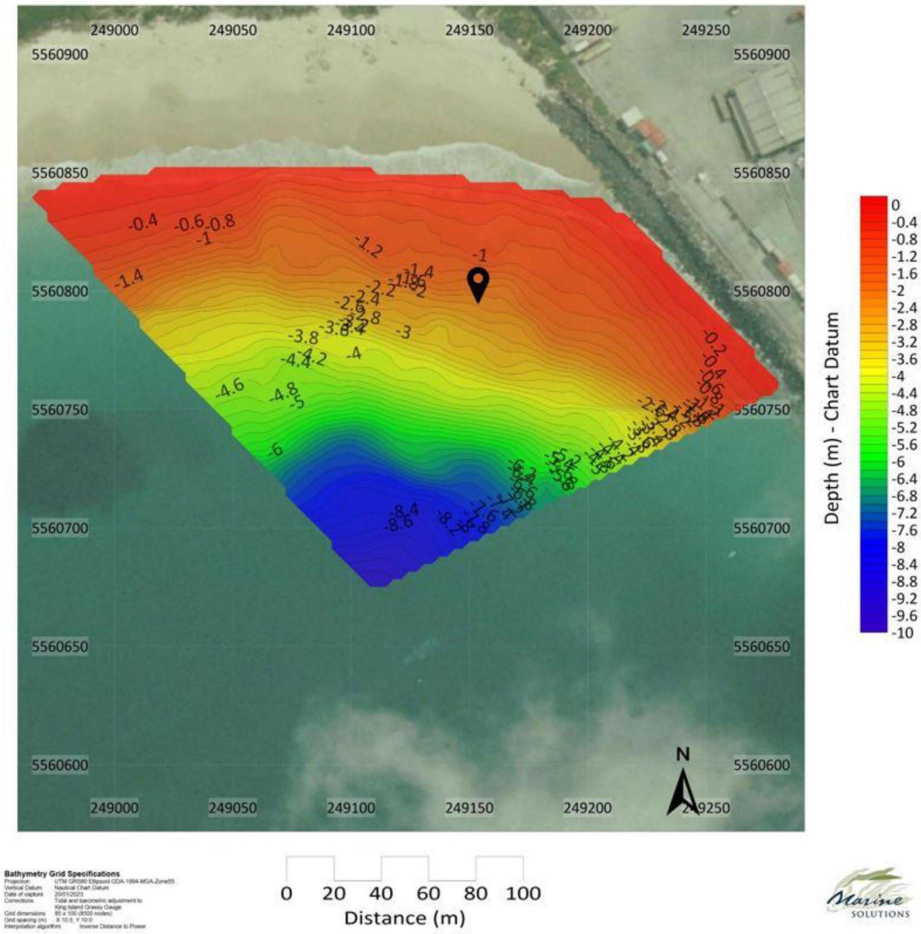

Figure 2. Bathymetric contour map of the UniWave deployment area. The approximate location of the UniWave at the time of the survey is represented by a black pin. The map is tidally and barometrically corrected to Chart Datum.

3 Underwater Habitat Characterisation

3.1 Methods

An underwater habitat characterization was conducted by divers on the 19th of December 2022 in the vicinity of the UniWave and the surrounding area (Appendix 1). Specifically, the underwater habitat survey was conducted at three different locations: at the UniWave (split into East and West components) and two nearby reference sites at a local reef further to the west and marina to the east (Figure 1, Appendix 2). The purpose of the survey was to provide information on habitat structure, community type and species composition and to assess any impact of the UniWave installation relative to the reference sites.

The dive surveys were conducted using a random roaming visual census technique for approximately 10 minutes at each site with the divers swimming from the deepest to the shallowest contour of the seabed. The survey was filmed using an Olympus TG-6 camera in an Aquapazza housing along with a GoPro to collect continuous video footage of the seabed. The video footage is available from Marine Solutions upon request (Appendix 3).

3.2 Results

3.2.1 UniWave - Primary Site

The visibility in the water at the time of the survey was around 10 m. The substrate surrounding the UniWave was comprised of fine and coarse sand and largely devoid of algae, seagrass and invasive species. Rockbags used to hold the unit down and prevent scour were exposed on the seabed (Figure 3b). Along both sides of the hull was a uniform growth of brown and green algae (primarily *Ulva sp.*) together with a sparse presence of turbo snails (*Turbo undulatus*) and soft sponge species. Barnacles were present in small numbers with an increasing abundance along the intertidal zone of the hull relative to the subtidal and supratidal zones.

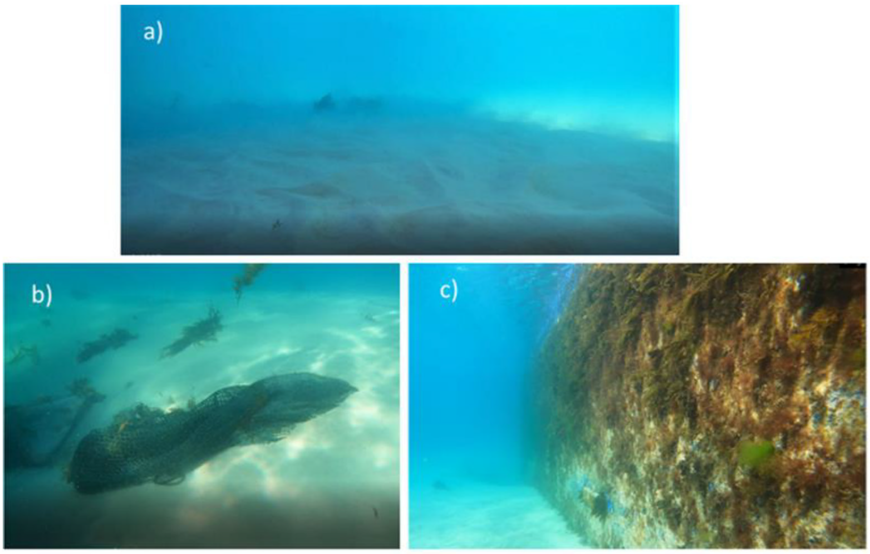

Figure 3. Images from the underwater habitat survey surrounding UniWave showing a) sandy sediment substrate b) exposed 'rockbags' on the seabed c) brown and green algae growing on the hull.

To the west of the unit was dislodged brown algae (*Phyllospora comosa* & *Ecklonia radiata*) accumulating in a turbid pinch point. To the east side of the unit was a remnant kelp (*E. radiata*) garden and the presence of numerous purple wrasse (*Notolabrus fucicola*).

3.2.2 Reef – Control Site

The reef control site was approximately 100 – 150 m west from the UniWave and dominated by brown algae. There was a noticeable sand depression between two bomboras with a high abundance of blue-throated wrasse (*Notolabrus tetricus*) and scalyfin (*Palma victoriae*) around the reef. Short-spined sea urchins (*Heliocidaris erythrogramma*) were also present (Figure 4).

Figure 4. Images from the underwater habitat survey at the control reef site. Top: *H. erythrogramma* between two boulders. Bottom: Brown algae growing on the reef.

3.2.3 Marina – Control Site

The area surrounding the marina control site consisted of a mixture of rocky reef and seagrass habitat (Figure 5). The reef was dominated with turf algae and had a higher fish abundance compared to the other two sites. Additionally, the sediment at the marina was visibly coarser and darker in colour.

Figure 5. Images from the underwater habitat survey at the marina control site.

4 Water Quality Profiling

4.1 Methods

Water column profiles from the seabed to the sea surface were obtained in the vicinity of the deployment and at the two reference locations (Figure 1). A Xylem EXO 3 multi-parameter water quality sonde was used for *in situ* water quality profile measurements of temperature (±0.05 °C), salinity (±0.1 ppt), dissolved oxygen (±1% air saturation) and turbidity (±0.3 FNU).

4.2 Results

4.2.1 Stratification

As anticipated for shallow sites in the littoral zone, all sites exhibited a well-mixed and essentially homogenous water column from the surface to the seafloor.

4.2.2 Temperature

Characteristics of the water column were broadly similar across the different sites and depths. Temperature ranged from approximately 15 – 16 °C with the highest temperature of 16.2 °C being recorded in the surface waters at the marina reference site and the lowest temperature of 15.2 °C recorded in the surface water at UniWave E.

4.2.3 Salinity

Salinity values ranged from 34.8 to 35.1 ppt with the lowest salinity value being recorded in the surface water at the marina reference site. Overall, salinity values near the UniWave were consistent with those at the reference sites.

4.2.4 Dissolved Oxygen

Dissolved oxygen levels were all just above 100% air saturation, with some slight variation through the water column across the different sites (Figure 6).

At the UniWave site, dissolved oxygen levels stayed relatively consistent throughout the shallower, wave-mixed water column with levels persisting around 104 %. In contrast, both the reef and marina sites had increasing dissolved oxygen from the surface to the seafloor, with a minimum 101 -103 % in the 0 -1 m depth range at the marina reference site and a maximum of 107% at 6m depth at the reef reference site. This sub-surface elevation of dissolved oxygen is common during early morning surveys where photosynthesis is occurring. The relatively high dissolved oxygen at the Control Reef site may correlate to increased photosynthetic activity in a localised area of higher plant biomass. All values are above 100% saturation.

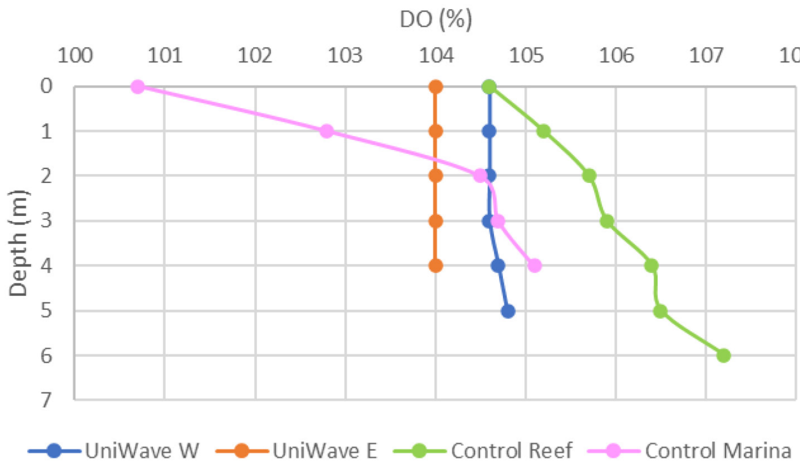

Figure 6. Dissolved oxygen profiles for different sampling sites in Grassy Harbour.

4.2.5 Turbidity

Potentially the most likely water quality parameter to be impacted by a moored installation, turbidity values ranged from 0.25 to 3.47 FNU at the time of sampling (Figure 7). These are relatively low values indicative of a benign environment. The highest turbidity levels were recorded in 0 - 1 m depth at the UniWave and gradually decreased with increasing depth. Turbidity levels at the two reference sites showed little variation with increasing depth and consistently stayed below 1 FNU.

Although the recorded turbidity levels are considered low across all sites and depths, small variations in readings, for example in the case of the higher turbidity readings at the sea surface, may be from the interaction of the wind-driven waves at the time of sampling (10 knots from the NE), creating greater surface turbulence at WSE-East, relative to the other side of the installation at WSE-West.

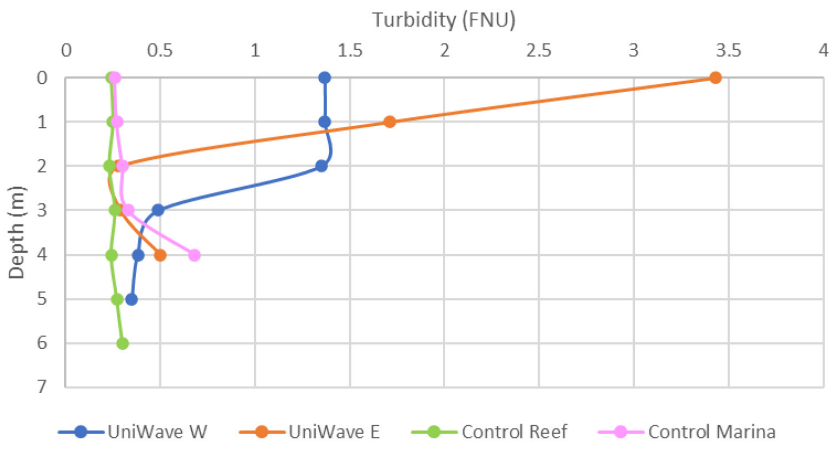

Figure 7. Turbidity profiles across the different sampling sites in Grassy Harbour.

4.2.6 Summary of Water Quality Properties

Overall, the water quality properties surrounding Grassy Harbour do not appear to be influenced by the UniWave deployment, with all properties near the deployment broadly consistent with those at reference sites.

5 Sediment Contaminants and Particle Size Analysis

5.1 Methods

Sediment samples were collected at the UniWave and the two reference sites (Figure 1) for an assessment of contaminants, specifically heavy metals (and metalloids) and total petroleum hydrocarbons (TPHs). Sediment particle size was also investigated to give an indication of substrate composition and stability. Since particle size influences both chemical and biological characteristics, it can be used to account for any possible variability found in contaminant testing results and ecological datasets.

5.1.1 Contaminants

Duplicate benthic sediment samples were collected by a diver using a handheld corer at two locations for each of the three sites (total of 12 samples). At the UniWave, one sample was taken to the west of the unit while the other sample was taken to the east of the unit (Figure 1).

The top 10 cm of the cores were extruded into clean laboratory glassware and sent to Analytical Services Tasmania (AST) - a NATA accredited laboratory - for analysis. Specifically, the samples were tested for the following parameters:

- Metals including As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn and Hg.
- Total Petroleum Hydrocarbons (TPH total, TPH C06-C09, TPH C10-C14, TPH C15-C28, TPH C29-C36)

Laboratory results for the above parameters were then compared to the Australian & New Zealand Guidelines (ANZG) toxicant default guideline values for sediment quality (ANZG, 2019 - Table 1).

The default guideline values for sediment quality (ANZG DGVs) indicate the concentrations below which there is a low risk of unacceptable effects occurring, and should be used, with other lines of evidence, to protect aquatic ecosystems. In contrast, the DGV-High values provide an indication of concentrations at which one might already expect to observe toxicity-related adverse effects.

5.1.2 Particle Size

Two sediment cores were sampled at each site (same sites as above) (Figure 1) and extruded into glassware. Particle size distribution of the different sites was assessed volumetrically in-house by wet sieving sediment samples through a series of stainless-steel sieves (4 mm, 2 mm, 1 mm, 500 µm, 250 µm, 125 µm and 63 µm). The content of each sieve was drained and transferred to a measuring cylinder, beginning with the coarsest sediment fraction (4 mm) and working down to the finest (63 µm). The volume of sediment in the measuring cylinder was recorded for each size class. The sediment fraction < 63 µm was assumed to be the total volume of the sample minus the combined volume of all other size classes.

5.2 Results

5.2.1 Contaminants

Concentrations of all metal contaminants at the UniWave and the Control Reef site were below the recommended Australian & New Zealand threshold default guideline values (DGVs) (ANZG 2019) (Table 1). At the Control Marina site, all metal concentrations were significantly higher, with both arsenic (As) and nickel (Ni) slightly above the DSG threshold at Control Marina A. These results are not unexpected for an active marina in an enclosed port area.

Table 1. Results of contaminant analysis of sediment samples. Cells highlighted in yellow indicate levels that exceed the ANZG toxicant default guideline values (DGVs) (ANZG 2019).

Analyte	Units	ANZG DGV	ANZG DGV - High	Site					
				UniWave – E	UniWave – W	Control – Reef A	Control Reef B	Control – Marina A	Control – Marina B
As	mg/kg	20	70	2	3	4	3	21	9
Cd	DMB	1.5	10	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Co		-	-	<1	<1	<1	<1	4	6
Cr		80	370	3	3	7	3	43	68
Cu		65	270	<1	<1	<1	<1	19	33
Mn		-	-	10	10	66	14	488	697
Ni		21	52	<1	<1	2	<1	18	25
Pb		50	220	<1	<1	<1	<1	2	2
Zn		200	410	<1	<1	3	<1	21	29
Hg		0.15	1.0	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Total Petroleum Hydrocarbons (TPH)		280	550	<100	<100	<100	<100	<100	<100
C6-C9		-	-	<25	<25	<25	<25	<25	<25
C10-C14		-	-	<25	<25	<25	<25	<25	<25
C15-C28		-	-	<100	<100	<100	<100	<100	<100
C29-C36		-	-	<100	<100	<100	<100	<100	<100

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5.2.2 Particle Size

The sediment sample at UniWave E consisted of fine sand and silt (0.125 mm or smaller) interspersed with approximately 41.8% coarse sediment (0.5 mm or larger – see Figure 8). The sediment sample at UniWave W was similar to UniWave E but with a slightly higher proportion of coarse sediment (~ 53.8%).

The sediment collected from Control Reef A was predominantly comprised of fine sand (0.125 mm) and silt (<0.063) apart from one large piece of granite (~ 5 cm) and a few larger pieces of shell grit. However, the sample from Control Reef B had a much higher abundance of coarse sediment and nearly no silt. The variation in particle size at the reef may be due to the reef's structural diversity and complexity and samples being collected in slightly different habitat zones. For example, Control Reef A was sampled at a reef depression in 4-5 meters depth and Control Reef B was sampled from a reef crest at 5-6 m depth.

Both sediment samples from Control Marina A and B predominantly contained fine sediment along with a few small broken urchin spines and shells. Overall, the results of the particle size analysis show no evidence of particle size disturbance from the UniWave.

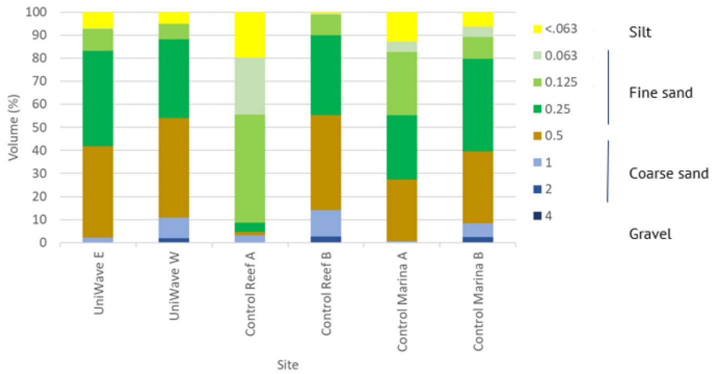


Figure 8. Particle size distribution measured at the different sampling sites.

6 Conclusion

Based on the findings from the field surveys in December 2022, the surrounding environment in Grassy Harbour does not appear to be detectably influenced by the UniWave installation or its operation, with the exception of relatively benign impacts of the presence of the physical structure (i.e. physical footprint on seabed, structure for substrate for colonising algae).

The seafloor surrounding the unit appeared uniform with no notable depressions or crests. It is possible that there will be a temporary depression in the sediment when the UniWave unit is removed but due to the fine particle size in the area, it is expected that the depression will fill up relatively quickly.

Analysis of the underwater habitat indicated that there were no patterns in the abundance of seaweed or species composition relating to the installation/operation of the UniWave. Instead, patterns in the distribution of seaweed and ecological community types are largely related to the broad distribution of seabed structures (sand, cobble or reef) across the study area.

The hull of the UniWave had been colonized by green and brown algae. This is expected as most underwater structures offer substrate for algae and fouling organisms to grow on. It is possible that any ongoing deployment of the unit would create an extended habitat for local marine species and increase their presence in the area. This may include both native and introduced species.

As anticipated, the results from the water quality profiles showed little variation across the sites for all parameters and were confirmed to not be influenced by the UniWave installation.

Similarly, heavy metals, metalloids and total petroleum hydrocarbon levels near the UniWave were all below the Australian & New Zealand toxicant default guideline values for sediment quality. While Arsenic (As) and nickel (Ni) exceeded the ANZG lower DSG threshold at the marina reference site, this is most likely related to activities inside the marina (DCCEEW, 2022; EPA, 2007).

Particle size varied between locations, likely due to the different underwater habitat at each sampling site,. Particle size distribution was broadly consistent at each site with the exception of the reef reference site that had two very different particle size samples. However, reefs normally have a large variety of seabed structures and particle size, it was therefore expected to show slightly different particle size compositions.

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.

7 References

Australian & New Zealand Guidelines for Fresh and Marine Water Quality [ANZG] 2019, viewed 26 January 2023, < https://www.waterquality.gov.au/anz-guidelines/guideline-values/default/sediment-quality-toxicants>.

Department of Climate Change, Energy, the Environment and Water [DCCEEW] 2022, viewed 6 February 2023, < https://www.dcceew.gov.au/environment/protection/npi/resource/student/arsenic-and-compounds>.

EPA 2007, *Review of Sediment Sampling Program - Tasmanian Boat Maintenance and Repair Facilities*, Aquatic Science, <https://epa.tas.gov.au/Documents/Report%20-%20Review%20of%20Sediment%20Sampling%20Program%20-%20Tasmanian%20Boat%20Maintenance%20and%20Repair%20Facilities%20-%20DTAE%20-%20October%202007.PDF>.

Wave Swell Energy [WSE] 2021, viewed 23 January 2023, <https://www.waveswell.com/king-island/wave-swell-energys-UniWave-is-installed-at-king-island/>.

8 Appendices

Appendix 1. Operational Summary

Date	Personnel*	Time (start)	Time (end)	Air temp (°C)	Cloud	Rain	Wind	Swell	Current	Tide**	Works conducted
19/12/2022	T. Jones C. James	08:00	11:00	18	1/8	None	10 knots NE	0-1m	None	High	Habitat characterisation Water quality profiling Sediment collection Bathymetry

* Personnel are from Marine Solutions unless otherwise indicated.

** Tide chart information is from the Bureau of Meteorology's predictions. Descriptions are as per on-site observations.

Appendix 2. GPS Positions of sampling locations (GDA94)

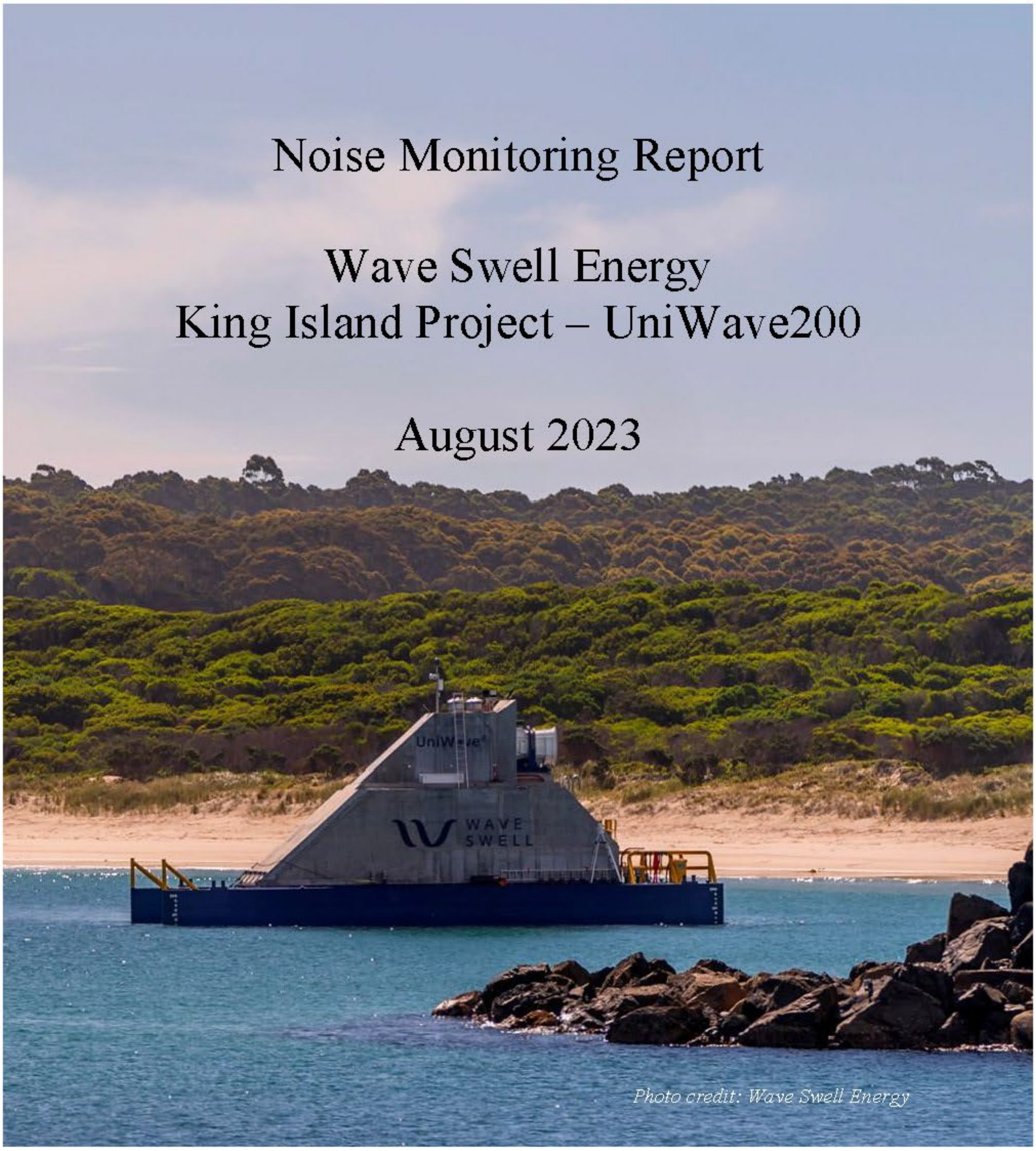
Name	Zone	Easting	Northing	Notes
UniWave E	55	249150.38	5560786.58	
UniWave W	55	249138.65	5560787.53	
Control Reef	55	248959.34	5560735.36	
Control Marina	55	249603.66	5560948.38	

Appendix 3. Video Files

Refer to the following video files, available from Marine Solutions on request:

- *"Western Reef Control 1"*
- *"Western Reef Control 2"*
- *"GP Southern Reef Control"*
- *"GP Southern Reef Control 2"*
- *"GP Eastern Marina Control"*
- *"GP Eastern Marina Control 2"*
- *"UniWave site"*
- *"GP UniWave site"*
- *"GP UniWave site 2"*
- *"UniWave 200 site 2"*
- *"UniWave 200 site 3"*
- *"UniWave site*

6.4. Ecopulse – Noise monitoring report



Prepared for:	Wave Swell Energy
Prepared by:	Christina Giudici (Ecopulse)
Document #:	Revision 0
Date:	18 August 202

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Executive summary

Wave Swell Energy (WSE) deployed the UniWave200 Wave Energy Converter (WEC) at Grassy Harbour, King Island, in early 2021. The project received planning and environmental approvals from King Island Council. A licence and lease for the WEC footprint and marine cable route was received from Crown Land Services.

There is a relatively high background noise from a working port and mine within close proximity to the deployment zone. Due to this context, and expected low noise emissions, the environmental impact assessment documents concluded there was very low risk of noise impacts to recreational beach users and marine fauna from the project.

The installation was approved by King Island Council without a requirement for detailed noise modelling or baseline noise measurements. There were no complaints from stakeholders or the general public regarding noise disturbances, and no evidence for any impact on marine fauna arising from noise emissions.

During operation, WSE undertook a campaign of noise monitoring to provide input for future assessments, and for scoping more detailed studies for future projects. Eight locations above water and on land were selected, and sound pressure levels were measured with a hand-held device, and the results recorded and collated.

The results confirm that noise levels from the turbine operation at the WEC itself increased with turbine operational speed. The noise from the airflap vents was consistent across turbine speeds.

For receptors at the nearest accessible point on the beach (50m from the WEC), the highest recorded sound level was 64.3dB, which is a little louder than normal conversation, and a little softer than a washing machine.

For monitoring locations on the water or the beach at 100m from the WEC or beyond, little discernable increase in noise with operation of the turbine and increasing turbine speed was detected.

It is not possible to directly compare the results of the noise monitoring to the proposed limits for vessels and motors operated on water in the EPA guidelines, as the monitoring locations were generally greater distances than those in the proposed EPA limits. This reflected the exclusion zones created for the WEC, and the minimum distance of a potential receptor on the beach to the device.

The EPA Guideline proposed limit is 74dB measured at 25m distance. The readings taken in the noise monitoring campaign did not exceed 64.3dB measured at 50m distance.

The noise monitoring program for the King Island UniWave200 project collected limited data (no baseline, limited acoustic detail eg frequency, tonal components, impulsiveness, modulation etc), however it verifies the expectations of the pre-approval environmental assessment documents. The results provide useful scoping information for designing acoustic studies if required for future projects in noise sensitive environments. These studies should also consider the need for measurement of vibration in the underwater environment.

1 Introduction

The primary purpose of Wave Swell Energy's UniWave200 King Island project was to validate the models used in the creation of the technology, in particular to demonstrate and validate the technology's power conversion process. These results provide WSE with a baseline and the tools and inputs from which to develop the technology further as part of Project Bluefire, the company's planned technology enhancement program.

The Uniwave200 WEC was installed in Grassy Harbour, King Island, in early 2021, and connected to the island's electricity grid. After a successful period of energy generation and data capture, the decommissioning of the WEC and associated infrastructure commenced in early 2023.

1.1 Purpose and scope of this document

This document outlines the regulatory and approval framework for the project, describes the noise monitoring program that was undertaken, presents the results of the monitoring, and discusses the results.

1.2 Environmental Approvals and assessment criteria

The project received planning approval, including environmental conditions, from King Island Council. A Licence and Lease from Crown land services was also obtained, with conditions.

The potential noise impacts on recreational shoreline users, nearby residents, and marine fauna were expected to be minimal. Background noise including from the adjacent working port, the operations on Group 6 Metals mining lease and reclamation area, and the noise from waves breaking onto the breakwater and the beach was expected to mask the noise from the turbine within the WEC.

Due to this context and the expected low noise emissions from the device, there were no specific noise assessment criteria required in the approval documents. No baseline measurements or noise modelling was required, or undertaken.

A desktop assessment of the potential impacts of the Project on the marine environment was conducted by Marine Solutions Tasmania Pty Ltd. The desktop assessment considered potential impacts on Little Penguins, and cetaceans and seals, as outlined in the following excerpts:

> *"Above water noise levels have the potential to impact little penguins through masking of biologically relevant sounds and have the potential to affect nesting behaviour. However anthropogenic noise is considered 'of less concern' for Little penguins. Little penguins swimming past the unit could utilise avoidance behaviour, and it is unlikely that noise will be heard at levels warranting concern from individuals on the shore. . .*
>
> *Consideration of cetaceans and seals should be included for any development likely to create underwater acoustic disturbances. Due to their mobile and migratory nature, and the proximity of the development to the shore, it is expected that any*

presence of threatened whales or seals in the vicinity of the development will be short in duration. . . .

The development is predicted to create minimal noise pollution as there are no underwater moving parts or underwater pressure vacuums. There may be some underwater noise produced due to vibrations from the turbine through the unit, however this is expected to be minimal, and no greater than ambient underwater noise or underwater noise produced by regular shipping operations in the harbour.

The development is not considered to pose a threat to marine mammals."

1.3 Sources of noise from the wave energy converter

The wave energy converter is an Oscillating Water Column (OWC) technology, which is an artificial blowhole consisting of a chamber that is open underneath the waterline. As waves pass the OWC, the water rises and falls inside, forcing the air to pass by a turbine at the top of the chamber. This turbine generates electricity, and is the primary source of noise from the device. There are also valves which control and direct air to the turbine, and these are an additional source of noise during operation.

1.4 Noise assessment during operations

No noise complaints from recreational users or residents were received by WSE or King Island Council during the project operating period.

There was no evidence of noise impacting the behaviour of marine fauna, including Little penguins.

The noise monitoring campaign, as outlined in Section 3 below, was undertaken in early 2023 prior to decommissioning of the WEC.

2 Noise policy and guidelines

The overarching principles and objectives for noise management in Tasmania are provided in the *Environment Protection Policy (Noise) 2009.*

The main legislation controlling environmental noise in Tasmania is the *Environmental Management and Pollution Control Act 1994* – particularly section 53, which deals with 'environmental nuisance'. Specific requirements relating to noise levels and hours of operation are principally covered by the *Environmental Management and Pollution Control (Miscellaneous Noise) Regulations 2016* and permits issued for particular activities.

As described in Section 1 above, no noise limits were set by the approval authority for the UniWave200 project on King Island. Given this, reference has been made to noise limits contained in the EPA *Noise Limit Guidelines 2016* (the Guidelines).

The Guidelines are not directly enforceable. However, they may assist in demonstrating compliance with the provisions of the relevant laws and regulations, and the general common law requirement for owners and users of noise-producing vehicles and equipment to respect the health, amenity and values of other members of society.

There is no limit proposed in the Guidelines for Wave Energy technology, however the table below presents the limits proposed for vessels and motors being operated on water that have been endorsed by the Director, EPA.

Item	Noise Limit (dB(A))	Measurement Distance (m)
Vessels	74	25
Outboard Motors	74	25
Vessel at an Organised Racing Event	95	30

Table 1: Extract from EPA Noise Limit Guidelines 2016 for Vessels and Motors being operated on water

3 Design of monitoring program

The noise monitoring program was devised and undertaken in-house by Wave Swell Energy. As far as possible, the equipment, locations and protocols used are in accordance with the EPA *Noise Measurement Procedures Manual 2008.*

Noise monitoring was conducted above water at various locations and using equipment and protocols as outlined in Sections 3.1 - 3.3 below.

An underwater microphone was used to record the noise at the entry to the OWC and at 20m distance from the OWC opening. This measurement did not provide a sound pressure reading, however the recording is available for interpretation of sound characteristics that may be relevant to devising noise monitoring to assess impacts on marine life in future projects using similar technology.

3.1 Locations

Eight locations were selected for the above water measurement of sound with a hand held measuring device. These are shown on Figure 1, and are:

1. Top deck of the device 1m offset from turbine
2. Back deck of the device 1m offset from flap vents
3. 50m from the device on the beach at closest point
4. 100m south of the device on the water (from a boat)
5. 100m from the device on the beach to the west
6. Tasport – closest business approx. 215m
7. Portlinks apartments – closest accommodation approx. 420m
8. 2850 Grassy road – house in closest township (Grassy) approx. 2.5km

3.2 Equipment

The equipment used was a Protech C-DSM1 Handheld Sound Level Meter which conforms to the IEC651 type 2, ANSI S1.4 type 2 for sound level meters. The User manual, containing equipment specifications, is included in Appendix A.

Calibration and user advice was provided by the equipment supplier.

Figure 1 Locations of sound level recording

3.3 Protocol

Sound level measurements and records were made by the Wave Swell technical team using a protocol which referenced the EPA *Noise Measurement Procedures Manual 2008*.

Several readings were taken at each location, and reading which picked up extraneous noise such as passing cars or vessels were excluded. Peak sound pressure levels were recorded at a set range of operational speed of the turbine at each location.

4 Results

4.1 Meteorological conditions

The meteorological conditions at the time of the recordings were:

- Prevailing southerly breeze 15-20 knots
  (onshore breeze averaging 18 knots – approx. 9.26 m/s)
- Clear skies
- Sea state: 1m swell
- Tide: low

4.2 Sound pressure levels

The results from the sound pressure readings were compiled and are presented below.

Reading Location	**Operational Speed of Turbine**			
	0 RPM	**1000 RPM**	**1500 RPM**	**2000 RPM**
1. On device - 1m from Turbine	68.9 dB	82.1 dB	94.7 dB	113.6 dB
2. Back deck 1m from Airflap vents	Varied consistently 88.5 dB to 91.2dB			
3. Beach - 50m from device	58.1 dB	59.6 dB	60.7 dB	64.3 dB
4. Beach - 100m to the West	57.7 dB	57.7 dB	57.7 dB	57.7 dB
5. 100m South of device (boat)	57.0 dB	57.0 dB	57.0 dB	57.0 dB
6. TasPort Port - Closest Business	55.8 dB	55.8 dB	55.8 dB	60.1 dB
7. Portlinks - Closest residence	55.1 dB	55.1 dB	55.1 dB	55.6 dB
8. WSE house - 2850 Grassy Road	39-42 dB	Values not affected at WSE house		

Table 2: Average peak sound pressure readings above water at all locations

5 Discussion and conclusions

The results presented above essentially verify the expectations outlined in the pre-approval environmental assessment documents.

It is not possible to directly compare the results of the noise monitoring to the proposed limits for vessels in the EPA guidelines, as the monitoring locations were generally greater distances than those in the proposed limits. This reflected the exclusion zones created for the WEC, and the minimum distance of a potential receptor on the beach to the device.

The Guideline limits proposed for vessels was 74dB measured at 25m distance. The readings taken in the noise monitoring campaign did not exceed 64.3dB measured at 50m distance.

Within the context of the King Island project, the results indicate that:

- At the device itself, the noise associated with the turbine increases with turbine operational speed
- The airflap vent noise is reasonably consistent across the range of turbine speeds
- A receptor on the beach at the closest accessible point to the WEC would potentially notice a marginal increase in noise with turbine operation and increased turbine speed. 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
- A receptor on the beach at 100m distance, or on the water at 100m distance, or at the nearest business or residence would perceive only marginal, if any, increase in noise with operation of the turbine and increasing turbine speed
- Receptors in the nearest suburb would not discern the operational noise of the WEC, even though the background noise (presumably waves breaking on the beach and breakwater) was substantially lower than at the locations nearer the beach

Although the noise monitoring program collected limited data (no baseline, limited acoustic detail eg frequency, tonal components, impulsiveness, modulation etc) the monitoring is considered to provide useful scoping information for designing acoustic studies if required for future projects in noise sensitive environments. These studies should also consider the need for measurement of vibration in the underwater environment.

Appendix A – User Manual for Sound Level Meter