bombora wavepower

Invisibly ***Powering*** Our ***World***

Cost effective electricity from the ocean

Report: COST OF ENERGY STUDY
Document No: P003-REP-G-002

Document issue details

Rev	Description	Author	Checked	Approved	Date
A	Draft	SKR	SRL	SRL	22/7/2016
0	Draft final for ARENA review	SKR	SRL	SRL	16/8/2016
1	Final Issue to ARENA	SKR	SRL	SRL	30/9/2016

Disclaimer:

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Funding Agreement Details

Project Title	Emerging Renewables Program Funding Agreement for a revised "Cost of Energy" feasibility study into the Bombora Wave Power system
Grant number	NA
Recipient Name	Bombora Wave Power
Project Commencement Date	25 August 2015
Project Completion Date	30 April 2016
Project Partners/ Participants/ Sub-contractors	NA
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Budget Summary

Total Project Cost at completion	$429,818 (ex. GST)
Original Project Budget	$420,573 (ex. GST)
Total ARENA Funding Paid	$210,286 (ex. GST)
Total Recipient Contributions	$219, 513 (ex. GST)

1.0 DESCRIPTION AND ANALYSIS OF THE MEASURE

1.1 Overview

This study investigates the economics of a 60MW wave farm consisting of 40 Bombora Wave Energy Convertors at a site near Peniche in Portugal.

Bombora Wave Power Pty Ltd (Bombora) has developed a membrane style wave energy converter called mWave™ that rests on the sea floor, similar to a fully submerged reef. As ocean waves pass over the mWave™, the membrane deflects pumping air through a turbine to generate electricity. The mWave™ is unique among wave energy converters as it simultaneously addresses the 'cost of energy' and 'ocean wave survivability' challenges.

The mWave™ technology is protected by international patents. Bombora Wave Power Pty Ltd is based in Perth, Western Australia.

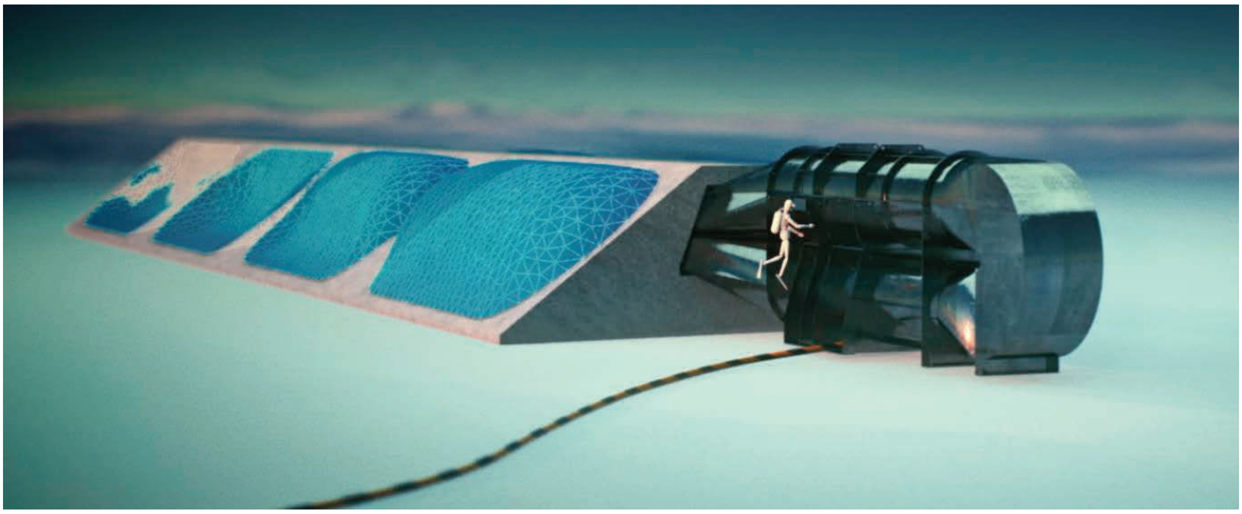


Figure 1 - Bombora Wave Power's Wave Energy Convertor – Design Case 5

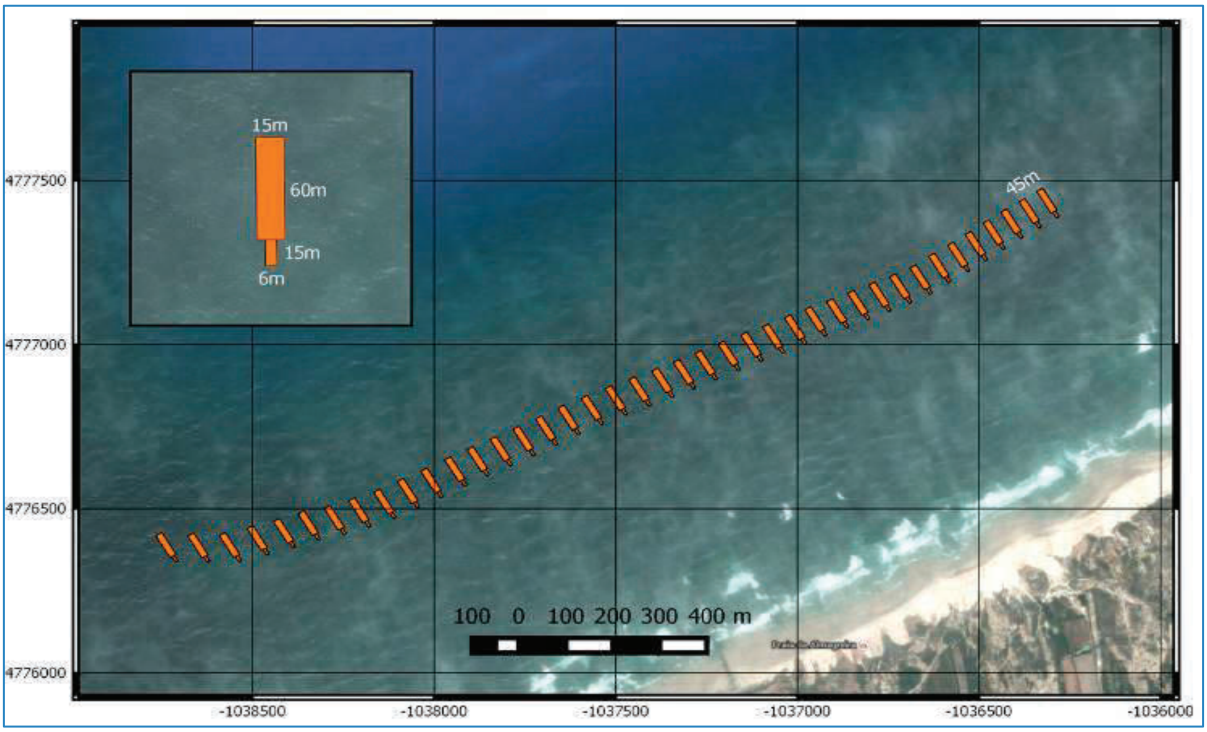


Figure 2 - Potential 60MW farm layout at Peniche, Portugal

Since completing its benchmarking Pre-Feasibility Study report in 2013, Bombora has continued to develop and refine the concept. These works included performing small scale tank testing, mid-scale sea trail tests, the development of more sophisticated computer modelling techniques and engagement with key supply chain partners to advance and deepen the technical understanding of the mWave™. Bombora has adopted a clear and pragmatic roadmap for future development and commercialisation as outlined in Figure 3. This report summarises the key findings of the "Cost of Energy Study".

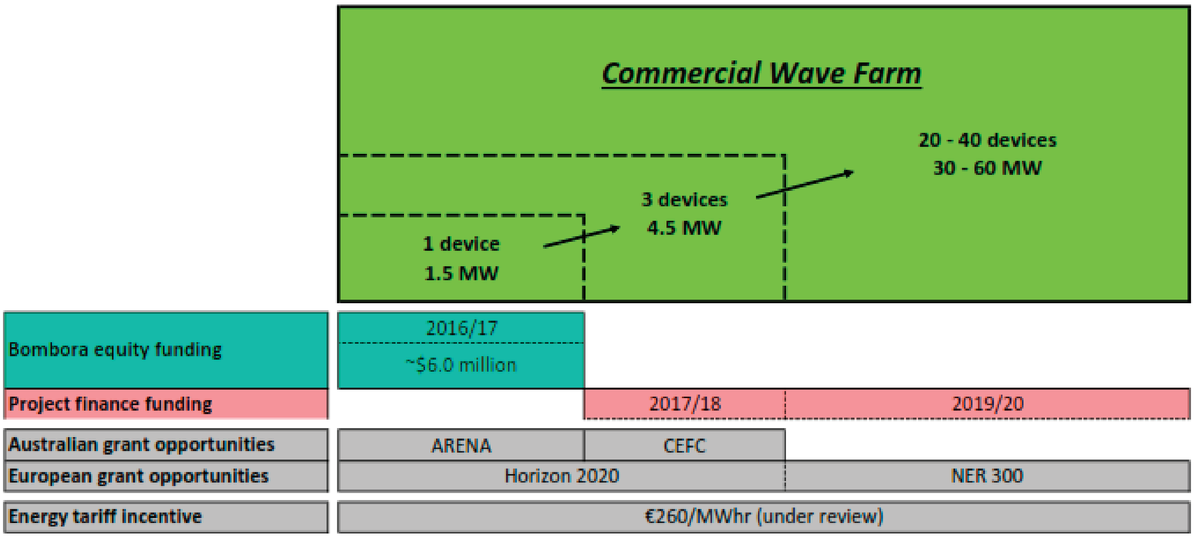


Figure 3 – Bombora commercialisation roadmap

1.2 Key outcomes

The key outcome of this study was the development of a robust Bombora wave energy converter design that meets the full range of requirements for utility scale, renewable, wave farms to be established:

- Robust product design
- Acceptable capital costs
- Acceptable operating and maintenance costs
- Good electrical power output
- Good process for construction, deployment, operations and maintenance
- An attractive "Levelised Cost of Energy (+/-30%)"

This study has confirmed the potential of Bombora's wave energy converter to be commercially viable at wave farm scale.

1.3 Study objectives

The key objective of this study was to refine the "levelised cost of energy" for a Bombora Wave Farm to a +/-30% accuracy by completing the following activities:

1. Engineering and design
    - Conduct engineering and product development projects (Membrane, valves, PTO)
    - Develop supply chain linkages
    - Design industrial scale device (refinement and optimisation of the system design, construction, installation and maintenance)
    - Produce industrial scale concept design drawings
2. Performance analysis
    - Refine the engineering models used to predict the "Mean Annual Energy Production" from the Bombora wave energy collector.
    - Conduct Mean Annual Energy Production simulation runs using the wave energy climate for the proposed wave farm at Penich, Portugal.
    - Conduct detailed sensitivity analysis on product design features
3. Cost analysis
    - Confirm costs with suppliers:
        - Capital costs
        - Deployment costs
        - Maintenance costs
4. Financial analysis
    - Confirm the Levelised Cost of Energy (LCOE) produced by an industrial scale device to the Carbon Trust's Marine energy cost estimation model.
    - Determine future areas of development to reduce LCOE
    - Compare LCOE projections to market expectations

1.4 Engineering and design

With assistance from consultants and key supply chain, Bombora applied the process shown in Table 1 to develop a detailed understanding of the "cost of energy".

Stage		Activities	
1	Site Selection	1.1	Wave climate (annual distribution, direction, extreme events, tidal information
		1.2	Site bathymetry and geology
		1.3	Environmental impact assessment
		1.4	Electrical grid access
2	Preliminary design concepts	2.1	Structure options
		2.2	Deployment process
		2.3	Maintenance process
3	Preliminary LCOE analysis	3.1	Annual energy production (MAEP using mWave2)
		3.2	Foundation loading and design (NGI)
		3.3	Structural loading and design (WP)
		3.4	Device cost analysis (WP, Airgasco, ECG, suppliers)
		3.5	Deployment cost analysis (WP, NGI)
		3.6	Maintenance cost analysis
		3.7	Preliminary LCOE assessment
4	Design Selection	4.1	Structure, foundation, PTO, control system, electrical cabling, electrical substation
		4.2	Deployment, commissioning, decommissioning
		4.3	Operations and maintenance planning
5	LCOE analysis	5.1	LCOE analysis (energy production, device costs, O&M costs)
		5.2	Sensitivity analysis
6	LCOE assessment	6.1	LCOE target – comparison to other sources
		6.2	Weighted average cost of capital assessment
		6.3	Learning rate assessment

Table 1 - Analysis methodology steps

Bombora engaged a range of expert consultants for support with the engineering and design and to augment our in-house capabilities (see Table 2).

Area of Design	Consultant / Key Supply Chain
Site Selection	WaveC (Portugal)
Membrane collector design	Trelleborg (UK)
Valve design	Praher Valves (Austria) / Vulcan Mould (China)
Structure design	WorleyParsons (Perth)
Foundation	Norwegian Geotechnical Institute (Perth)
Turbine design and generator design	Airgasco (Sydney)
	Dresser Rand - Siemens (UK)
Control system	ECG Engineering (Perth)
Electrical infrastructure	ECG Engineering
Transportation and Installation	WorleyParsons & NGI
Maintenance process	WorleyParsons / Airgasco / ECG
Performance modelling	Applied Renewables Research (Ireland)
	Curtin University (Perth)
	Australian Maritime College (Launceston)

Table 2 – Key consultants and supply chain utilised for the assessment

To ensure a suitable "real world" assessment was undertaken, a range of global wave farm sites were considered in this project. The keys selection criteria for a suitable site were:

- wave resource (high annual resource with low seasonal variability),
- suitable location for the wave farm (10m deployment depth)
- suitable bathymetry (allows wave energy to reach the wave farm) and
- access to the local or national electrical grid.

There are a multitude of potential wave farm sites that meet this criteria. For this investigation we selected a site just north of Peniche in Portugal. This site has been gazetted for wave energy and has good local support and infrastructure facilities.

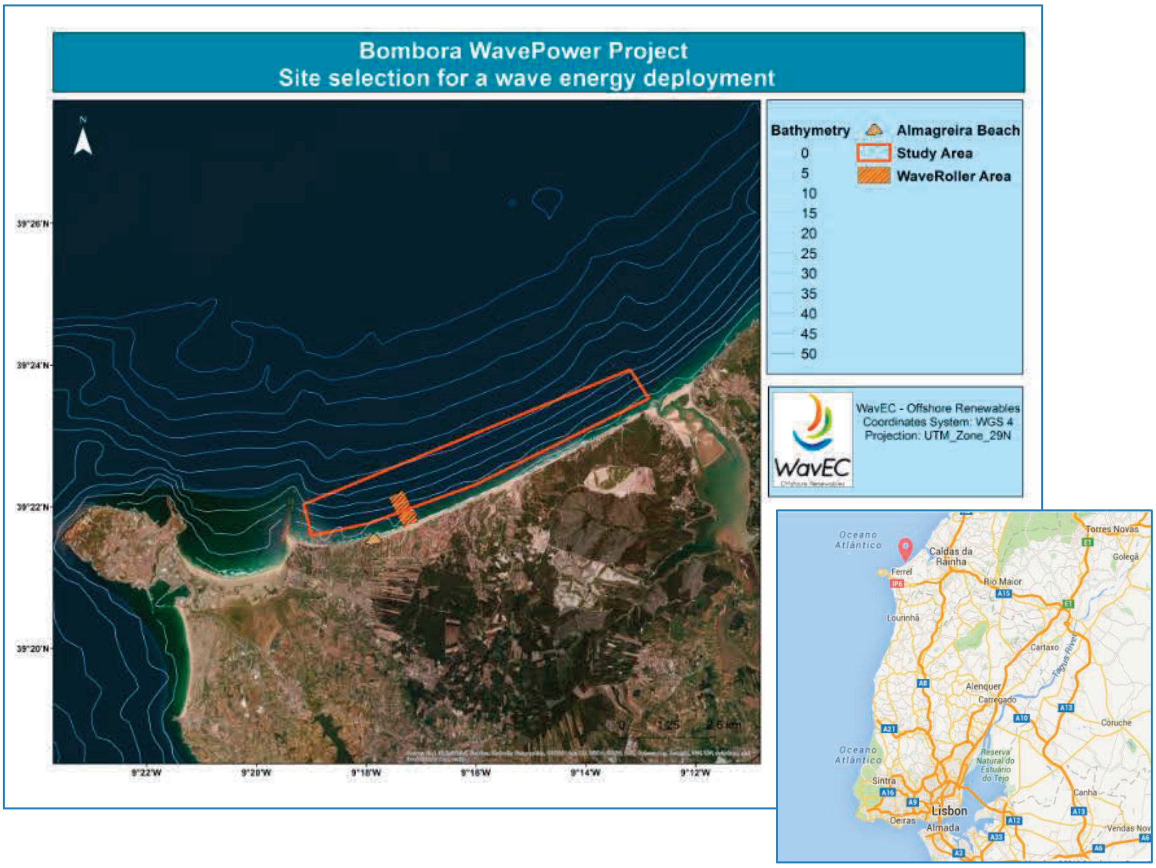
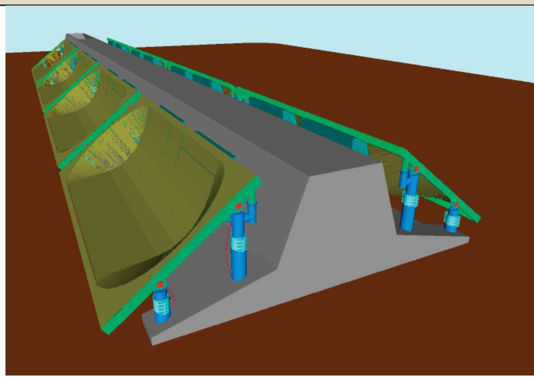


Figure 4 – Peniche, Portugal: Site selected for detailed study

A range of design options were considered and four alternative cases were selected for more detailed evaluation (see Table 3).

Case	Primary structure type	Foundation type	Installation technique	Thumbnail Image
1	Concrete	Ballast	Wet tow	

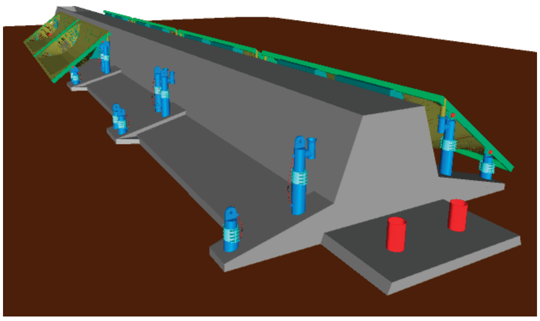
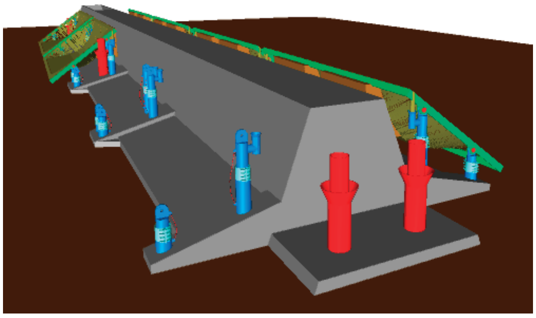
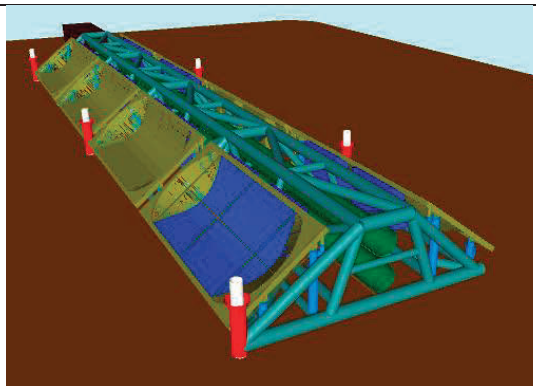
2	Concrete	Shear piles	Wet tow	
3a	Concrete	Grouted piles	Wet tow	
3b	Concrete	Grouted piles	Bombora barge	
4	Steel lattice	Grouted piles	Wet tow	

Table 3 - Design options considered

All four cases included removable steel cells for easy maintenance during the initial development period. Key component reliability data is not yet available and maintenance accessibility was identified as being highly desirable. Based on Case 3a, a subsequent Case 5 was considered where the cells are cast into the concrete primary structure. This transition from prototype design (case 3a) to product design (Case 5) can be expected to occur as reliability data is proven for the membrane and valves. Whilst Case 5 is conceptually designed, further engineering assessment is required to finalise the design concept.

1.5 Performance analysis

An empirically validated linear numerical performance model, mWave™, developed in conjunction with Dr Matt Folley of Applied Renewables Research was used to derive energy production estimates. mWave™ was developed in conjunction with other numerical and empirical studies including non linear Computational Fluid Dynamic simulations by Curtin University (Research Connections grant) and tank testing at the Australian Maritime College, University of Tasmania (Australian Research Council Linkage Project). mWave™ model development and validation is presented in Figure 5.

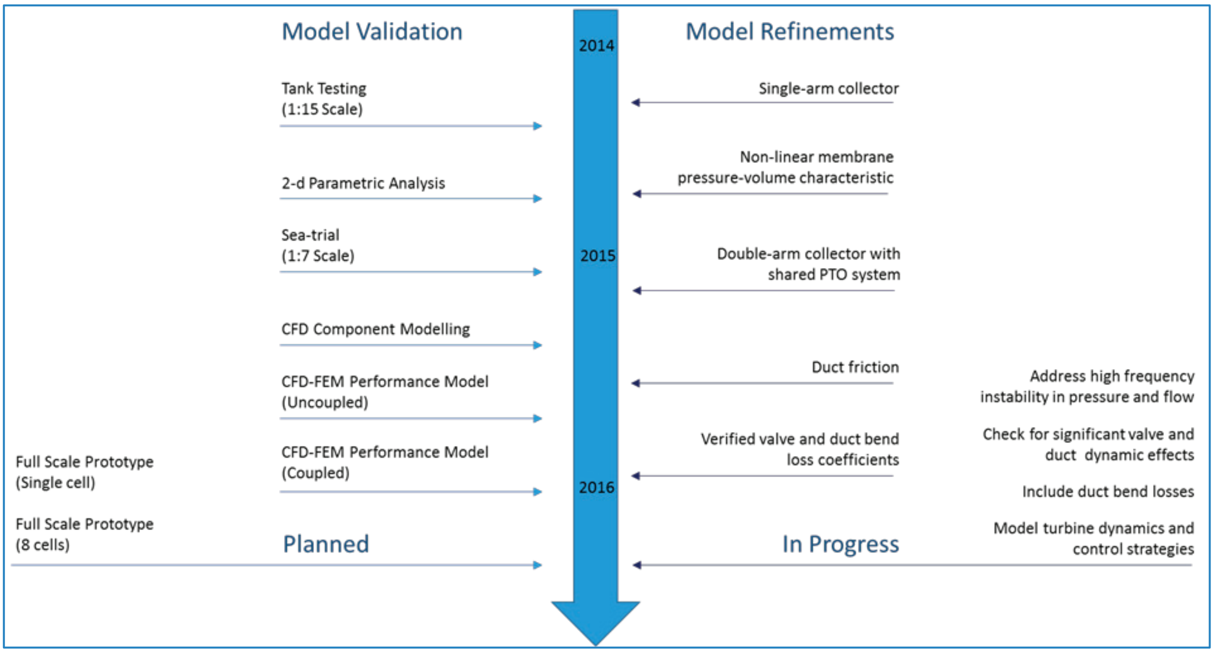


Figure 5: Progress of performance modelling validation and development.

mWave™ comprises of three main components. These are:

- Hydrodynamic model (Linear potential flow theory and BEM solver NEMOH)
- Simplified membrane model
- Power take-off model (Thermodynamic)

The inputs and outputs of mWave™ are summarised in Figure 6.

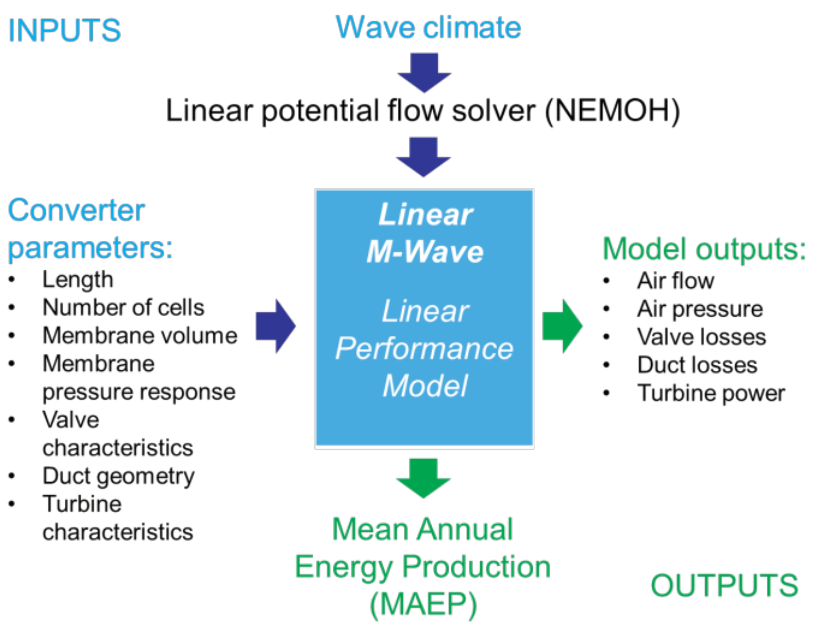


Figure 6: Summary of numerical model inputs and outputs

The relationship between Mean Annual Energy Production (MAEP) and each key design parameter was defined and analysed. Interactive effects of parameters when found to be important were also considered. The analysis provided optimised design parameters and was used to develop the system's basis of design.

mWave™ estimates incident wave power, power capture, capture width and factor, and mean annual energy production. Utilising sea-states obtained for the Baleal Este site (within the study area) as the input conditions (refer Figure 7) output results are derived, presented in Table 4.

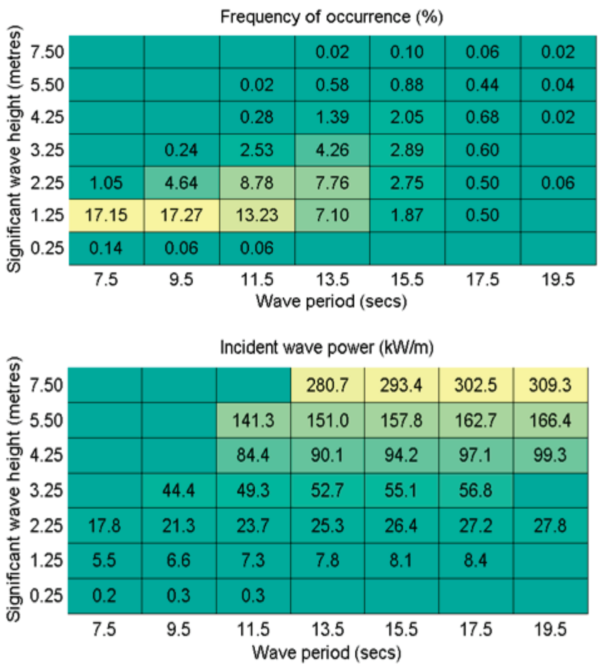


Figure 7 - Incident energy Baleal Este site

Parameter	Unit
Mean annual energy production	2100 MWhr
Mean capture width	10.3 m

Table 4: Estimated annual converter performance - Electrical power

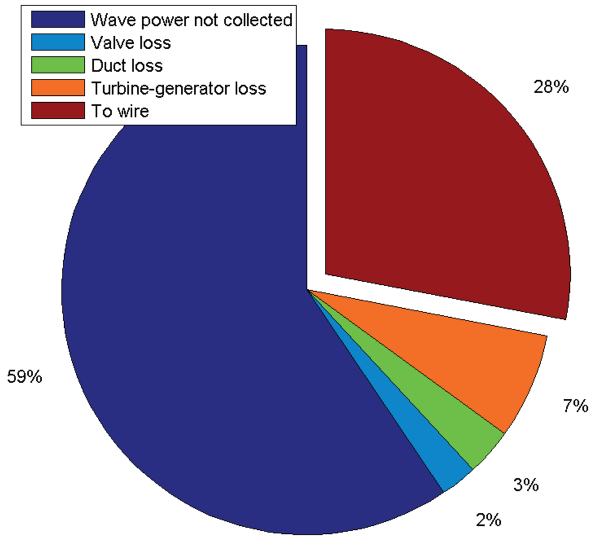


Figure 8: Proportion of total annual incident energy (wave power energy split expressed as a percentage of total incident energy).

1.6 Cost analysis

Capital cost, operating cost and decommissioning cost estimates were developed for each design option. Pricing was obtained from the market or estimated by consultants where appropriate. When sought from the market pricing uncertainty requested was to +/-30%.

The costs for Case 3a are shown in Table 5 and Figure 9. This configuration provided the lowest cost for a structure with removable cells.

Heads of expenditure	**Cost ($,000) (for 60MW wave farm, 40 Bombora converters)**
Capital Costs (including installation)	
Structure	121,538
Foundations/moorings	2,000
Control/instrument	4,484
Power Take-off	22,715
Grid connection	49,271
Installation surveys	1,125
Installation of structure	7,335
Installation of mooring	18,024
Installation of grid connection	14,975
Commissioning	1,000
Management and other	11,112
Total Capital Cost (including installation)	253,579
Operations and Maintenance Costs	
Planned maintenance (cost per year)	3,453
Monitoring/Control (cost per year)	881
Unscheduled repair (cost per year)	2,400
Rent (cost per year)	0
Insurance (cost per year)	1,268
Total Annual Costs	8,001
Decommissioning Costs	
Total Decommissioning Costs	8,000

Table 5 –Cost estimates for full farm- Case 3a

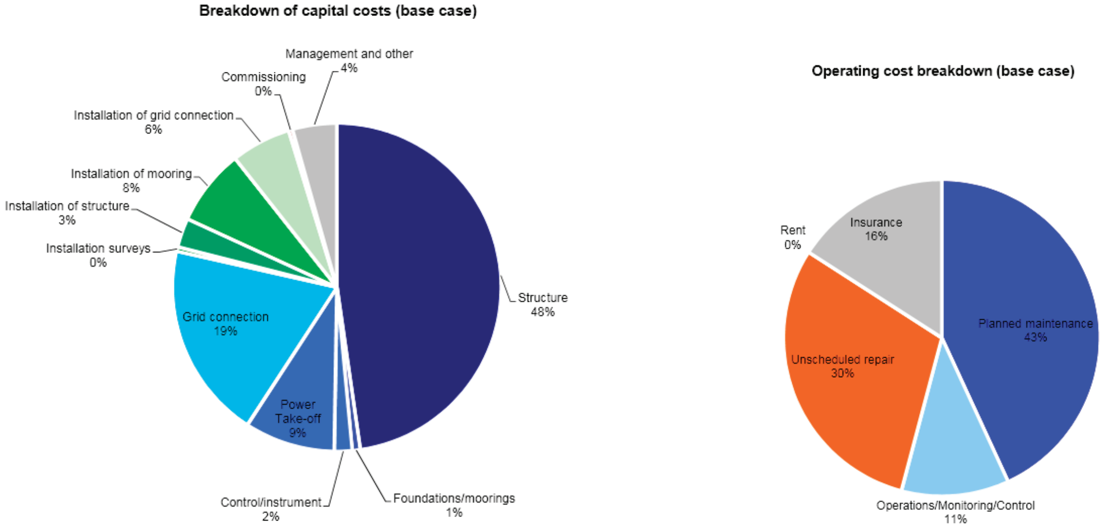


Figure 9 – Estimated capital and operational cost breakdown percentages – Case 3a

Case 5 shown in Table 6 and Figure 10. This configuration provided the lowest cost for a structure with integrated cells.

Heads of expenditure	**Cost ($,000) (for 60MW wave farm, 40 Bombora converters)**
Capital Costs (including installation)	
Structure	51,717
Foundations/moorings	2,000
Control/instrument	4,484
Power Take-off	22,715
Grid connection	49,271
Installation surveys	1,125
Installation of structure	7,335
Installation of mooring	18,024
Installation of grid connection	14,975
Commissioning	1,000
Management and other	11,112
Total Capital Cost (including installation)	183,758
Operations and Maintenance Costs	
Planned maintenance (cost per year)	3,453
Monitoring/Control (cost per year)	881
Unscheduled repair (cost per year)	2,400
Rent (cost per year)	0
Insurance (cost per year)	901
Total Annual Costs	7,635
Decommissioning Costs	
Total Decommissioning Costs	8,000

Table 6 - Cost estimates for full farm- Case 5

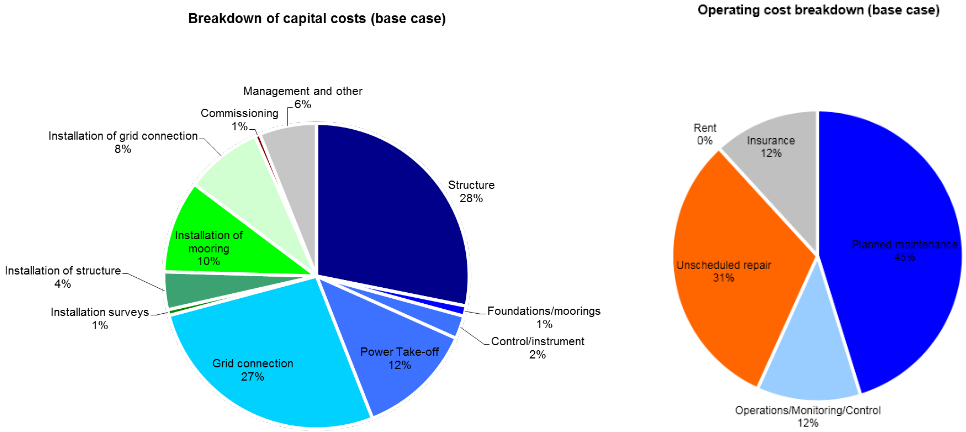


Figure 10 – Estimated capital and operational cost breakdown percentages – Case 5

1.7 Financial analysis

Bombora utilised the Carbon Trust's marine energy cost estimation model to perform a wave farm full lifecycle cost analysis. The factors shown in Table 6 were applied and considered reasonable for the level of development.

Design life	The design life of the majority of the device.	years	25
Transmission efficiency	Efficiency of the farm to grid transmission system.	%	98%
Device availability	Time when device is available to generate whether wave climate is suitable or not, I.e. time when not being serviced, or broken.	%	90%
Annual farm energy capture	Net annual energy delivered to point of connection to the electricity grid including all losses and downtime.	kWhr/yr	74,088,000

Table 7- Estimated full farm parameters used in Carbon Trust model

Bombora's costing analysis assessed the sensitivity of LCOE to Mean Annual Energy Production (MEAP) from the mWave™. The nominal MAEP was set at 2100MWhrs/annum, with a pessimistic case of 2000MWhrs and optimistic case of 2200MWhrs.

Capital, operating and decommissioning cost sensitivities were also assessed, with the pessimistic case set at +10% and the optimistic case set at -10%. A 33% allowance has been applied to installation estimates to allow for weather windows. Project contingency has been considered and then excluded from the analysis on the basis that it is inappropriate when assessing sensitivity. For a project seeking financial close, budget contingency and risk mitigations strategies would be implemented with a contingent effect expected on LCOE.

Bombora is undertaking a design spiral approach to its development. At the current level of design it is normal that there is uncertainty in the development of pricing estimates and MAEP. Bombora's analysis provides an insight into the sensitivity of LCOE to factors and is not intended to be representative of an absolute LCOE range. Stochastic modelling will provide greater understanding around uncertainty of pricing and MAEP and prioritise development areas in the future program of works.

Figure 11 below represents the cost of energy for the Case 3a design. The upper bounding line of the shaded area represents the pessimistic outcome, lower bounding area representing the optimistic outcome and the mid line representing the base case. The light blue region represents the range of pricing between optimistic and pessimistic over a range of discount rates (cost of capital).

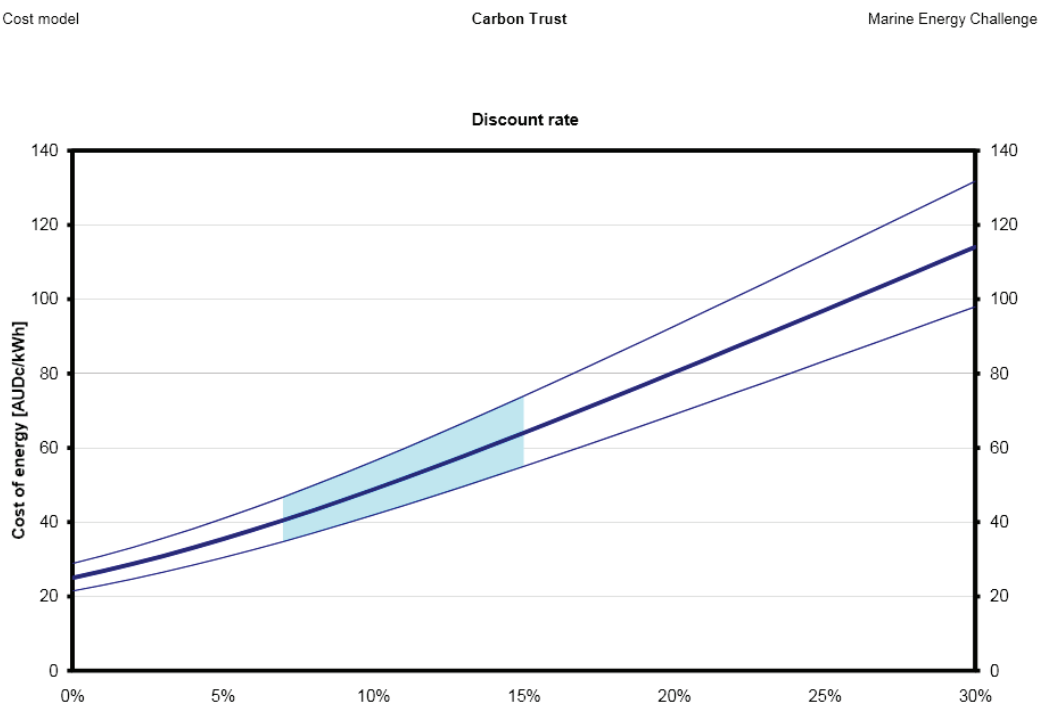


Figure 11 – AUDc/kWhr cost of energy estimates for a range of pessimistic and optimistic scenarios and various discount rates – Case 3a

A range of areas were identified to improve the "Levelised cost of Energy". An example for each key improvement area is listed below;

Capital cost improvement:

- Increased operational experience provides the opportunity for integrated cells. This will reduce the steel component cost contribution. Bombora estimate that this will reduce the overall structure costs by as much as 60% from $ $3,038,441 to $ $1,292,915 per mWave™.

Performance improvement:

- Improved availability to increase from 90% to 97% as is the historical trend for wind farms with increasing deployment.

Financial improvement:

- Discount rate improvement from 14% towards 7% (or even 5% as is the case with solar PV).

To provide a context for impacts these changes will have on LCOE, Bombora developed Case 5 and undertook a similar analysis to that presented above. This analysis only captured the capital cost improvement and availability increases outlined above. The results of this analysis are represented in Figure 12 below.

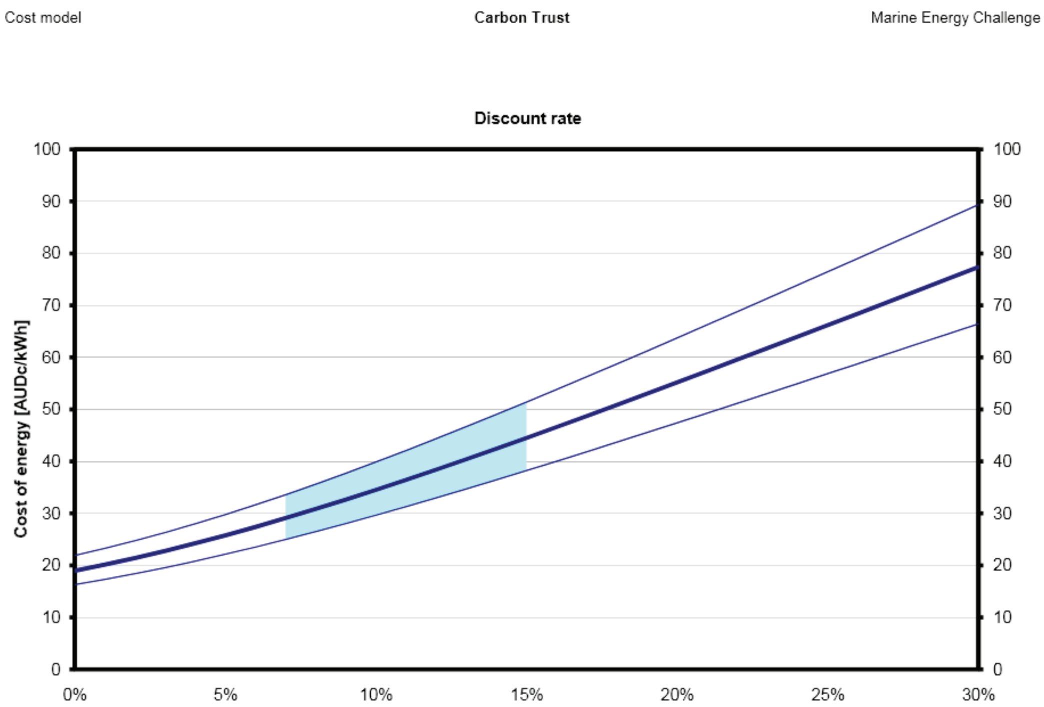


Figure 12 – AUDc/kWhr cost of energy estimates for Case 5

Table 8 below shows the significant improvements to LCOE the above improvements would have on the LCOE.

Design Case	Case 3a	Case 5
Pessimistic (@14% discount rate)	AUD70.32c/kWhr (€0.47/kWhr)	AUD49.81c/kWhr (€0.33/kWhr)
Optimistic (@7% discount rate)	AUD34.77c/kWhr (€0.23/kWhr)	AUD25.33c/kWhr (€0.17/kWhr)

Table 8 - LCOE ranges within the financial analysis

1.8 Market comparison

The current estimates for all marine generated electricity costs exceed the present commercial market rates for electricity. However it is recognised that there will be a very significant development and cost reduction "learning rate" as deployment capacity across the industry increases. This is historically evident across other renewable sectors such as solar and wind (both onshore and offshore).

SI ocean, an EU funded project, specifically assessed this aspect for the wave sector. The expected cost reductions through time and deployment are represented in Figure 13. The Irish Marine Renewable Industry Association updated the graphic to include the current market expectations represented by various support mechanisms such as regional European Feed in Tariffs and LCOE targets.

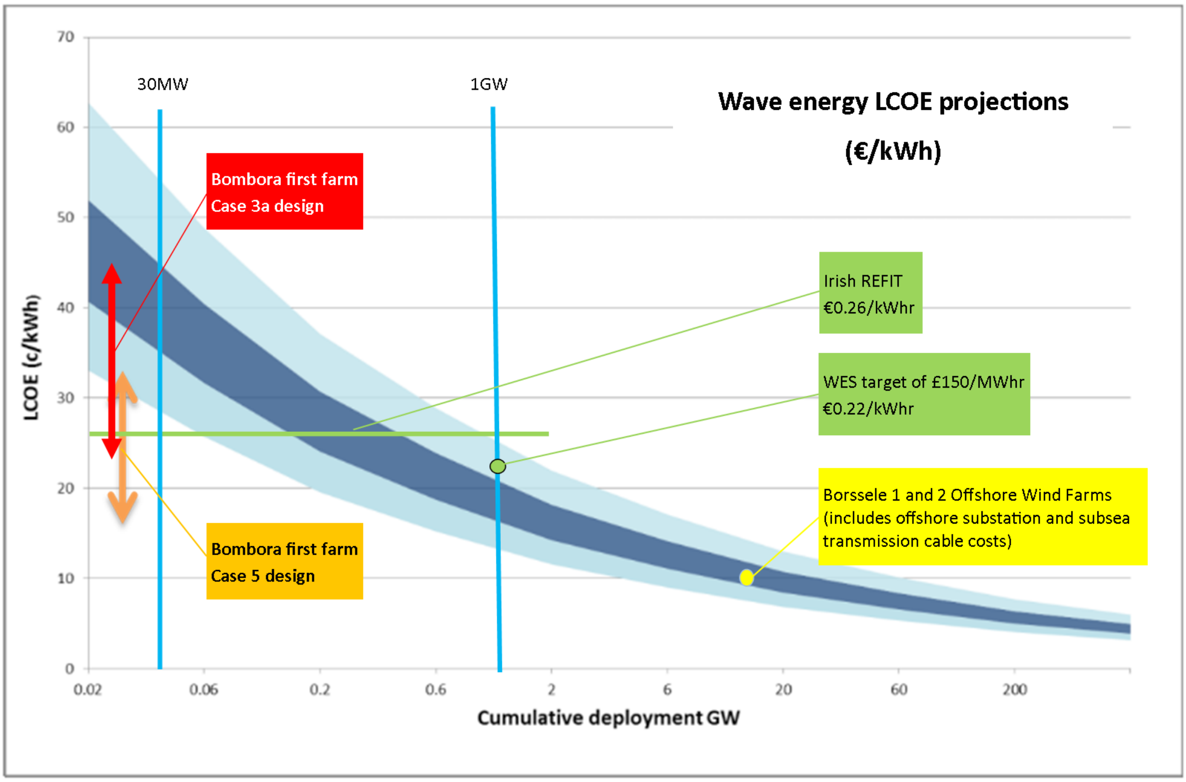


Figure 13 – Wave Energy LCOE (€ currency) ranges (deployment on logarithmic scale) over-layered in green by MRIA (SI Ocean, 2013) (MRIA, 2016)

Case 3a (red arrow) and Case 5 (orange arrow) LCOE range estimates have been overlayed on Figure 13. It is evident that Bombora Wave Power's mWave™ can potentially deliver a Levelised Cost of Electricity below current market expectations.

As a comparison to other market segments within offshore renewables, it is worth noting that the installed capacity for global offshore wind (fixed, not floating) exceeded 12GW in 2015. The most recent tender process was the Borssele 1 (350MW) and 2 (350MW) Offshore wind farms. The tendered price was €0.07/kWhr[1] excluding transmission, which equates to €0.10/kWhr when transmission to shore is included, ie the infrastructure costs of the offshore substation and submarine cable. The record low price was €0.05/kWhr below the tender ceiling price. The previous lowest tender price was Horns Rev 3 in Denmark in 2013, where the price was €10.3/kWh, excluding grid connection costs.

Within the context that costs are reduced through increasing capacity (commonly labelled as learning rates), the initial cost projections of Bombora's Wave Energy Converter indicates a strong initial economic proposition and further development is warranted.

[1] http://www.owjonline.com/news/view,dutch-tender-puts-offshore-wind-on-a-par-with-conventional-power-generation_43868.htm

1.9 Recommendations and next steps

The following key recommendations are proposed for the future development of the Bombora's mWave™:

- Move from the Carbon Trust methodology to using the stochastic modelling to refine the LCOE estimation.
- Refine the wave resource analysis incorporating localised bathymetric effects as detailed site investigations are completed.
- Undertake further modelling to account for the actual distribution of tide heights.
- Implement a PTO and control system design project to optimise energy extraction.
- Undertake physical membrane and value development projects to define and refine performance characteristics.
- Refine retrieval and deployment methodologies.

2.0 KNOWLEDGE SHARING AND COMMUNICATION

The following knowledge sharing and communication activities were performed during the project.

2.1 Reporting

Bombora provided ARENA a technical report (REP-G-001) on 29th April 2016. This report was independently reviewed by BMT-WBM.

BMT-WBM concluded that Bombora were at a Technology Readiness Level (TRL) of between a high end 5 and mid-level 6. BMT-WBM also found the level of analysis by Bombora was appropriate for the stage of MWave™ development.

A number of technical and economic observations were raised by BMT-WBM in its review and these have subsequently been clarified or adopted for future development.

2.2 Conferences and technical presentations

Bombora presented at the following conference during the project period:

- International Conference of Ocean Energy 2016, Edinburgh February 23–25. *Numerical Modelling of a Full-Scale Flexible Membrane Wave Energy Converter*

Bombora will present at the following conferences post project completion:

- Australian Ocean Renewable Energy symposium 2016, Melbourne October *Testing membrane volume effects on the performance of Bombora Wave Power's wave energy converter*.
- Asian Wave and Tidal Energy Conference 2016, Singapore October 25-28. *Tank-testing for the validation of Bombora Wave Power's linear numerical performance model.*
- Australian Geomechanics Society Western Australia, Technical Presentation 2016, Perth Aug 9 *Harnessing wave energy – Geo development challenges*

2.3 Patents

A provisional patent (PCT 2016900640) was filed during the project (Feb 2016) with a further draft patent under development.

2.4 Event Hosting

The following events were hosted during the project:

- Midscale field trial official opening 3rd September 2015:

http://www.sciencewa.net.au/topics/technology-a-innovation/item/3778-clean-electricity-ebbs-and-flows-from-the-swan-river

- Bombora hosted ARENA representatives (Mr's Grierson and Sinclair) at the midscale field trial site on 3rd September 2015.

2.5 Industry collaboration

Bombora conducted an information sharing session with Carnegie Wave Energy on 3rd May 2016 to present and discuss the study outcomes and learnings. Whilst commercially sensitive information was withheld, a range of shared learnings and common industry issues were discussed.

2.6 Media exposure

The following media exposure occurred during the project:

- https://www.businessnews.com.au/article/Bombora-makes-mWave-breakthrough
- http://bomborawavepower.com.au/bombora-secures-eip-program-funding/
- http://renews.biz/102867/bombora-bolsters-crew/
- https://twitter.com/pawseycentre/status/676659296487137280
- https://www.facebook.com/pawseycentre/posts/1000911046644451

3.0 MILESTONES

The following table outlines the deliverables that were established to track and milestone progress.

Milestone	Activity	Completed	Discussion
1	1 Recipient's wave device design 50% complete, as evidenced by internal certification and engineering drawings with 50% design reviewed stamp;	Yes	Refer Table 1. Multiple design configurations were considered. Initial engineering was undertaken.
	2 A Signed Service Agreement / contract, including detailed CV of corporate advisor as evidence of appointment of an corporate advisor to assist with / raise further equity and	No	Removed from scope of contract under variation.

	advance technology licensing		
	3 A Risk Management Plan in accordance with requirements in clause 3.3;	Yes	A stand alone deliverable completed prior to contract implementation.
	4 Evidence that any Knowledge Sharing Activities due to be completed before this milestone date have been completed;	Yes	Refer 2.4. Bombora hosted events to showcase its developments.
	5 Evidence that the Recipient and Other Contributions due to be used for the Measure before the invoice date have been used for the Measure;	Yes	Interim financial accounts were provided.
2	1 Recipient's wave device design 100% complete, as evidenced by internal certification and engineering drawings with 100% design reviewed stamp;	Yes	Refer Table 1. Multiple design configurations were considered and engineering progressed for costing purposes. Refer Table 3.
	2 Completed Cost Analysis, as evidenced by Pricing Schedule of system material take-off;	Yes	Refer section 1.6
	3 Evidence that any Knowledge Sharing Activities due to be completed before this milestone date have been completed;	Yes	Refer section 2.2
	4 Evidence that the Recipient and Other Contributions due to be used for the Measure before the invoice date have been used for the Measure;	Yes	Interim financial accounts were provided.
	5 Evidence of completion for the new IP development & IP licensing application, as evidenced by (draft Provisional Patent applications).	Yes	Refer section 2.3.
3	1 The Cost of Energy report;	Yes	Refer section 2.1
	2 The completed AETA or other mutually agreeable LCOE model ;	Yes	Refer section 2.1
	3 Evidence that any Knowledge Sharing Activities due to be completed before this milestone date have been completed;	Yes	Refer Section 2.5
	4 Evidence that the Recipient and Other Contributions due to be used for the Measure before the invoice date have been used for the Measure.	Yes	Audited Financial accounts were provided

Table 9 - Milestone table extract from contract schedules

4.0 HIGHLIGHTS, BREAKTHROUGHS AND DIFFICULTIES ENCOUNTERED

Bombora considers a major highlight was that it was able to successfully contribute in making marine renewable energy solutions more affordable with the potential to increase and diversify the supply of renewable energy.

Funding accelerated the engagement of consultants and enabled new design concepts to be established and proven. It also permitted greater engagement with the whole supply chain and project stakeholders.

During the project period Bombora required a variation to contract, due to scope change, unbudgeted contracting costs and a time extension, due to delay during the contract execution phase. Timing and scoping of milestone activities is an important consideration. Grant remittance cycles can extend the period between outgoings and grant payments. The above aspects can be particularly difficult for a small enterprise to manage and care should be taken when considering impact on cash flow.

5.0 ACKNOWLEDGEMENTS

Bombora wish to acknowledge that this investigation was supported by an Emerging Renewables Program grant from the Australian Renewable Energy Agency (ARENA). Support from this grant allowed Bombora to increase the level of engagement with key industry suppliers and improved the confidence level in the technical and commercial aspects of the investigation.

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