Post Access Report

Techno-Economic Assessment

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Executive Summary

Background: The University of Massachusetts (UMass) is developing a 2-body WEC device that is converting mechanical power into electricity using a mechanical motion rectifier that allows the system to couple to a flywheel. UMass has completed numerical modeling, wave tank testing, and PTO sub-system testing and needed assistance in developing a techno-economic model to enable optimization of their topology, comparison to a generic heaving point absorber topology, and guide the next steps in their development efforts. The core objective was to develop a techno-economic approach and modeling tool that allows benchmarking of the two topologies across a wide range of scales to evaluate their respective competitiveness in different application spaces.

Work Carried Out: Re Vision started with a detailed review of the R&D carried out to enable detailed implementation planning efforts. In the process, we addressed some fundamental feasibility issues related to the device and PTO topology. Subsequently, Re Vision engaged in a structured assessment process including:

- Developed numerically efficient time-domain models for the two WEC topologies to enable performing trade-off studies.
- Validated numerical models against wave tank testing data and a medium fidelity model previously developed at UMass.
- Evaluated the performance of a set of different device configurations that captured the parametric space of interest. Over 100 different configurations were evaluated, requiring over 300,000 time-domain runs.
- Developed an Excel-based structural model to evaluate different buoy configurations and validated the structural model using FEA and empirical design data.
- Developed a set of cost-scaling functions that allowed the model to scale in the relevant dimensions.
- Implemented the techno-economic model in Excel and automated various trade-off functions using Visual Basic macros. The effect of design uncertainties on LCoE was evaluated using Monte Carlo simulations.

Key Challenges: The key challenge of this project was to develop this model without being able to rely on any detailed engineering data and having to rely on public-domain cost data. A secondary challenge was that the topologies needed to be scaled over two orders of magnitude, which required a sufficiently flexible approach to accomplish the objective.

A combination of first-principles physics-based model scaling combined with data available from Reference Model efforts was used to adapt this assessment process. The resulting methodology and example could be expanded to various WEC device topologies and improve our ability to assess WEC technologies at a low TRL. Wind-related efforts inspired the methodology in the 70s and 80's that heavily relied on these types of first principles based on scalable techno-economic models. The difference between these efforts and today's efforts in the marine energy sector is that the design diversity is much broader today than it was back then, creating additional complexities.

Key Deliverables: This report, in combination with the Excel-based data, is made available publicly to start the conversation on suitable LCoE assessment processes that can meaningfully advance the industry.

Key Results: For this report, we evaluated the techno-economic methodology of the two topologies at utility and blue economy scales. At the utility scale, the WEC device dimensions were optimized for a 100MW deployment at the PacWave site in Oregon using device trade-off studies. Once optimized, the impact of key parameters on LCoE was studied using a set of sensitivity studies. The following table provides a summary of key results from the study. All costs are expressed in constant 2020 dollars. We purposefully picked a pre-pandemic reference cost year as subsequent supply-chain issues distorted cost elements, making apples-to-apples comparisons difficult.

Table 1 - Key Results Summary

Dimensions/Performance	**2-Body Design**	**1-Body Design**
Device Diameter	11m	8m
Device Height	6.7m	5.5m
Absorber Volume	317m^3	147m^3
Reaction Mass	2905t	0t
Average Power Absorbed	151kW	30.8kW
Structural Steel Weight	130t	27t
Power/Volume Ratio	0.6 kW/m^3	0.3kW/m^3
Weight/Power Ratio	0.9 t/kW	0.9 t/kW
Capacity Factor	30%	30%
Cost & Economics		
CAPEX	$5,232 / kW	$5,667 / kW
OPEX	$135/kW-year	$145/kW-year
LCoE	$216/MWh	$239/MWh

The structural efficiency of the WEC device clearly drives economics at the utility-scale. A useful first-order metric of structural efficiency for volumetric displacement devices is the ratio of structural steel required to the kW of rated capacity. For heaving point absorbers, a related metric is the Power/Volume metric, which is essential because volumetric displacement device structural cost scales linearly with cost. The following shows a comparison of the P/V ratio for the range of buoy sizes studied herein. It shows that optimal control could be a game-changer for these devices.

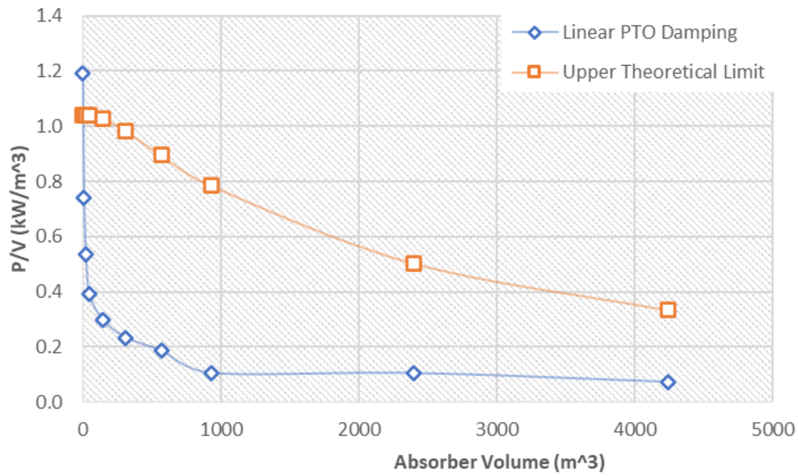

Figure 1 - P/V values for a range of different absorber volumes

The second set of scenarios were evaluated for blue-economy applications, which was assumed to consist of a single WEC device providing power to an at-sea payload located on the seabed. The LCoE at this scale is driven by marine operational costs including installation and O&M activities. We excluded permitting and environmental monitoring costs from this assessment as it remains unclear what requirements would be placed on such devices. We believe that eventually, such devices (especially if small) should be classified as a vessel with a class-type approval similar to a small boat – making this cost insignificant. The following chart shows the relative LCoE for the two topologies studied.

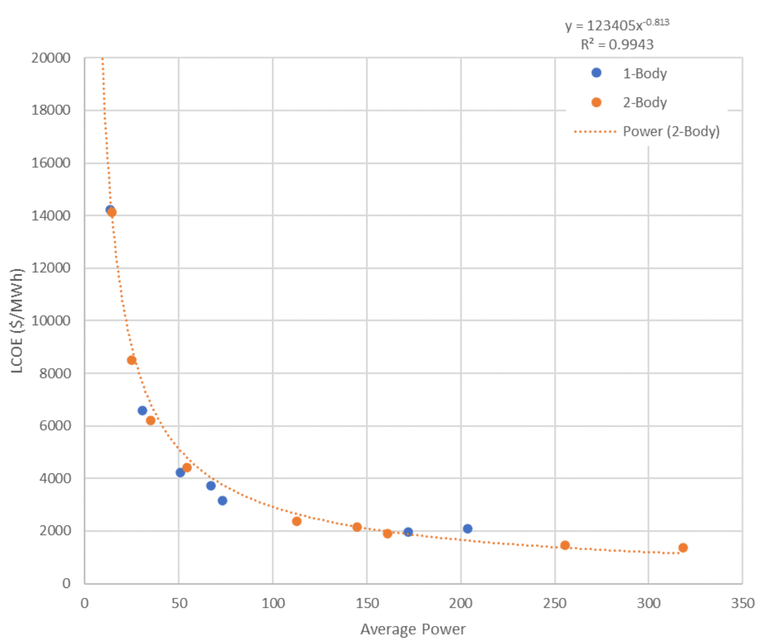

Figure 2 - LCoE vs Average Power for Blue Economy Applications

It shows that LCoE is mostly scale-dependent and that the topology has little effect on economic competitiveness. This is because at small scales, the LCoE is dominated by marine operational costs during the installation and O&M processes. This points to a need for Blue Economy WEC systems to be fully autonomous, eliminating the need for vessel intervention to provide competitive energy.

Our efforts identified several uncertainties:

- The performance of the 2-body topology will need to be studied further, specifically as it applies to effectively imposing motion amplitude limits. This will likely require the application of an effective time-domain control approach. The current modeling effort imposes constraints in an incomplete manner, which may have led to an overestimation of the performance of the 2-body topology.
- A point design of the system should be established at an appropriate scale that consistently addresses all the major structural and system integration issues. Such a design package could be completed at a conceptual level but would improve the cost prediction accuracy and design confidence.

A number of interesting R&D pathways were identified that could advance the current concept in a meaningful manner, including:

- Using a variable reaction mass in combination with optimal control (MPC) could significantly improve the two-body performance and economic viability. SeaVolt Technologies developed a similar device in the 2000 time period, but it was done before the advent of MPC-based control, which could warrant a re-visit of this topology.
- The current flywheel-based PTO topology relies on a flywheel operating at relatively low rotational velocities, resulting in minimal impact on the power-production cycle. The automotive industry has developed flywheel-based storage devices for F1 cars that operate at ~50,000rpm and are coupled to the drivetrain over a continuously variable transmission. This technology is known as KERS (Kinetic Energy Recovery Systems). This type of technology could be adapted to this concept and potentially address the common peak-to-average power flow issue in WEC devices.
- Alternative materials, including inflatable structures, could be leveraged to substantially improve device economics at the utility-scale and potentially make the system more portable and easier to transport at Blue Economy scales. An example is the NetBuoy concept developed under a program funded by Wave Energy Scottland (WES).
- At small blue-economy scales, tuning the device resonance to wind waves with wave periods of 1-3s makes sense. These waves are consistently present in most deep-water offshore locations and are typically not reported in wave resource assessments. The shorter wave periods would result in a much smaller reaction mass to tune the device and naturally detune the system in larger waves, solving a key challenge related to de-tuning in these larger waves. We performed a rudimentary assessment for a location offshore of Oregon and found that capacity factors on the order of 50% should be attainable.

1 Introduction to the Project

The proposed system is a self-reactive ocean wave energy point absorber containing one floating buoy, one submerged reactive body, and an R&D 100 Award-winning power takeoff (PTO). This design can tune the damped system's natural frequency by properly selecting the mass (physical and added) of the submerged body to match the ocean wave excitation frequency to maximize the power extraction.

The power take-off is a mechanical motion rectifier (MR) enclosed inside a cylinder connected to the second body. A push tube connects the floating buoy with the ball nut and drives the ball screw into bi-directional rotation using the relative reciprocating linear motion between the buoy and submerged reactive body. The bidirectional rotation is then rectified into the unidirectional rotation and drives the generator. Lab tests and simulations show that MMR-based PTO can significantly improve the energy transfer efficiency and increase the overall system reliability.

Re Vision will carry out a techno-economic assessment and benchmarking of the system to enable UMass to move forward with developing a techno-economic model. This will enable UMass to optimize their topology, compare it to a heaving point absorber topology, and guide next steps in development efforts.

2 Roles and Responsibilities of Project Participants

The team consists of Re Vision Consulting, which is conducting a parametrically driven techno-economic assessment, and UMASS, which is conducting numerical modeling of the device to establish baseline performance and structural loads.

2.1 Applicant Responsibilities and Tasks Performed

UMASS will apply its validated numerical model to (1) establish a performance baseline, (2) establish quasi-static extreme loads, and (3) establish parametric trade-offs. Work will be carried out on two topologies: (1) the two-body resonance-tuned WEC device as designed by UMASS and (2) a heaving point absorber tethered against the seabed.

2.2 Network Facility Responsibilities and Tasks Performed

Re-Vision will develop (1) A structural baseline analysis to determine structural steel requirements for the different components, (2) parametrically scalable models for various sub-systems and structural components, and (3) an economic analysis.

3 Project Objectives

The project objectives can be summarized as follows:

- Establish a techno-economic benchmark.
- Establish parametric cost functions for the device to enable systems-level optimization. This will allow fundamental parametric optimization of system parameters such as floater diameter, reaction mass, PTO rating, etc.

- Compare the UMASS baseline against a tethered heaving point absorber.
- All the metrics will be established/compared at a commercial-size farm level.

Work by Aqua Harmonics, a WEC device developer who won the first prize in the DoE wave energy prize competition, suggested that a heaving point absorber tethered against the seabed is a WEC topology with a superior techno-economic profile. This makes this device a suitable benchmark against which we would like to benchmark our WEC topology.

UMASS's analysis has demonstrated that our two-body WEC topology significantly improves power capture over a broad range of sea states when compared to a single-body heaving point absorber, suggesting that this topology may have an advantage over heaving point absorber devices. Moreover, the MMR-based power takeoff shows an advantage in conversion efficiency and reliability. However, the large submerged body and the MMR gearbox might increase costs. So, the techno-economic LCoEs of the MMR-based two-body WECs compared to the popular baselines are unknown.

It should be pointed out that the wave energy prize competition's ACE metric was heavily weighted to structural efficiency while ignoring the added cost required to implement a more complex PTO required to tune a heaving point absorber. We believe that all lifecycle costs need to be considered to establish a suitable trade-off analysis that allows us to benchmark our approach.

4 Test Facility, Equipment, Software, and Technical Expertise

Re Vision Consulting has been involved in the techno-economic assessment and optimization of WEC devices for over 15 years. The PI on this study, Mirko Previsic, has led cost and economic assessment for a wide range of clients including (1) The US Department of Energy, (2) the Electric Power Research Institute, (3) the International Energy Agency, (4) Sandia National Laboratories, (5) National Renewable Energy Lab, and (6) a wide range of technology developers in the marine renewable energy space.

This deep background in the techno-economic analysis and optimization of marine energy systems is unique and will give us confidence in our technology and market development activities moving forward.

5 Test or Analysis Article Description

The proposed system is a self-reactive ocean wave energy point absorber that contains one floating buoy, one submerged reactive body, and an R&D 100 Award-winning power takeoff (PTO). This design can tune the damped system's natural frequency by adequately selecting the mass (physical and added) of the submerged body to match the ocean wave excitation frequency to maximize the power extraction.

The power take-off is a mechanical motion rectifier (MR) enclosed inside a cylinder connected to the second body. A push tube connects the floating buoy with the ball nut. It drives the ball screw into bi-directional rotation using the relative reciprocating linear motion between the buoy and submerged reactive body. The bidirectional rotation is then rectified into the unidirectional rotation and drives the generator. Lab tests and simulations show that MMR-based PTO can significantly improve energy transfer efficiency and increase overall system reliability. The wave tank test also indicates that the proposed WEC can achieve two times higher capture width ratio as the Reference Model 3 (RM3).

6 WORK PLAN

6.1 NUMERICAL MODEL DESCRIPTION

The numerical models established consist of (1) A WEC-Sim model for the two reference topologies that is utilized to compute loads and performance, (2) an Excel model to parametrically model costs and economics, and (3) an Excel-based structural model that can be driven parametrically. A Brief description of these models follows:

WEC-Sim Model

Virginia Tech will perform numerical modeling using a WEC-Sim model previously validated by them using a wave tank testing program. This work will be performed at Virginia Tech and is not funded by Teamer. The model relies on hydrodynamic coefficients obtained from Nemo and is complemented by quadratic viscous drag terms in the time domain. The model allows us to compute the main structural loads (at connection points) and performance on a sea-state by sea-state basis. The wave-tank validation work carried out by Virginia Tech and wave-tank testing carried out by us on similar devices suggest that the BEM methods behind this wave/structure interaction problem are adequate. We have seen higher-order loads on near-shore devices and during breaking wave impacts. Such slam-load events will be exceedingly rare in the water depths envisioned for deployment (50m – 200m). It should also be noted that the experience of working on the Oyster device has shown that even for a near-shore device (where one would expect slam-load impacts to be a vital issue) the structural design is still driven by fatigue loads. Over the life cycle of a device (15+ years), we see a degradation of the yield strength in mild steel on the order of 70% due to cyclic fatigue.

However, we will review wave tank testing data provided by Virginia Tech and verify that higher-order loads are not a problem. These higher-order “slam-type” loads can be an effect of both dynamic device response and breaking wave impacts.

The model allows for changes to be accommodated relatively straightforwardly. This will enable us to scale the device diameter and height of the cylinder and the reaction mass relatively straightforwardly. We envision the parametric scaling incorporating on the order of 6 different geometries, which is best modeled by re-running the existing model (including the geometry pre-processing in Nemo).

Excel-based cost and economic model

The model to be established will be purpose-built but will leverage its structure from the Reference Model Project cost assessment efforts carried out by Re Vision Consulting. The model will contain a sub-model for the major sub-systems in a similar structure as the reference model. All the cost models will include the ability to scale the dimensions.

Detailed (bottoms-up) baseline cost models will be developed to quantify these individual cost centers. Scaling functions will be developed to quantify the scaling effects from the baseline. Performance will be based on (1) the scatter diagram for the reference site, (2) sea-state-specific device performance, and (3) estimated losses. The cost and performance estimates will be uncertain on a sub-system level, and its impact on LCoE will be quantified using Monte Carlo simulations.

Excel-based structural model

To estimate the amount of steel used for the structural components of this device, we will utilize an Excel calculator model tool that leverages beam equations to estimate the size of major structural members. This model was previously established under industry-led projects and provides a simplified modeling environment to enable parametric variations of structural shapes and related loading conditions. The model leverages beam equations and structural design rules utilized in ship design. To internally validate the model, we will develop a few validation points using the BEM model available within Solidworks Pro.

Key Metrics

It is unclear how to define a test matrix or establish metrics, so here is a short description of what we are after. Our core result metric is LCoE at the utility scale, and it is sensitive to the device and farm-level design parameters. The majority of efforts are aimed at reducing uncertainty and establishing credible cost estimates. UMASS has already performed a lot of the key work with respect to device performance and loads, and what is included herein is solely meant to provide inputs to our core task of establishing a techno-economic model. The following provides a high-level table of the major aspects and model interactions.

Table 2 - Modeling Dependencies Breakdown

WEC Sim Model Provides	
	Device Performance for each Sea-State
	Structural Loads for each Sea-State
	Mooring Loads
Structural Model Provides	
	Tons of steel used as a function of complexity for major structural components
	Incorporating Safety Factors based on an assessment of cyclic fatigue, corrosion allowance and mfg allowance
	Alignment with appropriate standards where applicable
Cost Breakdown Structure Determined By	
	PTO Model based on design specific bottom-up estimates
	Structural Cost Model based on Tons of Steel and Steel Mfg Cost Model
	Mooring Model established based on Loads and Displacement
	Grid Interconnection model based on array layout and distance to shore
	Permitting and Environmental based on Reference Model Data and Subsequent PNNL work
	O&M Cost based on Process Breakdown, Vessel Cost and Operational Schedule
	Installation cost based on Operational timing breakdown and vessel cost data
Economics based on	
	Economic assumptions based on utility model
	Uncertainty assigned at the systems level for cost and performance and evaluated using Monte Carlo Simulation
Parametric Functionality	
	Driven at the Sub-systems level
	Incorporating relevant driving considerations
	Based on curve-fitted cost data
Outputs/Graphs generated	
	Parametric Sensitivity studies
	Monte Carlo Outputs

6.2 Test and Analysis Matrix and Schedule

The following tasks outline the tasks/scope agreed to with UMASS. The level of effort estimates are provided assuming full-time work. Most of the efforts will be spread out over a 6-month period and will be carried out by Mirko Previsic. Only efforts by Re Vision are indicated in this task breakdown. UMASS will participate in efforts related to establishing performance and loads, but efforts are not listed as they are not supported by TEAMER funding.

Task 1: Establish performance model

Baseline performance will be established using performance models established and validated by Virginia Tech. These models will be re-run with altered geometric dimensions, which requires a re-run of the BEM code with altered inputs. Note that the BEM model NEMO can be used to define geometries parametrically. Baseline models will be established using simple velocity-dependent damping terms optimized on a sea-state-by-sea-state basis. Optimal damping terms will be established iteratively. Upper limits to device performance will be identified using analytical methods.

Task 2: Establish structural loads using environmental loads – 1 Month

Design-driving structural loads acting on the various structural and PTO components will be identified from task 1 outputs and met-ocean data obtained for the reference site. We believe that the driving design loads for this structure are fatigue-driven, which is very typical for WEC devices. We will perform some initial checks to ensure that is the case and come up with suitable load cases and design factors that account for the cyclical fatigue of the steel structural components.

Task 3: Establish parametrically driven-structural models

Structural models will be established using first-order approaches. These will be used to identify the subsystem weights that can be used for subsequent cost-estimating purposes. These structural models will be largely based on beam-type analysis.

Task 4: Establish parametrically driven cost models for various sub-systems

The outputs of Task 3 will be used to establish a parametrically driven cost model that leverages standard rates for the cost of manufactured materials, adjusts for manufacturing volume, and brings all estimates back to a common reference year.

Task 5: Trade-off analysis and sensitivity studies

The models under task 4 will be used to establish the relevant trade-off and sensitivity studies to produce benchmarking outputs.

Task 6: Final report

The final report with the associated techno-economic model will be publicly available upon project completion.

6.3 Safety

All work performed are desktop-level studies.

6.4 Contingency Plans

We do not have any contingency plans.

6.5 Data Management, Processing, and Analysis

6.5.1 Data Management

Because UMass is a university, we will publish all the data developed under this award. We will generalize the results Where cost estimates are derived from commercially sensitive sources. We will provide cost model outputs in Excel format for subsequent public-domain access.

6.5.1 Data Processing

Data will be processed at Re Vision Consulting, and various processing steps will be included to ensure that cost and performance data can be used in normalized terms. This may include adjustments for inflation and other factors affecting the source data supplied. We will also assign uncertainty ranges to each data point that can subsequently be used in Monte Carlo simulations to quantify uncertainties.

We will compare the data against other cost datasets where possible and applicable. This will allow us to quantify uncertainties further and evaluate their relative impact on LCoE.

6.5.2 Data Analysis

The relative economic trade-off studies will likely include:

1. The physical dimensions of the individual device
2. The plant size (number of WECs installed)
3. Distance to shore
4. Water depth
5. Distance to port
6. Wave resource characterization

These trade-off studies will be processed, and plots generated that can be provided to MHKDR. It will define the trade-off space and the uncertainty embedded in the cost assessment.

7 Project Outcomes

7.1 Results

Two topologies were evaluated and compared: (1) a heaving point absorber working against a reaction mass and (2) a heaving point absorber reacting against the seabed. To enable topology-level optimization, Re Vision developed a suitable techno-economic approach that leverages simple cost-correlation functions that can capture the major cost drivers and numerically efficient time-domain modeling approaches to estimate the performance of different device configurations.

Performance for the WEC topologies studied were obtained from time-domain simulations that utilize hydrodynamic properties obtained from Nemo. Because the tool was used to run a large number of alternative configurations, we made several simplifications to accelerate run speed including:

- Device dynamics were reduced to 1-DoF (heave only)
- For the 2-body device, we modeled the second body without considering the second body's radiation-damping and excitation forces.
- A standard quadratic viscous drag coefficient of 0.3 was applied in the time domain.
- Absorber-buoy motion amplitude limits were imposed by limiting the excitation forces to the buoy displaced volume. This provided an easy-to-implement approach to capture the most dominant non-linearity.
- Validations for the 1-body topology were carried out against wave tank testing data by Re Vision Consulting in 2017. The results showed good agreement with an error in mean absorbed power of < 10%.
- The 2-body topology used the same Nemo-derived SS model used for the 1-body version and as such was validated through the 1-body validation work. A limited number of validation runs were conducted against a higher-fidelity model the University of Michigan developed. The results showed that the models agreed with a maximum error of < 30%. The process also allowed us to fix some remaining modeling problems within their model. Validations against their previously carried out wave tank testing were of limited value as the device topology had evolved since the testing was completed.
- Upper-performance limits for the 1-body device were computed using point-absorber and volumetric limits of the absorber device to provide an upper-limit benchmark for the WEC device and provide an idea of the level of improvements theoretically possible if advanced controls were to be applied to the device. This upper limit benchmark leveraged an approximation of upper limits in irregular seas developed by Re Vision Consulting in a previous controls optimization project.

Parametric performance runs – The absorber geometry was parametrized to provide absorber sizes between 1m and 30m in diameter. The table below shows the main absorber dimensions chosen.

Table 3 - Absorber Buoy Properties Chosen

Diameter	m	2	3	4	5	8	11	14	17	25	30
Radius	m	1	1.5	2	2.5	4	5.5	7	8.5	12.5	15
Draft	m	1	1.5	2	2.5	2.92	3.34	3.76	4.18	5.3	6
Displacement	m^3	3	11	25	49	147	317	579	949	2602	4241

The 2-body topology used the same absorber buoy dimensions. The reaction mass for each buoy configuration was chosen to enable a natural device resonance of 5s- 20s using a discretization of 10 mass values in that range. The reaction mass was assumed to have a simplified tubular shape with a fixed length of 20m and a variable diameter. A drag coefficient of 0.3 was chosen to model the reaction mass viscous losses.

For each device configuration, performance was optimized in the time domain by sweeping a velocity-dependent damping term. Because the 2-body has large motion amplitudes in resonance conditions, absorber buoy maximum motion limits were imposed by limiting PTO forces in the time domain. This ensured the buoy never completely submerged or lifted out of the water and suppressed unrealistic larger power capture values during these conditions.

Time-domain simulation length was standardized to 2000s, with an average run-time of < 1s per run. A sea-state matrix of 56 sea-states was run for each configuration, resulting in > 300,000 time-domain runs required for the optimization process, which was run in about 3 days. It should be pointed out that a non-optimized equivalent medium-fidelity WEC-Sim model has a run-time on the order of about 1 minute per run. As a result, completing the 300k runs using a non-optimized model would have taken about six months to complete – clearly illustrating the value of a numerical model implemented numerically efficiently.

Site-Specific Performance Computation – Average power output was computed by multiplying the seastate reoccurrence matrix with the WEC device performance matrix and imposing a rated capacity limit on the power matrix. The sea-state re-occurrence matrix used was from the Oregon PacWave site. In addition, the following conversion factors were applied:

- PTO power conversion efficiency (mechanical to electrical): 80%
- Plant Availability: 95%
- Transmission Efficiency: 95%

Performance Normalization – The cost of volumetric absorbers with similar shapes can be approximated using a linear scale to absorber volume. This type of volumetric scaling is commonly used for sea-going vessels and was utilized here as well. As a result, the performance per unit displaced volume becomes the critical metric for normalizing results. The following figure shows the normalized performance for the 1-body device using our time-domain simulation and compares them against the upper theoretical limits that could be approached if optimal control is employed.

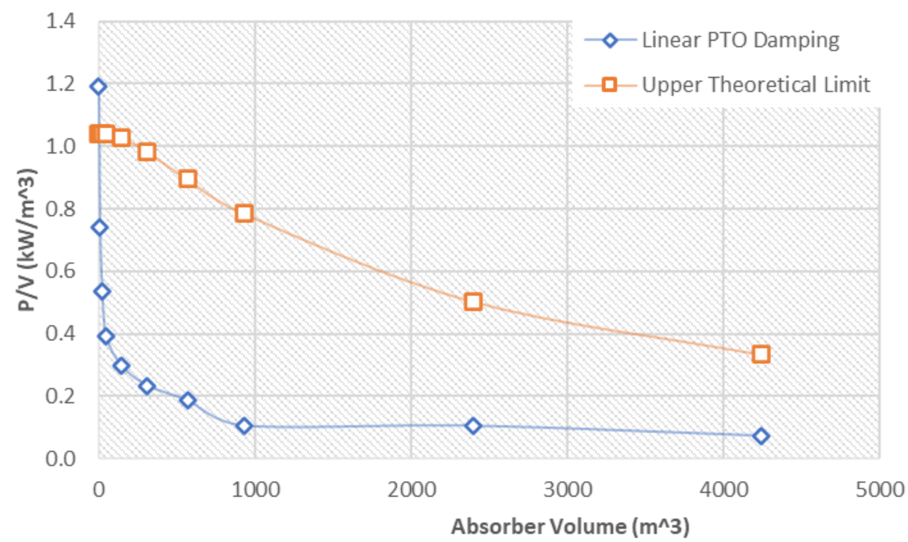

Figure 3 - P/V values for a range of different absorber volumes

It should be noted that this P/V metric is site-dependent and, in the above chart, represents average electrical power at the PacWave site. This metric is very convenient because the structural cost of most seagoing systems is a linear function of their volumetric displacement.

Structural Design of Absorber Buoy

A simplified structural design method was chosen to estimate the steel required for each configuration. To do so, a simplified reinforced beam structural design was established, mirroring the Reference Model 3 design. Material properties for mild steel with a yield strength of 36ksi were chosen. A safety factor of 1.4 was chosen to reflect structural design choices made during the Reference Model project. It should be noted that this safety factor allows the stress to stay within its endurance limit, meaning that cyclic fatigue does not become an issue.

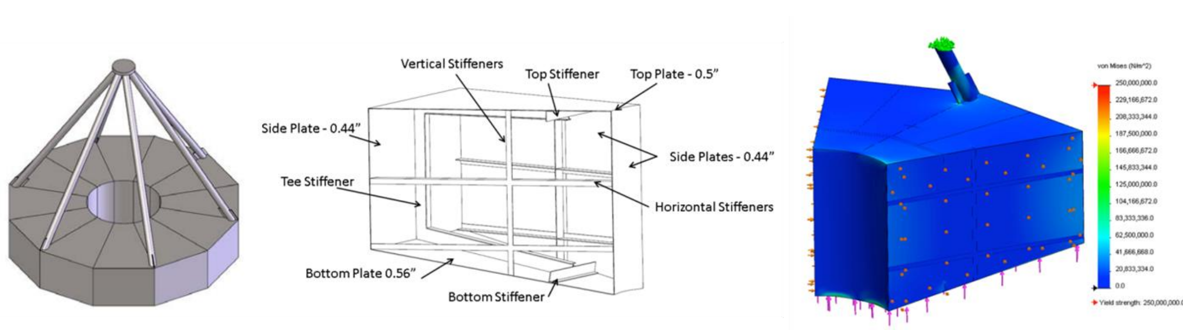

Figure 4 - Structural Design of Absorber buoy

Quasi-static loads were determined by using the stresses incurred when the buoy is completely immersed in the water, creating a hydrostatic pressure exerted across the walls and a transfer of these loads to the stress concentration point where the PTO connects. Sensitivity studies on a reference geometry using FEA showed that the design-driving loads were the pressure forces on the absorber buoy. To account for design details such as railings, ladders, and other un-accounted design details, a multiplier of 1.2 is applied to the overall structural weight.

The structural mass values from this parametric design exercise were compared to similar structures, including (1) the RM3 absorber buoy and (2) a 400ft offshore barge. Despite the large differences in geometric shape, these different systems had mass/volume ratios within 25% of our design, providing us with a useful level of certainty around our structural design efforts.

Structural Design of Reaction Mass

Several different embodiments were initially considered for the reaction mass design. The objective of the reaction mass is to enclose enough seawater to provide the reaction mass required for the system. The baseline design consists of a streamlined submerged body connected over a steel tubular member to the PTO. However, alternative embodiments are viable, and a simple generalized model was required to enable rapid design iteration/optimization. Some examples are shown in the following illustration.

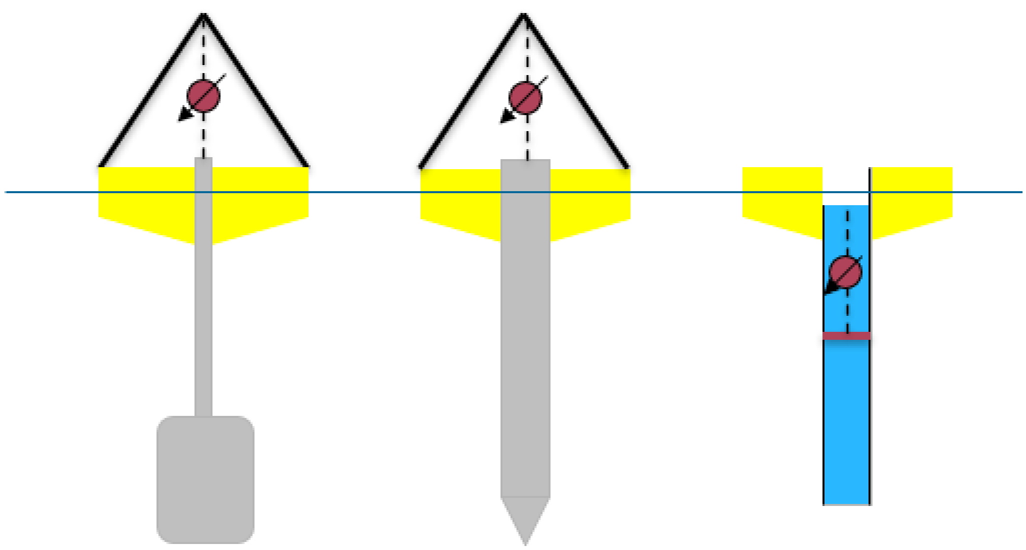

Figure 5 - Different Reaction Mass Embodiments

The structurally simplest (and lowest-cost) embodiment is a simple tubular member that extends from the top to the bottom. This type of tubular can be manufactured using a highly automated rolling/welding process, similar to the way tower elements in wind turbines or bridge piers are manufactured.

Structural loads on this design element consist of tension/compression loads transferred from the PTO and lateral loads imposed by the mooring points. Sensitivity studies around this design concept using FEA showed that the most dominant driver was the minimum steel thickness for the tubular members of 1/4 inches. This minimum steel thickness leads to a factor of safety of > 3 for most design configurations of the reaction mass considered and is driven by the commercial availability of common plate thicknesses and shipyard fabrication techniques.

Cost Estimating Process

The early-stage nature of the university-led design efforts required the development of a cost-estimating methodology that would allow us to compute realistic baseline costs in an effective manner without any detailed design information. It is quite common for early-stage innovators to underestimate the cost because the design details required for an actual design are not understood at this stage, and oftentimes, the required actual design complexity drives cost. Because of this, our approach was to re-use data from related, more mature efforts and consistently scale these results. The following is an example of a process for the PTO sub-system.

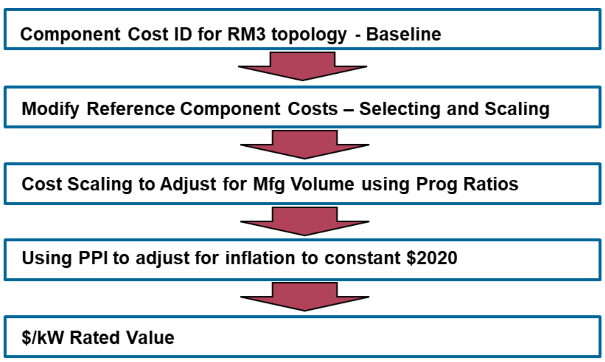

Figure 6 - Cost Estimation Process

Cost Breakdown Structure – CBS

The CBS used for this project was directly adapted from the latest DoE LCoE guidance developed by NREL[1]. A few modifications were made to better reflect the requirements of this project, specifically, this includes:

- Removed the project contingency budget as cost uncertainty is captured as part of the process using a Monte Carlo Simulation. While most developers will show a contingency budget, this is not an actual cost, as this budget is only used to cover overruns and increase the likelihood of a project being built. Characterizing the actual uncertainty using statistical methods is a better approach as it captures the estimated uncertainties in this early-stage design process.
- The Assembly and installation cost category was subdivided into two subcategories: subsea cables and devices. This allowed us to more conveniently separate the technology-specific cost from the infrastructure cost.

[1] https://openei.org/wiki/PRIMRE/Telesto/Economics

Table 4 - Cost Breakdown Structure with Values for a Reference Case

CAPEX

		Cost			Economics			Uncertainty		Multiplier
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total	+%	-%	MC
1.1	**Marine Energy Converter (MEC)**	**$ 29,202,111**	**$ 956,151**	**$ 3,575**	**$ 106**	**53%**	**36%**			
1.1.1	Structural Assembly	$ 12,004,159	$ 393,047	$ 1,470	$ 43	22%	15%	30%	-30%	100%
1.1.2	Power Take-Off System (PTO)	$ 14,015,165	$ 458,892	$ 1,716	$ 51	25%	17%	30%	-30%	100%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 3,182,786	$ 104,212	$ 390	$ 12	6%	4%	30%	-30%	100%
1.2	**Balance of System (BOS)**	**$ 29,237,090**	**$ 957,296**	**$ 3,579**	**$ 76**	**38%**	**36%**			
1.2.1	Project Development	$ 9,739,196	$ 318,886	$ 1,192	$ 35	18%	12%	30%	-30%	100%
1.2.2	Engineering and Management	$ 984,693	$ 32,241	$ 121	$ 4	2%	1%	30%	-30%	100%
1.2.3	Electrical Infrastructure	$ 2,073,468	$ 67,891	$ 254	$ 7	4%	3%	30%	-30%	100%
1.2.6	Assembly & Installation	$ 8,219,867	$ 269,139	$ 1,006	$ 30	15%	10%	30%	-30%	100%
1.2.6.1	*Device*	*$ 3,508,291*	*$ 114,870*	*$ 429*	*$ 13*	*6%*	*4%*	*30%*	*-30%*	*100%*
1.2.6.2	*Subsea Cables*	*$ 4,711,576*	*$ 154,269*	*$ 577*	*$ 17*	*9%*	*6%*	*30%*	*-30%*	*100%*
1.3	**Financial Costs**	**$ 5,021,933**	**$ 164,431**	**$ 615**	**$ 18**	**9%**	**6%**			
1.3.2	Insurance During Construction	$ 1,004,387	$ 32,886	$ 123	$ 4	2%	1%	30%	-30%	100%
1.3.3	Construction Financing Costs	$ 4,017,547	$ 131,545	$ 492	$ 15	7%	5%	30%	-30%	100%
Total CAPEX		**$ 97,720,158**	**$ 3,199,605**	**$ 11,963**	**$ 200**	**100%**	**78%**			

OPEX

		Cost			Economics			Uncertainty		Multiplier
		$/Farm	$/WEC	$/kW	$/MWh	in %		+%	-%	MC
2.1	**Operations**	**$ 1,098,202**	**$ 35,958**	**$ 134**	**$ 57**	**61%**	**19%**			
2.1.1	Environmental Monitoring	$ 121,000	$ 3,962	$ 15	$ 6	7%	2%	30%	30%	100%
2.1.3	Insurance	$ 977,202	$ 31,996	$ 120	$ 50	54%	17%	30%	30%	100%
2.2	**Maintenance**	**$ 710,918**	**$ 23,277**	**$ 87**	**$ 37**	**39%**	**13%**	**30%**	**30%**	100%
Total OPEX		**$ 1,809,120**	**$ 59,235**	**$ 221**	**$ 93**	**100%**	**32%**			
$/MWh					**$ 293**					

Cost estimation – Generic Sub-Categories

Since the focus of this project was on comparing device archetypes, we primarily used RM3 data and appropriate scaling mechanisms to estimate the cost at the required plant and unit scales. We use Producer Price Indices (PPI) to adjust for inflation where appropriate. We used 2020 as the reference year because the subsequent Covid time period created short-term price distortions that are difficult to capture and will not likely reflect longer-term trends.

1.2.1 Project Development – This cost center includes all the project development expenses up to the construction start. RM3 data was utilized and implemented as a function of cost vs. number of units. It includes:

- Design and Engineering
- Pre-installation Studies
- Post-installation studies
- NEPA & Process
- Site Assessment
- Design and Engineering

1.2.2 Engineering and Management – Is taken as 2% of total capital cost (excluding of financial cost). This is consistent with utility scale projects.

1.2.3 Electrical Infrastructure – This includes the subsea cables, terminations and connectors. We used RM3 costs and scaled it to # units and farm capacity. At larger farm scales and larger distances to shore, alternate array configurations may be required, changing the overall arrangement.

1.2.6.2 Assembly & Installation – Subsea Cables – This included all the project tasks associated with the subsea cable installation process. Cable installation costs are largely a function of # units, and as such, scaling was conducted in that way.

1.3 Financial Cost – This includes insurance during construction and construction financing cost. The construction financing rate default was set to 8% and the insurance to 2%. This assumes that the liability insurance during construction is covered by the marine construction operators. It should be noted that in typical utility generator (UG) models, the construction financing is a part of the Fixed Charge Rate (FCR) and it is important to understand this to avoid duplication.

2.1.1 Environmental Monitoring and Regulatory Compliance—RM3 data was used as a baseline, and a curve fitted to the wave farm's kW installed capacity. The cost centers included monitoring marine mammals and turtles, fish, seabirds, benthos, and acoustics.

2.1.3 Insurance – Insurance is taken as a percentage of wave farm CAPEX. The default input is 1%, although this assumes reasonable commercial maturity. As a benchmark, insurance rates for in-ocean prototypes have been at > 5%. Large-scale onshore solar and wind projects have insurance rates that are frequently < 0.5%.

Cost estimation – Device-Specific Sub-Categories

These costs make up the technology-specific attributes of the cost models. Because of the early stage of development, many sub-systems re-used component costs developed under the reference model program. Still, they indexed the cost for inflation and adjusted for manufacturing volumes using progress ratios.

1.1.1 Structural Assembly – This cost center includes all the structural steel components. The amount of structural steel utilized is computed by the device structural model and multiplied by a $/t value. Values for $/t are largely a function of manufacturing complexity. They can range from $2000/t for simple tower-type structures that can be robotically welded to > $10,000/ton for more complex shapes and small-scale production. Under RM3 efforts, we developed a detailed manufacturing cost model and evaluated sensitivities to manufacturing scale and labor costs at different unit scales of production. We curve-fitted the $/ton value vs. manufacturing scale and used a PPI to adjust for inflation and ring cost values to 2020.

1.1.2 Power Take Off System (PTO)—We developed a component cost breakdown for a geared direct-drive PTO and an electro-hydraulic power conversion system. The results showed that the two topologies are very similar, but the main sensitivity is in respect to the manufacturing scale.

It should be noted that the power conversion system of a wave energy device, compared with a wind turbine, is largely in need of a WEC device to incorporate power smoothing and accommodate large peak-to-average power flows. In a hydraulic system, this power flow smoothing is accomplished using hydraulic cylinders. In an electric drive system, the generator needs to have a higher rated capacity to accommodate the peak power flows, and energy smoothing is done in the electrical domain using batteries, flywheels, and/or ultra-capacitors.

1.1.3 Mooring, Foundation, and Sub-Structure

For self-reacting catenary WECs, the mooring system design and cost is directly driven by the horizontal loads applied to the system. The ideal mooring system restrains a WEC device in surge using a soft spring constant, which allows the device to move easily in response to waves but restrains the system from drifting away in currents. As a result, the amount of drag force experienced by the device and the mooring system component cost is a direct function of the WEC cross-sectional area. Depth is accounted for by scaling the rope members to the water depth, maintaining a fixed scope/depth ratio.

We developed a separate model for the bottom-fixed device. A structurally efficient embedment anchor is assumed to be used with a steel cable connecting the absorber buoy to the rotary winch-type PTO. Embedment anchors have a weight-to-holding capacity ratio of 1:20 to over 1:100. For this costing study, we assume an embedment anchor holding capacity ratio of 1:25, which is typical for a larger Suction Embedment Plate Anchor (SEPLA) installed in a sand/clay seabed. Anchor cost is estimated at $5000/t for the embedment anchor. The single-body WEC is directly connected to the seabed over a taught tendon member. This tendon member is costed as a stainless-steel stranded cable.

1.2.6.1 Assembly & Installation - Device

Installation costs are estimated at different device scales, and a curve-fitted model is used to relate costs to a number of devices and device scales. The installation cost model utilized is a process model that utilizes breakdowns for fully loaded vessel day rates and associated schedules to create a good representative cost breakdown for the overall system.

1.2.6.2 Assembly & Installation – Subsea Cables

Installation costs are estimated at different device scales, and a curve-fitted model is used to relate costs to a number of devices and device scales. The installation cost model utilized is a process model that utilizes breakdowns for fully loaded vessel day rates and associated schedules to create a good representative cost breakdown for the overall system.

2.2 Maintenance

Maintenance costs are difficult to estimate at this stage, given that the intervention frequency and type is a direct function of the PTO and WEC device topology. A simple % of CAPEX value was used to characterize that cost. The default value of 1.7% of CAPEX per year was used, but it is reasonable to assume that these costs could be substantially reduced with process automation and increased reliability.

Illustrative Model Outputs

The power of a low-fidelity parametrically driven techno-economic model such as the one developed under this effort comes from its ability to sweep design values and hone in on an optimal design envelope. This optimization process is critical for device developers as it allows for rudimentary optimization and a solid understanding of the sensitivity of design choices on LCoE in an early stage of development.

The Excel model outputs are publicly available and can be utilized by anyone to carry out their studies. We ask for proper acknowledgment of the model/data sources. What follows are some reference studies for the two device topologies studied. The major farm-level assumptions are shown in the table below.

Table 5 - Major Farm-level Parameters

Farm Parameters	
Water Depth	50m
Distance to Shore	2km
Wave Resource	Pac Wave – Oregon
Cost & Economics	
Fixed Charge Rate	7%
Construction Financing Rate	8%
Insurance Cost	1% of CAPEX per year
O&M Cost	1.7% of CAPEX per year
Performance	
Plant Rated Capacity	100MW
Capacity Factor	30%
PTO Efficiency	80%
Transmission Efficiency	98%
Plant Availability	95%

Case 1: 2-Body Topology at 100MW Deployment Scale Using Linear Damping

Device optimization process: To study this topology, 10 different absorber buoy sizes were investigated with diameters of 2m – 30m. For each buoy configuration, 10 reaction mass configurations were utilized to provide natural resonance periods of 4s-20s. This resulted in a total of 100 configurations used in the device-level optimization process. This process allowed us to find optimal device configurations at the envisioned 100MW farm scale.

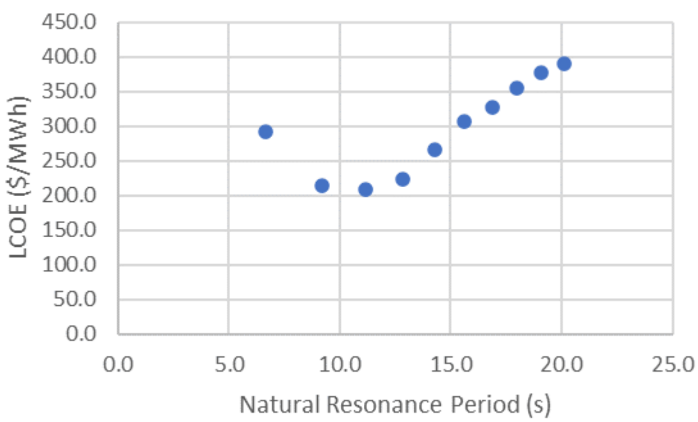

Figure 7 - LCoE vs. Reaction Mass Size for 11m Diameter Buoy

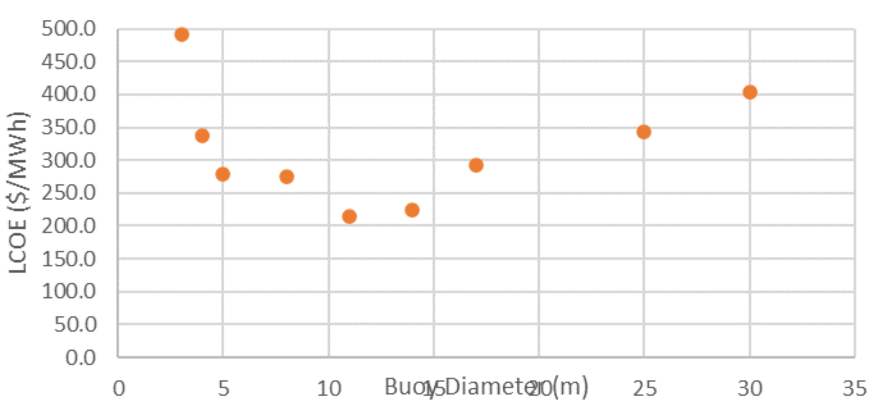

Figure 8 - Buoy Diameter vs. LCoE for Optimized Device Configurations

This optimization study showed that for the two-body topology, a WEC buoy diameter of 11m and a device natural resonance condition of 10-12s provide a device scale that will yield optimal economics for utility-scale applications. This configuration #84 studied has the following properties.

Table 6 - 2-Body Optimal Device Configuration

Device Parameter	**Value**
Device Index #	86
Absorber Buoy Diameter	11m

Absorber Buoy Reaction Mass	1937t of entrained water
Average Power Absorbed	151kW
Capacity Factor	30%
P/V	0.5kW/m^3
Steel Mass	123t
M/P	1.1t/kW

The M/P metric used in the above table represents the amount of structural steel required per kW rated capacity of the machine. As a reference point, land-based wind turbines have a M/P ratio of < 0.2. The P/V ratio determined for this configuration appears high, given that no active control is implemented. Further studies utilizing realistic controls will be needed to validate this figure, as some of the time-domain constraints implemented in the numerical model may lead to unrealistic results.

Table 7 - LCoE Breakdown

CAPEX							
		Cost			Economics		
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total
1.1	**Marine Energy Converter (MEC)**	**$ 334,334,077**	**$ 1,255,187**	**$ 3,343**	**$ 95**	**64%**	**44%**
1.1.1	Structural Assembly	$ 111,700,292	$ 419,355	$ 1,117	$ 32	21%	15%
1.1.2	Power Take-Off System (PTO)	$ 141,191,436	$ 530,074	$ 1,412	$ 40	27%	19%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 81,442,350	$ 305,758	$ 814	$ 23	16%	11%
1.2	**Balance of System (BOS)**	**$ 141,314,118**	**$ 530,534**	**$ 1,413**	**$ 40**	**27%**	**30%**
1.2.1	Project Development	$ 14,857,204	$ 55,778	$ 149	$ 4	3%	2%
1.2.2	Engineering and Management	$ 9,326,435	$ 35,014	$ 93	$ 3	2%	1%
1.2.3	Electrical Infrastructure	$ 31,675,780	$ 118,920	$ 317	$ 9	6%	4%
1.2.6	Assembly & Installation	$ 85,454,699	$ 320,822	$ 855	$ 24	16%	11%
1.2.6.1	*Device*	*$ 66,835,432*	*$ 250,920*	*$ 668*	*$ 19*	*13%*	*9%*
1.2.6.2	*Subsea Cables*	*$ 18,619,268*	*$ 69,902*	*$ 186*	*$ 5*	*4%*	*2%*
1.3	**Financial Costs**	**$ 47,564,820**	**$ 178,572**	**$ 476**	**$ 14**	**9%**	**6%**
1.3.2	Insurance During Construction	$ 9,512,964	$ 35,714	$ 95	$ 3	2%	1%
1.3.3	Construction Financing Costs	$ 38,051,856	$ 142,858	$ 381	$ 11	7%	5%
Total CAPEX		**$ 797,546,653**	**$ 2,994,221**	**$ 5,232**	**$ 149**	**100%**	**81%**

OPEX							
		Cost			Economics		
		$/Farm	$/WEC	$/kW	$/MWh	in %	
2.1	**Operations**	**$ 8,096,467**	**$ 30,396**	**$ 54**	**$ 33**	**50%**	**15%**
2.1.1	Environmental Monitoring	$ 121,000	$ 454	$ 1	$ 0	1%	0%
2.1.3	Insurance	$ 7,975,467	$ 29,942	$ 52	$ 33	49%	15%
2.2	**Maintenance**	**$ 8,126,362**	**$ 30,509**	**$ 81**	**$ 33**	**50%**	**15%**
Total OPEX		**$ 16,222,829**	**$ 60,905**	**$ 135**	**$ 66**	**100%**	**31%**
$/MWh					**$ 216**		

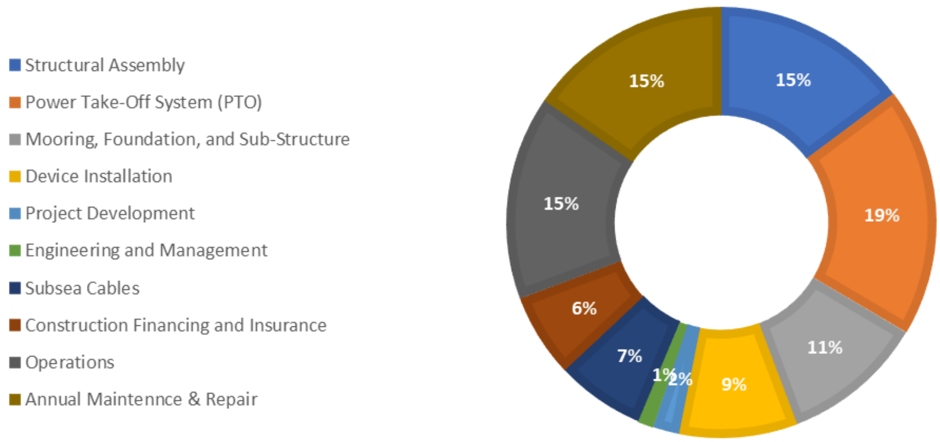

Figure 9 - LCoE Breakdown by Cost-Center

Variable sweeps were carried out to understand the sensitivity of the LCoE to the major design parameters and the impact of different parameters. The following provides sensitivities to the following design attributes:

- Plant Scale
- Machine Capacity Factor
- Fixed Charge Rate
- Structural Cost
- PTO Cost
- Mooring Cost
- Installation Cost
- O&M Cost
- Insurance Cost
- PTO Efficiency
- Plant Efficiency

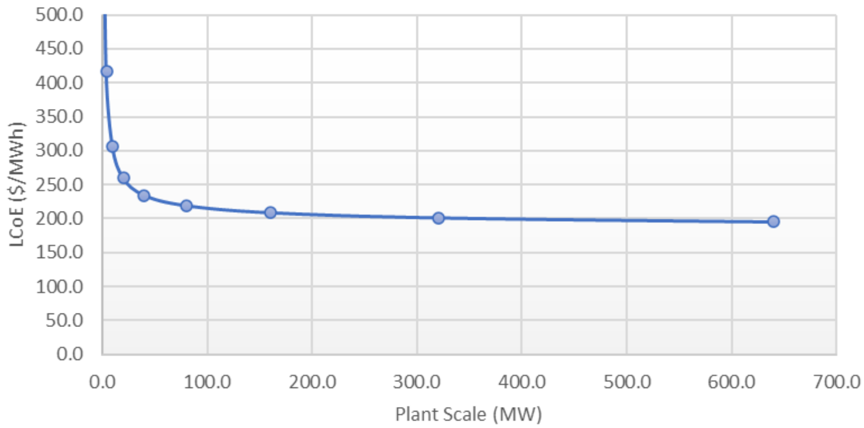

Figure 10 - LCoE vs. Plant Scale

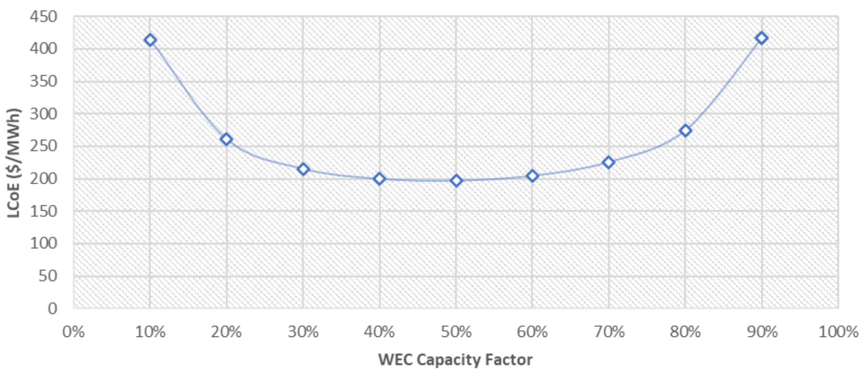

Figure 11 - LCoE vs. Capacity Factor

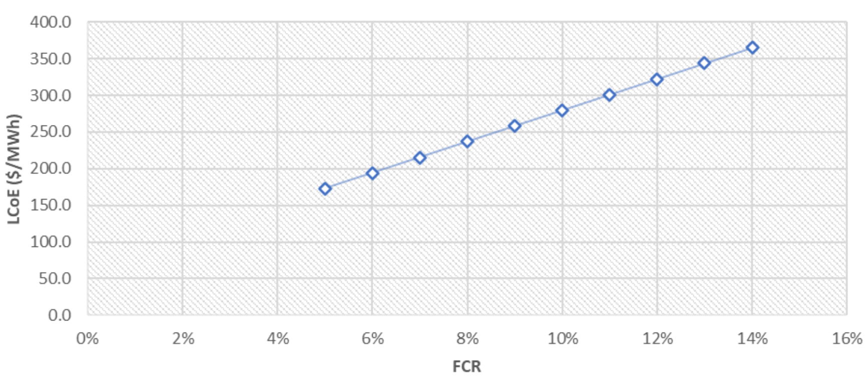

Figure 12 - LCoE vs Fixed Charge Rate

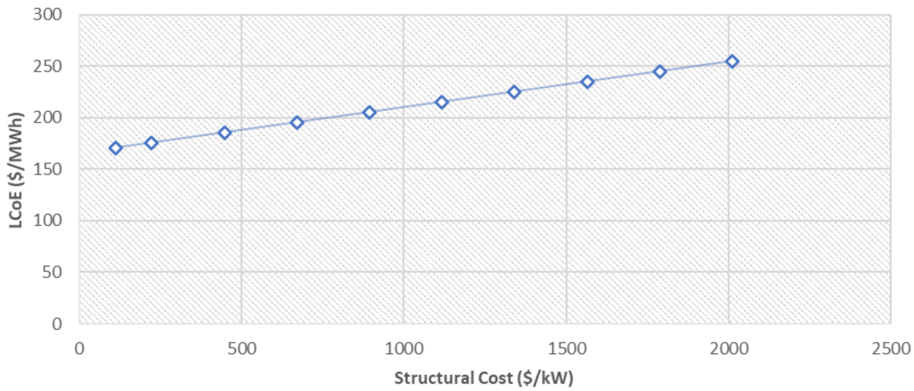

Figure 13 - LCoE vs Structural Cost

Figure 14 - LCoE vs PTO Cost

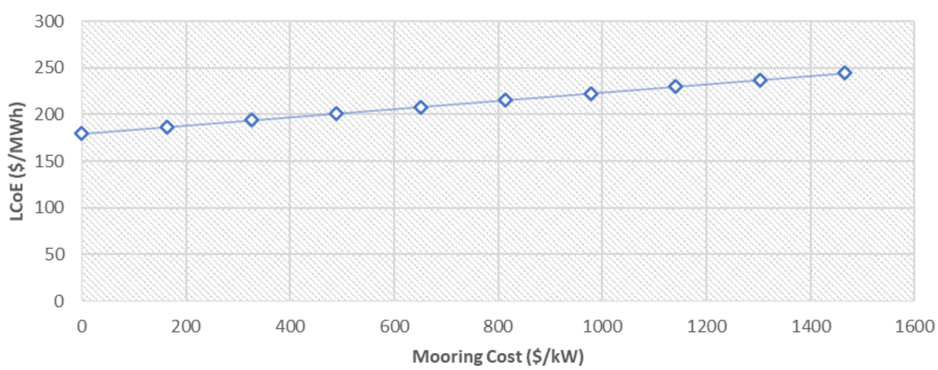

Figure 15 - LCoE vs Mooring Cost

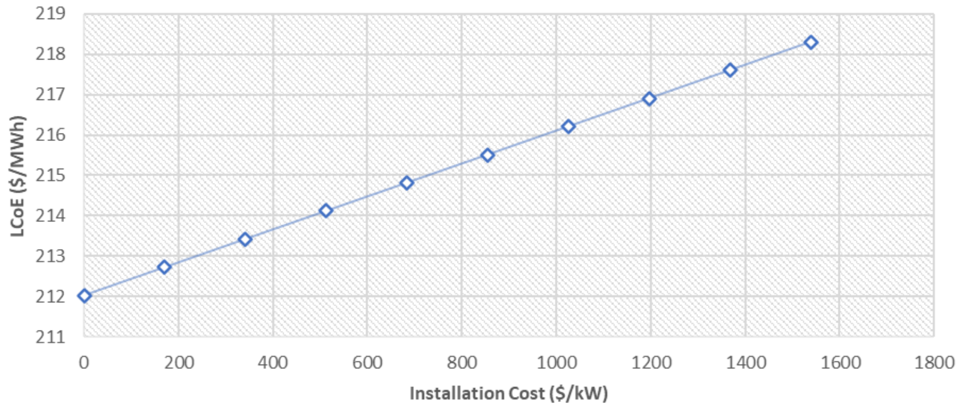

Figure 16 - LCoE vs Mooring Cost

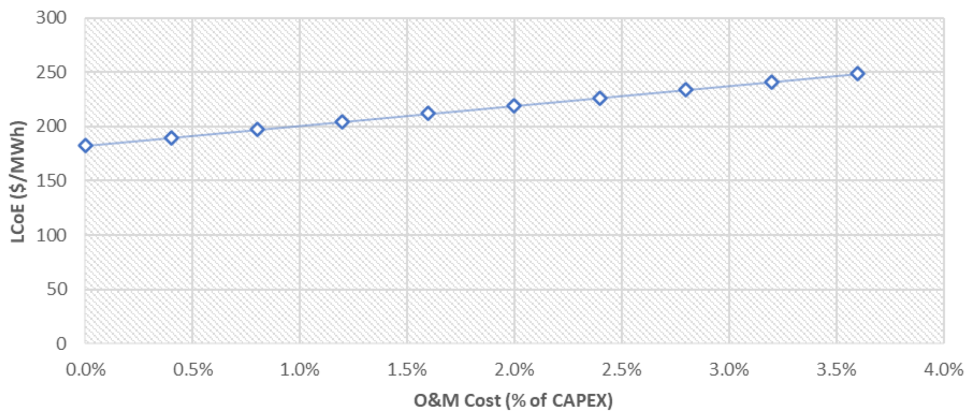

Figure 17 - LCoE vs O&M Cost

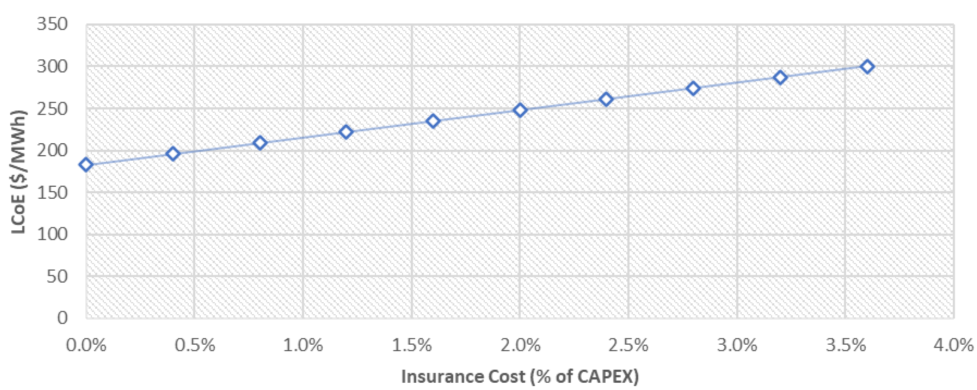

Figure 18 - LCoE vs Insurance Cost

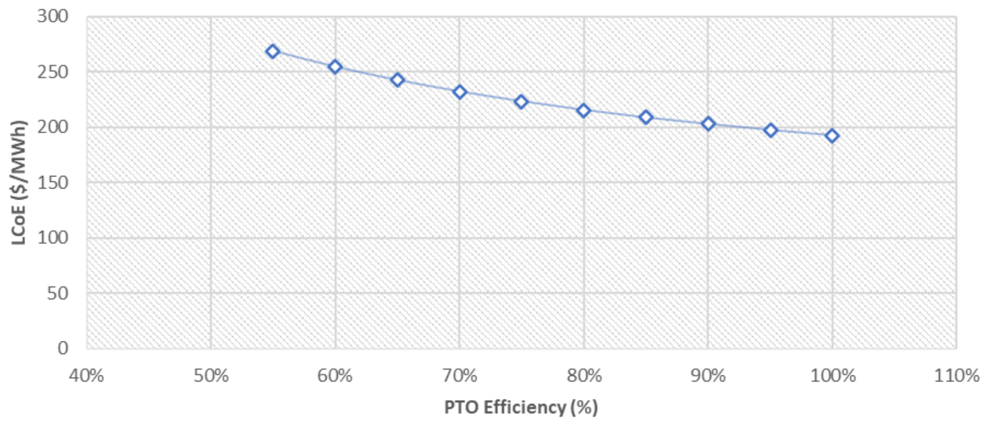

Figure 19 - LCoE vs PTO Efficiency

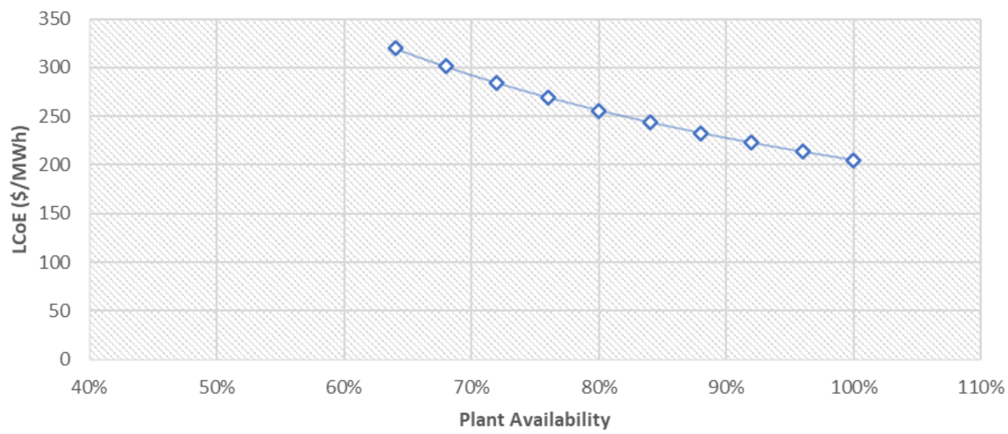

Figure 20 - LCoE vs Plant Availability

Given the limited technical certainty in the design process borne by the early-stage nature of the design concepts explored, it was crucial to evaluate the impact of the design uncertainty on the outcome—the LCoE at farm scale. We set up a Monte Carlo Simulation to evaluate those uncertainties, as shown in the following table.

Table 8 - Cost Estimating Uncertainties Assigned to the Cost Categories

		Cost			Economics			Uncertainty	
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total	+%	-%
1.1	**Marine Energy Converter (MEC)**	**$ 334,334,077**	**$ 1,255,187**	**$ 3,343**	**$ 95**	**64%**	**44%**		
1.1.1	Structural Assembly	$ 111,700,292	$ 419,355	$ 1,117	$ 32	21%	15%	50%	-50%
1.1.2	Power Take-Off System (PTO)	$ 141,191,436	$ 530,074	$ 1,412	$ 40	27%	19%	50%	-50%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 81,442,350	$ 305,758	$ 814	$ 23	16%	11%	50%	-50%
1.2	**Balance of System (BOS)**	**$ 141,314,118**	**$ 530,534**	**$ 1,413**	**$ 40**	**27%**	**30%**		
1.2.1	Project Development	$ 14,857,204	$ 55,778	$ 149	$ 4	3%	2%	100%	-50%
1.2.2	Engineering and Management	$ 9,326,435	$ 35,014	$ 93	$ 3	2%	1%	100%	-50%
1.2.3	Electrical Infrastructure	$ 31,675,780	$ 118,920	$ 317	$ 9	6%	4%	100%	-50%
1.2.6	Assembly & Installation	$ 85,454,699	$ 320,822	$ 855	$ 24	16%	11%	100%	-50%
1.2.6.1	*Device*	*$ 66,835,432*	*$ 250,920*	*$ 668*	*$ 19*	*13%*	*9%*	100%	-50%
1.2.6.2	*Subsea Cables*	*$ 18,619,268*	*$ 69,902*	*$ 186*	*$ 5*	*4%*	*2%*	100%	-50%
1.3	**Financial Costs**	**$ 47,564,820**	**$ 178,572**	**$ 476**	**$ 14**	**9%**	**6%**		
1.3.2	Insurance During Construction	$ 9,512,964	$ 35,714	$ 95	$ 3	2%	1%	50%	-30%
1.3.3	Construction Financing Costs	$ 38,051,856	$ 142,858	$ 381	$ 11	7%	5%	50%	-30%
Total CAPEX		**$ 797,546,653**	**$ 2,994,221**	**$ 5,232**	**$ 149**	**100%**	**81%**		

		Cost			Economics			Uncertainty	
		$/Farm	$/WEC	$/kW	$/MWh	in %		+%	-%
2.1	**Operations**	**$ 8,096,467**	**$ 30,396**	**$ 54**	**$ 33**	**50%**	**15%**		
2.1.1	Environmental Monitoring	$ 121,000	$ 454	$ 1	$ 0	1%	0%	100%	-50%
2.1.3	Insurance	$ 7,975,467	$ 29,942	$ 52	$ 33	49%	15%	100%	-50%
2.2	**Maintenance**	**$ 8,126,362**	**$ 30,509**	**$ 81**	**$ 33**	**50%**	**15%**	100%	-50%
Total OPEX		**$ 16,222,829**	**$ 60,905**	**$ 135**	**$ 66**	**100%**	**31%**		
$/MWh					**$ 216**				

The Monte Carlo simulation was set up using a triangular distribution of random numbers with 500 iterations to provide sufficient resolution. The results are shown below and indicate an overall LCoE uncertainty of +/—40%.

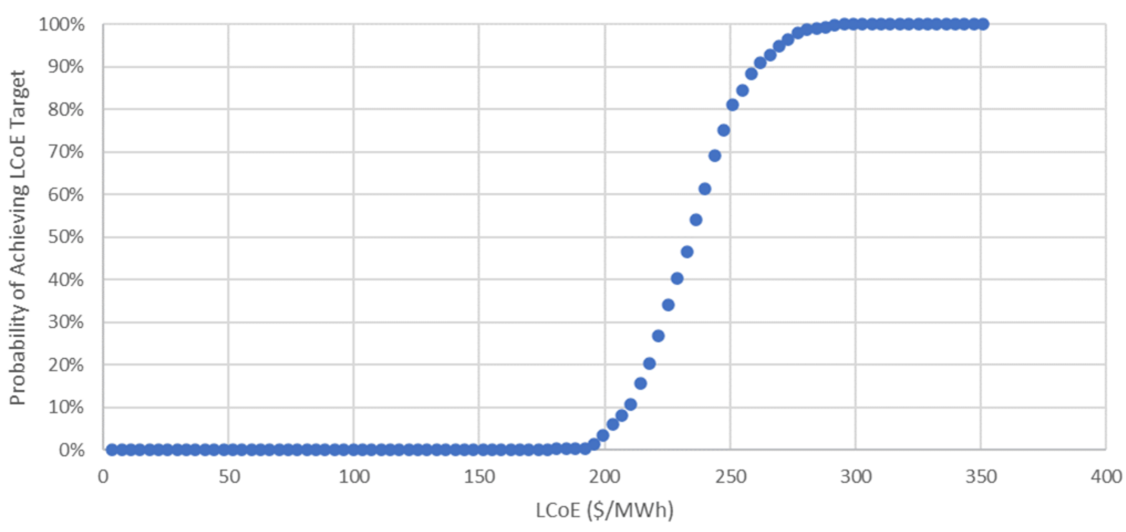

Figure 21 – LcoE Probability Distribution

Case 2: 1-Body Topology at 100MW Deployment Scale Using Linear Damping

Device optimization process: To study this topology, 10 different absorber buoy sizes with diameters of 2m—30m were investigated. This process allowed us to find an optimal WEC size at the envisioned 100MW farm scale. Performance optimization in the time domain was performed using a sea-state by sea-state optimized damping term proportional to velocity.

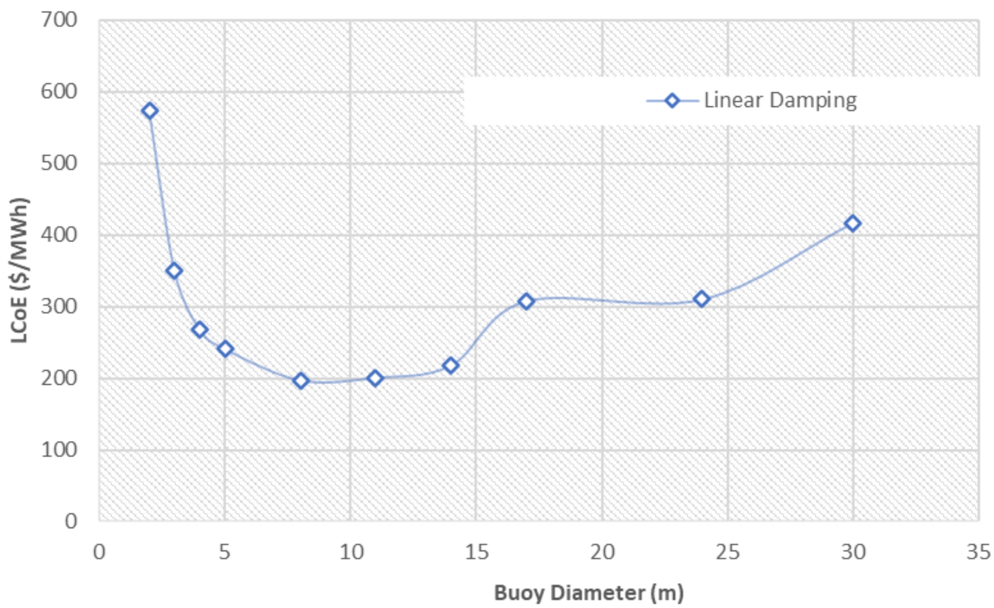

Figure 22 - Buoy Diameter vs. LCoE for 1-Body WEC

This optimization study showed that a WEC buoy diameter of 8m for the one-body topology provides a device scale that will yield optimal economics for utility-scale applications. This configuration #10 studied has the following properties.

Table 9 - 1-Body Optimal Device Configuration

Device Parameter	**Value**
Device Index #	10
Absorber Buoy Diameter	8m
Average Power Absorbed	30.8 kW
Capacity Factor	30%
P/V	0.27 kW/m^3
Steel Mass	27.2t
M/P	0.9 t/kW

The M/P metric used in the above table represents the amount of structural steel required per kW rated capacity of the machine. As a reference point, land-based wind turbines have a M/P ratio of < 0.2.

Testing & Expertise for Marine Energy

Table 10 - Cost and Economics of 100MW Plant

CAPEX										
				$ 3,467.83	$ 99.05					
		Cost			**Economics**			**Uncertainty**		**Multiplier**
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total	+%	-%	MC
1.1	**Marine Energy Converter (MEC)**	**$ 346,782,972**	**$ 355,220**	**$ 3,468**	**$ 99**	**61%**	**42%**			
1.1.1	Structural Assembly	$ 105,777,262	$ 108,351	$ 1,058	$ 30	19%	13%	50%	-50%	100%
1.1.2	Power Take-Off System (PTO)	$ 125,614,691	$ 128,671	$ 1,256	$ 36	22%	15%	50%	-50%	100%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 115,391,019	$ 118,198	$ 1,154	$ 33	20%	14%	50%	-50%	100%
1.2	**Balance of System (BOS)**	**$ 168,383,811**	**$ 172,481**	**$ 1,684**	**$ 48**	**30%**	**34%**			
1.2.1	Project Development	$ 19,139,661	$ 19,605	$ 191	$ 5	3%	2%	100%	-50%	100%
1.2.2	Engineering and Management	$ 10,101,309	$ 10,347	$ 101	$ 3	2%	1%	100%	-50%	100%
1.2.3	Electrical Infrastructure	$ 31,416,767	$ 32,181	$ 314	$ 9	6%	4%	100%	-50%	100%
1.2.6	Assembly & Installation	$ 107,726,074	$ 110,347	$ 1,077	$ 31	19%	13%	100%	-50%	100%
1.2.6.1	*Device*	*$ 48,404,066*	*$ 49,582*	*$ 484*	*$ 14*	*9%*	*6%*	100%	-50%	*100%*
1.2.6.2	*Subsea Cables*	*$ 59,322,008*	*$ 60,765*	*$ 593*	*$ 17*	*10%*	*7%*	100%	-50%	*100%*
1.3	**Financial Costs**	**$ 51,516,678**	**$ 52,770**	**$ 515**	**$ 15**	**9%**	**6%**			
1.3.2	Insurance During Construction	$ 10,303,336	$ 10,554	$ 103	$ 3	2%	1%	50%	-30%	100%
1.3.3	Construction Financing Costs	$ 41,213,343	$ 42,216	$ 412	$ 12	7%	5%	50%	-30%	100%
Total CAPEX		**$ 894,310,026**	**$ 916,068**	**$ 5,667**	**$ 162**	**100%**	**82%**			
OPEX										
		Cost			**Economics**			**Uncertainty**		Multiplier
		$/Farm	$/WEC	$/kW	$/MWh	in %		+%	-%	MC
2.1	**Operations**	**$ 9,064,100**	**$ 9,285**	**$ 58**	**$ 37**	**51%**	**16%**			
2.1.1	Environmental Monitoring	$ 121,000	$ 124	$ 1	$ 0	1%	0%	100%	-50%	100%
2.1.3	Insurance	$ 8,943,100	$ 9,161	$ 57	$ 36	50%	16%	100%	-50%	100%
2.2	**Maintenance**	**$ 8,746,665**	**$ 8,959**	**$ 87**	**$ 36**	**49%**	**15%**	100%	-50%	100%
Total OPEX		**$ 17,810,765**	**$ 18,244**	**$ 145**	**$ 73**	**100%**	**31%**			
$/MWh					**$ 235**					

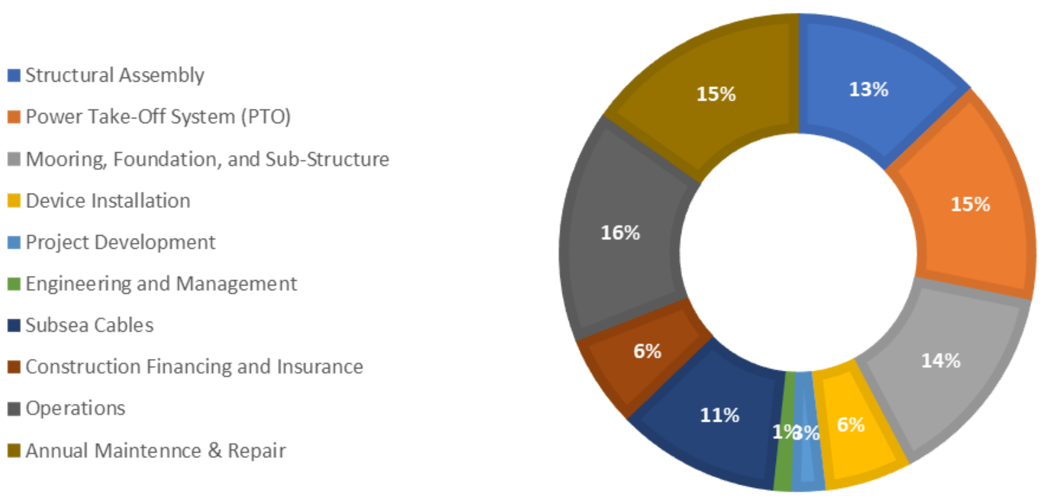

Figure 23 - LCoE Breakdown by Cost-Center

Variable sweeps were carried out to understand the sensitivity of the LCoE to the major design parameters and the impact of different parameters. The following provides sensitivities to the following design attributes:

- Plant Scale
- Machine Capacity Factor
- Fixed Charge Rate
- Structural Cost
- PTO Cost
- Mooring Cost
- Installation Cost
- O&M Cost
- Insurance Cost
- PTO Efficiency
- Plant Efficiency

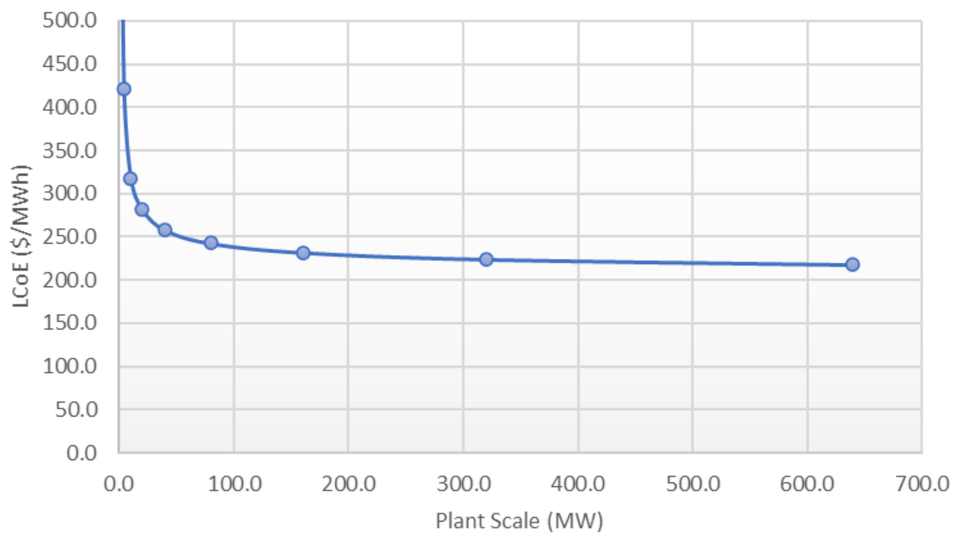

Figure 24 - LCoE vs. Plant Scale

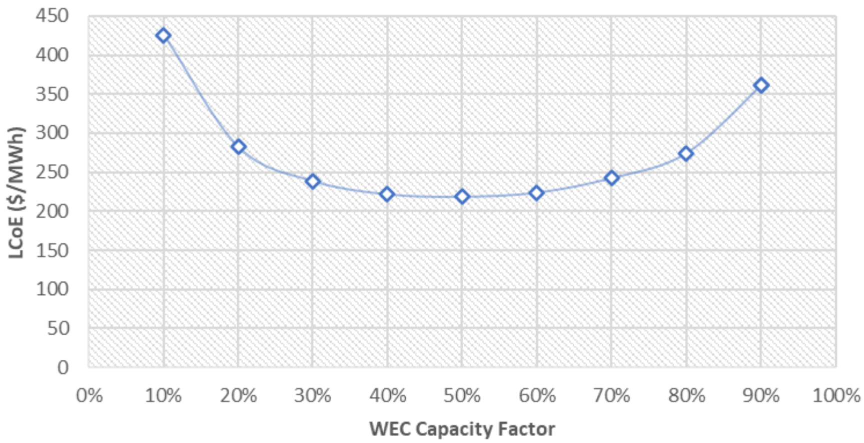

Figure 25 - LCoE vs. Capacity Factor

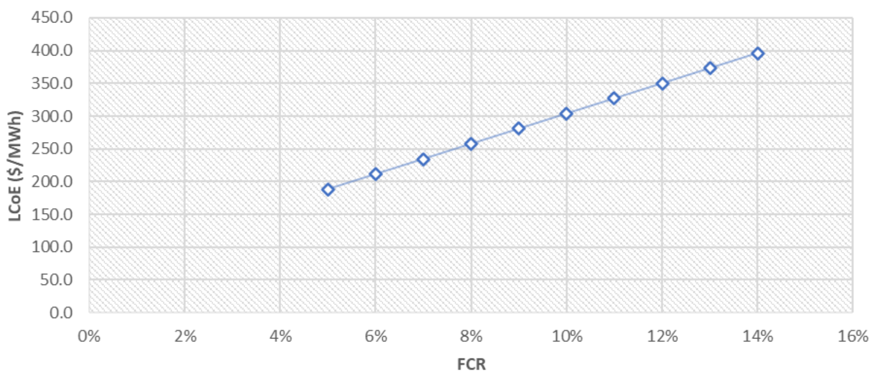

Figure 26 - LCoE vs Fixed Charge Rate

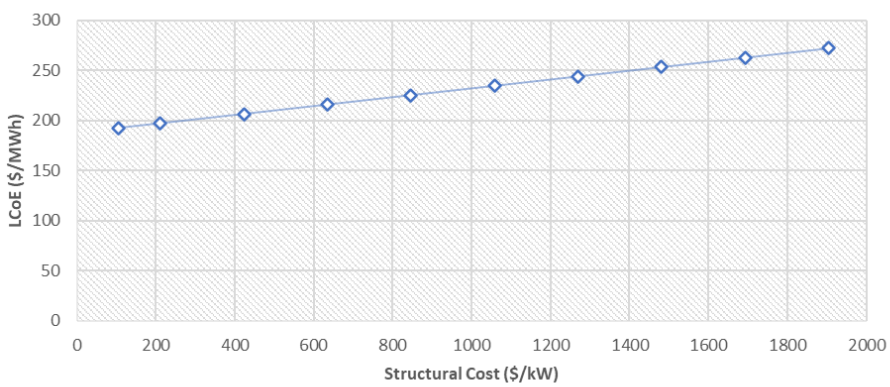

Figure 27 - LCoE vs Structural Cost

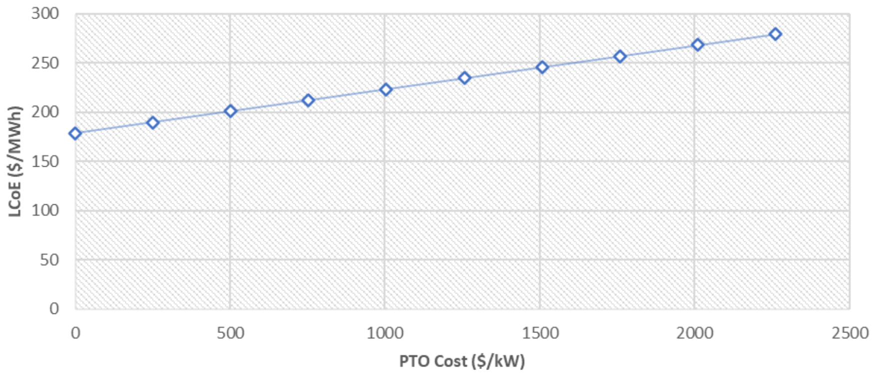

Figure 28 - LCoE vs PTO Cost

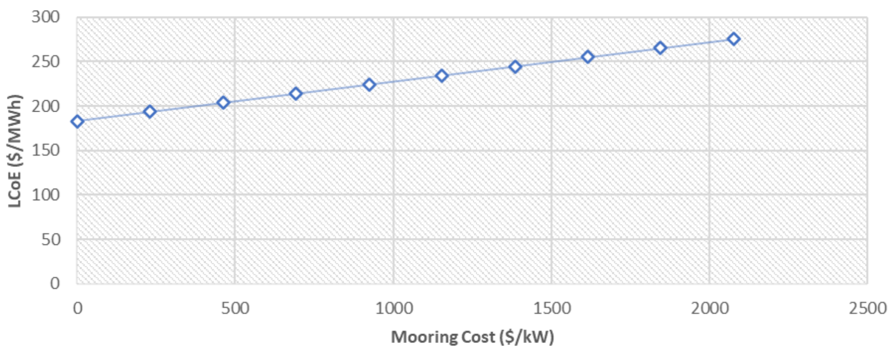

Figure 29 - LCoE vs Mooring Cost

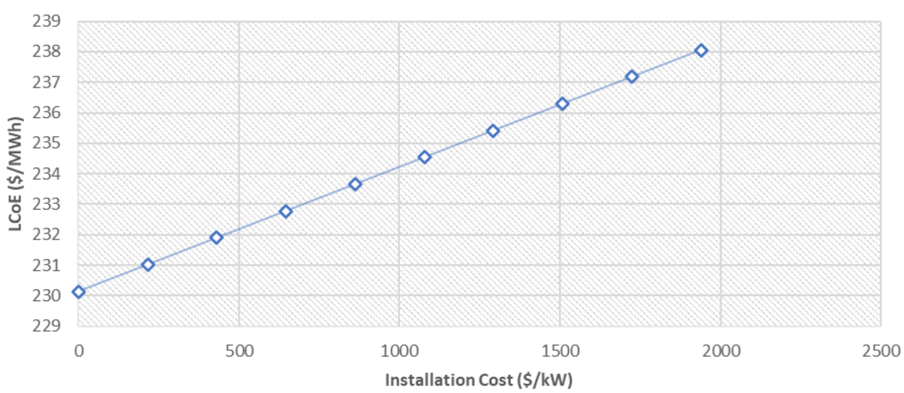

Figure 30 - LCoE vs Installation Cost

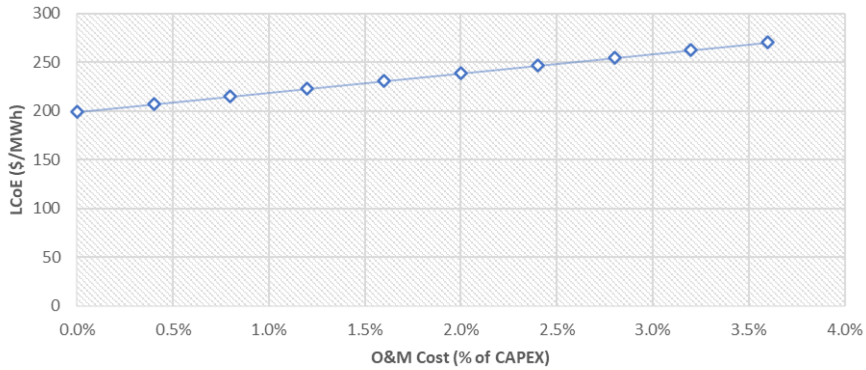

Figure 31 - LCoE vs O&M Cost

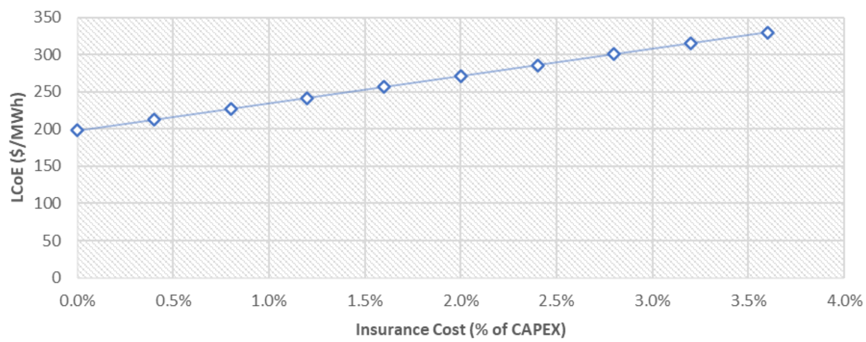

Figure 32 - LCoE vs Insurance Cost

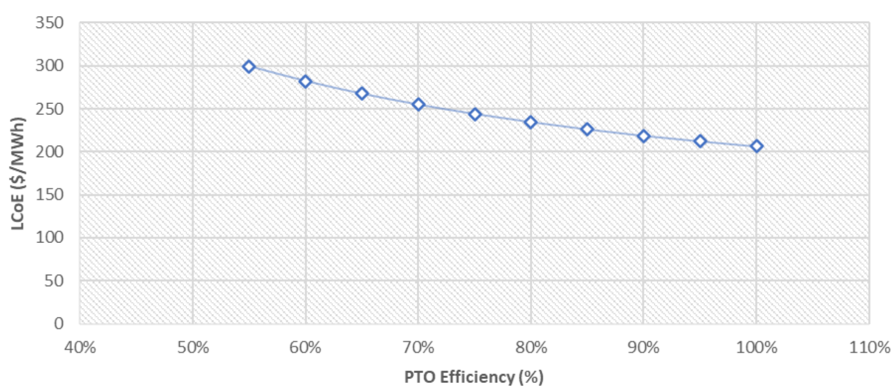

Figure 33 - LCoE vs PTO Efficiency

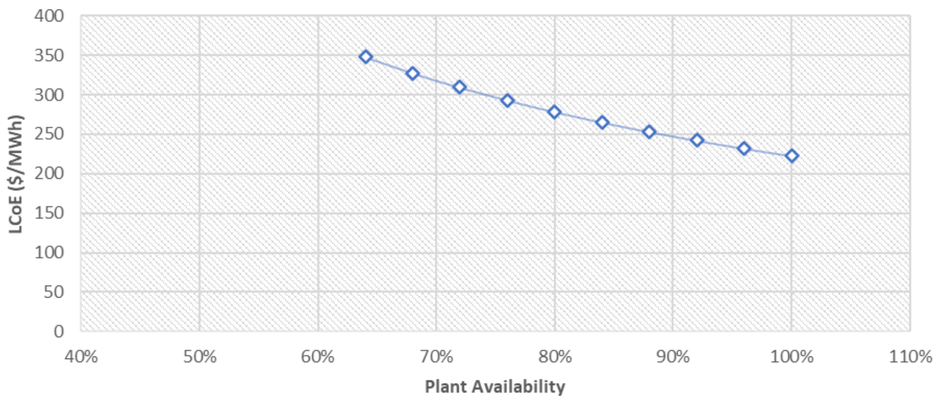

Figure 34 - LCoE vs Plant Availability

Given the limited technical certainty in the design process borne by the early-stage nature of the design concepts explored, it was crucial to evaluate the impact of the design uncertainty on the outcome—the LCoE at farm scale. We set up a Monte Carlo Simulation to evaluate those uncertainties, as shown in the following table.

Table 11 - Cost Estimating Uncertainties Assigned to the Cost Categories

		Cost			Economics			Uncertainty	
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total	+%	-%
1.1	**Marine Energy Converter (MEC)**	**$ 346,782,972**	**$ 355,220**	**$ 3,468**	**$ 99**	**61%**	**42%**		
1.1.1	Structural Assembly	$ 105,777,262	$ 108,351	$ 1,058	$ 30	19%	13%	50%	-50%
1.1.2	Power Take-Off System (PTO)	$ 125,614,691	$ 128,671	$ 1,256	$ 36	22%	15%	50%	-50%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 115,391,019	$ 118,198	$ 1,154	$ 33	20%	14%	50%	-50%
1.2	**Balance of System (BOS)**	**$ 168,383,811**	**$ 172,481**	**$ 1,684**	**$ 48**	**30%**	**34%**		
1.2.1	Project Development	$ 19,139,661	$ 19,605	$ 191	$ 5	3%	2%	100%	-50%
1.2.2	Engineering and Management	$ 10,101,309	$ 10,347	$ 101	$ 3	2%	1%	100%	-50%
1.2.3	Electrical Infrastructure	$ 31,416,767	$ 32,181	$ 314	$ 9	6%	4%	100%	-50%
1.2.6	Assembly & Installation	$ 107,726,074	$ 110,347	$ 1,077	$ 31	19%	13%	100%	-50%
1.2.6.1	*Device*	*$ 48,404,066*	*$ 49,582*	*$ 484*	*$ 14*	*9%*	*6%*	100%	-50%
1.2.6.2	*Subsea Cables*	*$ 59,322,008*	*$ 60,765*	*$ 593*	*$ 17*	*10%*	*7%*	100%	-50%
1.3	**Financial Costs**	**$ 51,516,678**	**$ 52,770**	**$ 515**	**$ 15**	**9%**	**6%**		
1.3.2	Insurance During Construction	$ 10,303,336	$ 10,554	$ 103	$ 3	2%	1%	50%	-30%
1.3.3	Construction Financing Costs	$ 41,213,343	$ 42,216	$ 412	$ 12	7%	5%	50%	-30%
Total CAPEX		**$ 894,310,026**	**$ 916,068**	**$ 5,667**	**$ 162**	**100%**	**82%**		

		Cost			Economics			Uncertainty	
		$/Farm	$/WEC	$/kW	$/MWh	in %		+%	-%
2.1	**Operations**	**$ 9,064,100**	**$ 9,285**	**$ 58**	**$ 37**	**51%**	**16%**		
2.1.1	Environmental Monitoring	$ 121,000	$ 124	$ 1	$ 0	1%	0%	100%	-50%
2.1.3	Insurance	$ 8,943,100	$ 9,161	$ 57	$ 36	50%	16%	100%	-50%
2.2	**Maintenance**	**$ 8,746,665**	**$ 8,959**	**$ 87**	**$ 36**	**49%**	**15%**	100%	-50%

The Monte Carlo simulation was set up using a triangular distribution of random numbers with 500 iterations to provide sufficient resolution. The results are shown below and indicate an overall LCoE uncertainty of +/—40%.

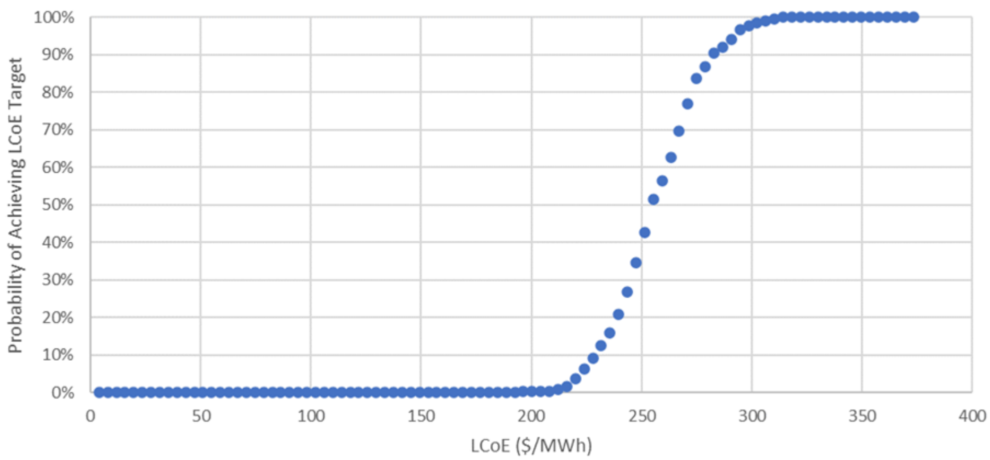

Figure 35 - Monte Carlo Results

Case 3: 1-Body Topology at 100MW Deployment Scale Using Theoretical Power Absorption Limits

Device optimization process: To study this topology, ten different absorber buoy sizes were investigated with diameters of 2m – 30m. This process allowed us to find an optimal WEC size at the envisioned 100MW farm scale. Mechanical power is computed analytically using the device's point absorber and volumetric limits, which approximates a buoy optimally controlled using MPC. These limits were established for sinusoidal waves, and an approximation was developed to apply them to irregular seas. As a result, the theory utilized for computing upper-performance bounds is an approximation and should not be considered a definite answer. This presented study is used as a benchmark of what could be achievable. It neglects the added cost of resonance tuning such a device as negative spring compensation (as used in the CorPower WEC), reactive power flow, and related energy losses.

The core benefit of optimal control can be shown by the P/V ratio at different scales. This term is largely a function of device size, and the following P/V curves were obtained for the Oregon PacWave site. They demonstrate that optimal control can improve the relative utilization of the absorber structure to a much higher degree than a linear damping term optimized on a sea-state to sea-state basis.

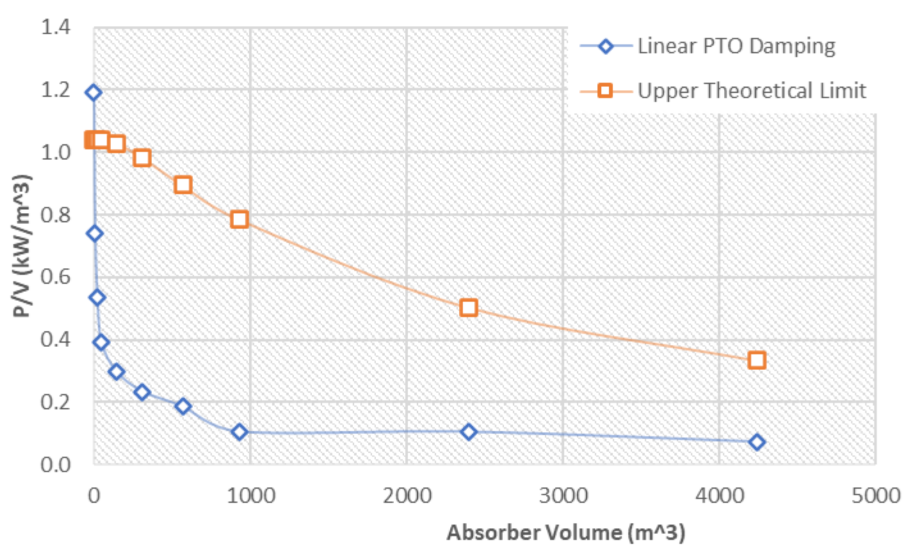

Figure 36 - P/V values for a range of different absorber volumes

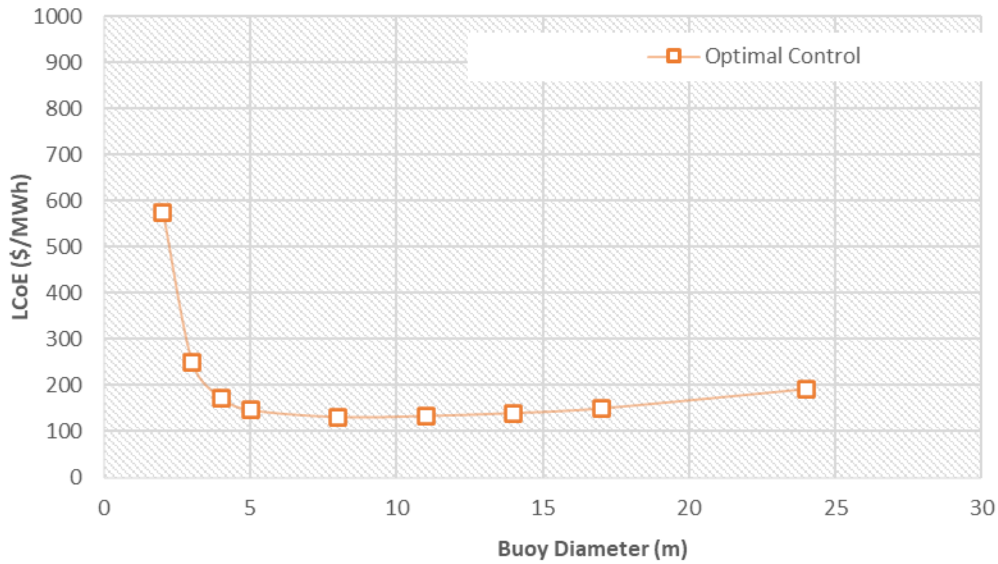

Figure 37 - Buoy Diameter vs. LCoE for 1-Body WEC Using Theoretical Performance Limits.

This optimization study showed that a WEC buoy diameter of 8m for the one-body topology provides a device scale that will yield optimal economics for utility-scale applications. This configuration #10 studied has the following properties.

Table 12 - 1-Body Optimal Device Configuration

Device Parameter	Value
Device Index #	10
Absorber Buoy Diameter	8m
Average Power Absorbed	126 kW
Capacity Factor	30%
P/V	0.9 kW/m^3
Steel Mass	27.2t
M/P	0.22 t/kW

The M/P metric used in the above table represents the amount of structural steel required per kW rated capacity of the machine. As a point of reference, land-based wind turbines have an M/P ratio of about 0.1t/kW. We would point out that CorPower's commercial projections suggest an LCoE target of about 70 Euro/MWh at a cumulative installed capacity of about 600MW.

Table 13 - Cost and Economics of 100MW Plant

CAPEX									
		Cost			Economics			Uncertainty	
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total	+%	-%
1.1	**Marine Energy Converter (MEC)**	**$ 198,561,621**	**$ 830,454**	**$ 1,985**	**$ 57**	**63%**	**43%**		
1.1.1	Structural Assembly	$ 25,906,677	$ 108,351	$ 259	$ 7	8%	6%	50%	-50%
1.1.2	Power Take-Off System (PTO)	$ 142,591,417	$ 596,367	$ 1,426	$ 41	45%	31%	50%	-50%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 30,063,527	$ 125,736	$ 301	$ 9	10%	7%	50%	-50%
1.2	**Balance of System (BOS)**	**$ 125,600,414**	**$ 525,305**	**$ 1,256**	**$ 25**	**28%**	**27%**		
1.2.1	Project Development	$ 14,547,656	$ 60,843	$ 145	$ 4	5%	3%	100%	-50%
1.2.2	Engineering and Management	$ 5,633,588	$ 23,562	$ 56	$ 2	2%	1%	100%	-50%
1.2.3	Electrical Infrastructure	$ 31,721,118	$ 132,669	$ 317	$ 9	10%	7%	100%	-50%
1.2.6	Assembly & Installation	$ 36,849,026	$ 154,116	$ 368	$ 11	12%	8%	100%	-50%
1.2.6.1	*Device*	*$ 19,792,849*	*$ 82,781*	*$ 198*	*$ 6*	*6%*	*4%*	100%	-50%
1.2.6.2	*Subsea Cables*	*$ 17,056,176*	*$ 71,335*	*$ 171*	*$ 5*	*5%*	*4%*	100%	-50%
1.3	**Financial Costs**	**$ 28,731,301**	**$ 120,164**	**$ 287**	**$ 8**	**9%**	**6%**		
1.3.2	Insurance During Construction	$ 5,746,260	$ 24,033	$ 57	$ 2	2%	1%	50%	-30%
1.3.3	Construction Financing Costs	$ 22,985,041	$ 96,131	$ 230	$ 7	7%	5%	50%	-30%
Total CAPEX		**$ 507,225,051**	**$ 2,121,393**	**$ 5,071**	**$ 90**	**100%**	**77%**		
OPEX									
		Cost			Economics			Uncertainty	
		$/Farm	$/WEC	$/kW	$/MWh	in %		+%	-%
2.1	**Operations**	**$ 5,193,251**	**$ 21,720**	**$ 52**	**$ 21**	**52%**	**16%**		
2.1.1	Environmental Monitoring	$ 121,000	$ 506	$ 1	$ 0	1%	0%	100%	-50%
2.1.3	Insurance	$ 5,072,251	$ 21,214	$ 51	$ 21	51%	16%	100%	-50%
2.2	**Maintenance**	**$ 4,808,372**	**$ 20,110**	**$ 48**	**$ 20**	**48%**	**15%**	100%	-50%
Total OPEX		**$ 10,001,622**	**$ 41,830**	**$ 100**	**$ 41**	**100%**	**31%**		
$/MWh					**$ 131**				
Technology LCoE		**$ 256,966,394**	**$ 1,074,724**	**$ 2,569**	**$ 111**	**177%**	**85%**		

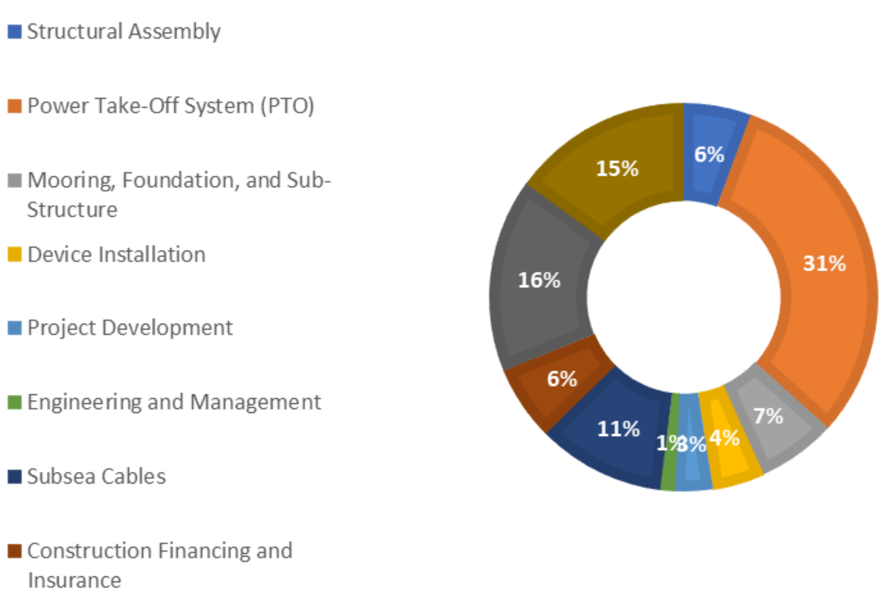

Figure 38 - LCoE Breakdown by Cost-Center

Case 4: Single Unit Blue Economy Deployment Scale Using Linear Damping

For Blue-Economy Application spaces, we envision a single WEC unit deployed to power a scientific or instrumentation payload onboard the device or on the seafloor. The installation and O&M costs drive total cost or LCoE at these scales. As a result, the larger the device and power output, the lower the LCoE. To understand this scale dependence, the plot below shows the relationship between LCoE and power output.

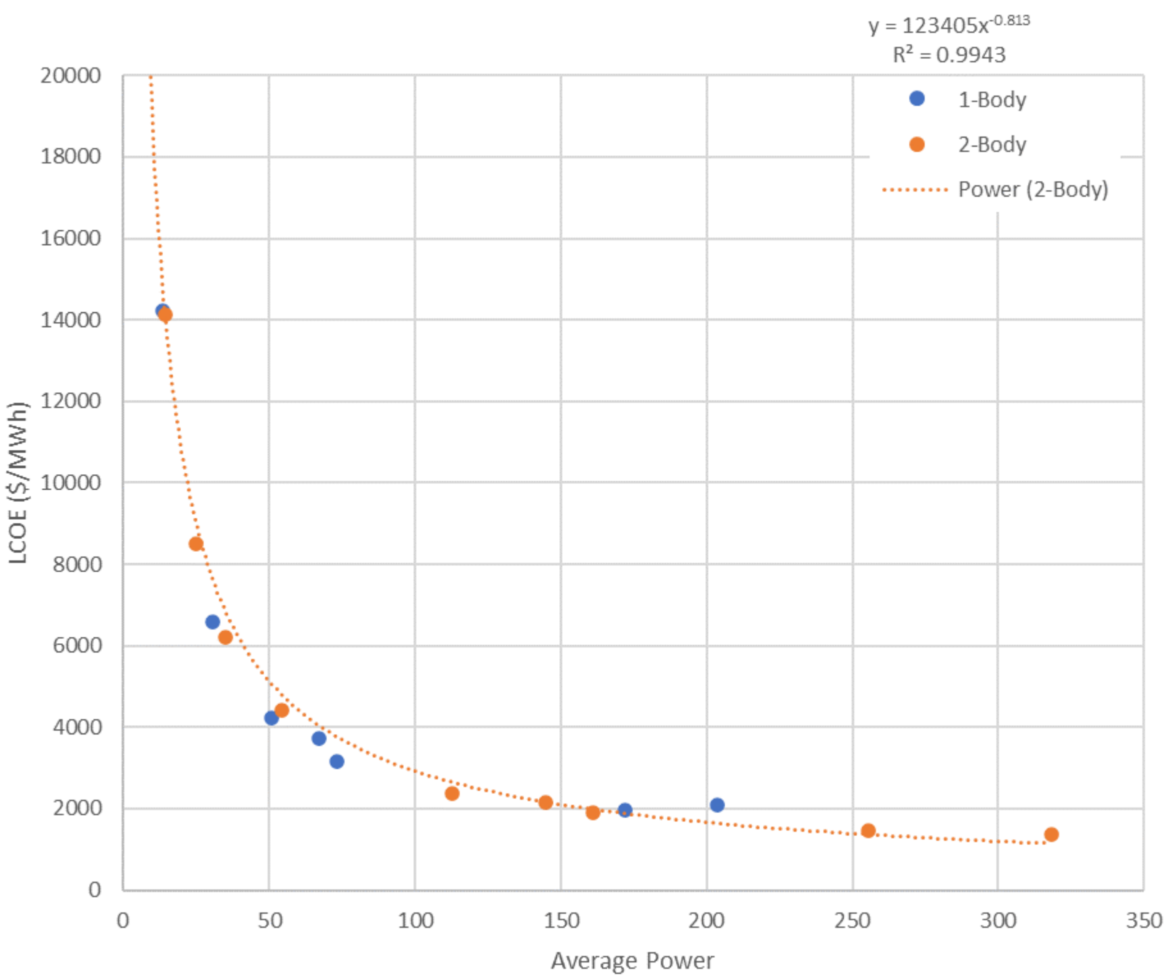

Figure 39 - Single Unit LCoE for Blue Economy Applications

Device optimization process: The same optimization process was used for the grid-connected plant, with the difference that project development costs and subsea cabling costs were set to zero. The current model likely under-estimates O&M costs as it used a utility-scale assumption.

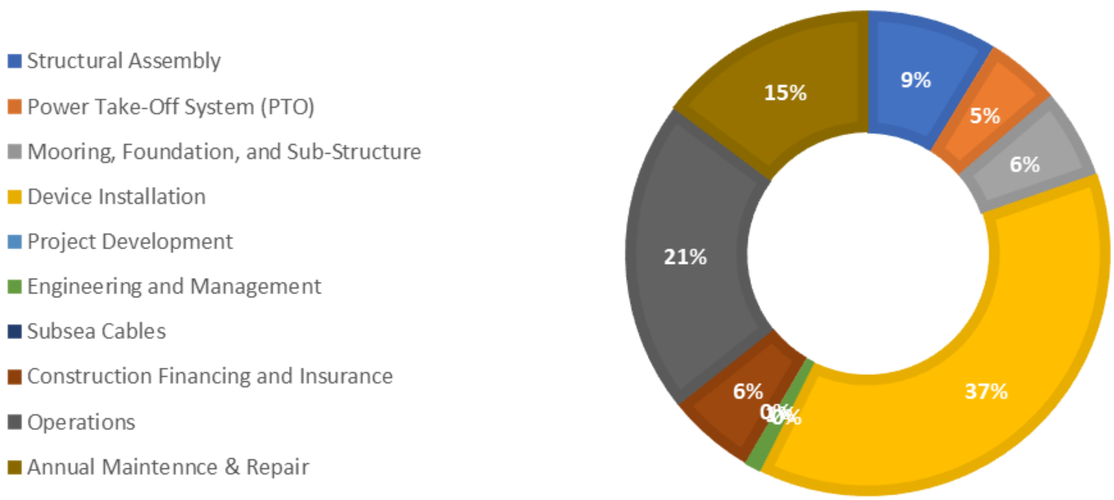

Figure 40 - LCoE Breakdown at 10kW average power scale

7.2 Lesson Learned and Test Plan Deviation

Because of the very early-stage nature of the proposed WEC design, our approach had to evolve. As a result, the work plan had to be adapted to the development of a foundational understanding of the technology and its application spaces. Specifically, we developed several design alternatives early in the design process to address shortcomings of the current design. We focused on validating existing numerical models developed by the UMASS team. We also created a set of numerical models in-house to enable the parametric studies required for this project. The following were the key adaptations to the process:

1. We developed concept-level design alternatives for the PTO system to address foundational issues with the PTO concept pursued.
2. We assessed alternate methods to suppress large resonance responses in large waves at resonance by changing reaction mass properties to de-tune the system, including utilizing a variable reaction mass and viscous damping flaps. In addition to de-tuning the system, the variable reaction mass concept can also be used to tune the WEC to different resonance periods adaptively.
3. We performed a resource assessment at a deep-water offshore site (near PacWave) to investigate the utilization of the device in short-period wave-induced waves. This resulted in a compact design for emerging blue-economy application spaces.
4. We spent considerable time working with UMASS to validate their numerical model. In the process, we developed in-house numerical models that leverage state-of-the-art state-space approximations

in a Simulink time-domain model. These simplified models were used to investigate design alternatives rapidly.
5. Because we spent more time than expected on the concept-level design issues, we developed a simplified cost and economic assessment approach to capture key trends and study design trade-offs. The model is focused on the design variables being investigated, including device embodiment, PTO, moorings, and device performance. It is built around a set of simplified cost-correlation functions.

Despite the deviations, the overall objectives were fully met in this effort. To some extent, we believe that these types of adjustments are unavoidable. This is still an R&D effort and there is a need to continually adjust project execution to achieve objectives.

8 Conclusions and Recommendations

The University of Massachusetts (UMass) has developed a 2-body WEC device that is converting mechanical power into electricity using a mechanical motion rectifier that allows the system to couple to a flywheel. UMASS has completed numerical modeling, wave tank testing, and PTO sub-system testing and needed assistance in developing a techno-economic model to enable optimization of their topology, comparison to a generic heaving point absorber topology, and guide the next steps in their development efforts. The core objective was to develop a techno-economic approach and modeling tool to benchmark the two topologies across a wide range of scales to evaluate their respective competitiveness in different application spaces.

Work Carried Out: Re Vision started with a detailed review of the R&D carried out to date to enable detailed implementation planning efforts. In the process it addressed some fundamental feasibility issues as it relates to the device and PTO topology. Subsequently, Re Vision engaged in a structured assessment process including:

- Developed numerically efficient time-domain models for the two WEC topologies to enable performing trade-off studies.
- Validated numerical models against wave tank testing data and a medium fidelity model previously developed at UMass.
- Evaluated the performance of a set of different device configurations that captured the parametric space of interest. In total over 100 different configurations were evaluated requiring over 300,000 time-domain runs.
- Developed an Excel-based structural model to evaluate different buoy configurations and validated the structural model using FEA and empirical design data.
- Developed a set of cost-scaling functions that allowed the model to scale in the relevant dimensions.
- Implemented the techno-economic model in Excel and automated various trade-off functions using Visual Basic macros. The effect of design uncertainties on LCoE was evaluated using Monte Carlo simulations.

Key Challenges: The key challenge of this project was to develop this model without being able to rely on any detailed engineering data and having to rely on public-domain cost data. A secondary challenge was that the topologies needed to be scaled over two orders of magnitude, which required a sufficiently flexible approach to accomplish the objective.

A combination of first-principles physics-based model scaling combined with data available from Reference Model efforts was used to adapt this assessment process. The resulting methodology and example could be expanded to a wide range of different WEC device topologies and improve our ability to assess WEC technologies at a low TRL. Wind-related efforts inspired the methodology in the 70’s and 80’s that heavily relied on these types of first principles based scalable techno-economic models. The difference between these efforts and today’s efforts in the marine energy sector is that the design diversity is much broader today than it was back then, creating additional complexities.

Key Results: For this report, we evaluated the techno-economic methodology of the two topologies at utility and blue economy scales. At the utility scale, the WEC device dimensions were optimized for a 100MW deployment at the PacWave site in Oregon using device trade-off studies. Once optimized, the impact of key parameters on LCoE was studied using a set of sensitivity studies. The following table provides a summary of key results from the study. All costs are expressed in constant 2020 dollars. We purposefully picked a pre-pandemic reference cost year as subsequent supply-chain issues distorted cost elements, making an apples to apples comparisons difficult.

Table 14 - Key Results Summary

Dimensions/Performance	**2-Body Design**	**1-Body Design**
Device Diameter	11m	8m
Device Height	6.7m	5.5m
Absorber Volume	317m^3	147m^3
Reaction Mass	2905t	0t
Average Power Absorbed	151kW	30.8kW
Structural Steel Weight	130t	27t
Power/Volume Ratio	0.6 kW/m^3	0.3kW/m^3
Weight/Power Ratio	0.9 t/kW	0.9 t/kW
Capacity Factor	30%	30%
Cost & Economics		
CAPEX	$5,232 / kW	$5,667 / kW
OPEX	$135/kW-year	$145/kW-year
LCoE	$216/MWh	$239/MWh

The structural efficiency of the WEC device clearly drives economics at the utility scale. Useful first-order metrics of structural efficiency for volumetric displacement device is the ratio of structural steel required to kW of rated capacity. For heaving point absorbers, a related metric is the Power/Volume metric, which is important because volumetric displacement device structural cost scale linearly with cost. The following shows a comparison of the P/V ratio for the range of buoy sizes studied herein. It shows that optimal control could be a game-changer for these devices.

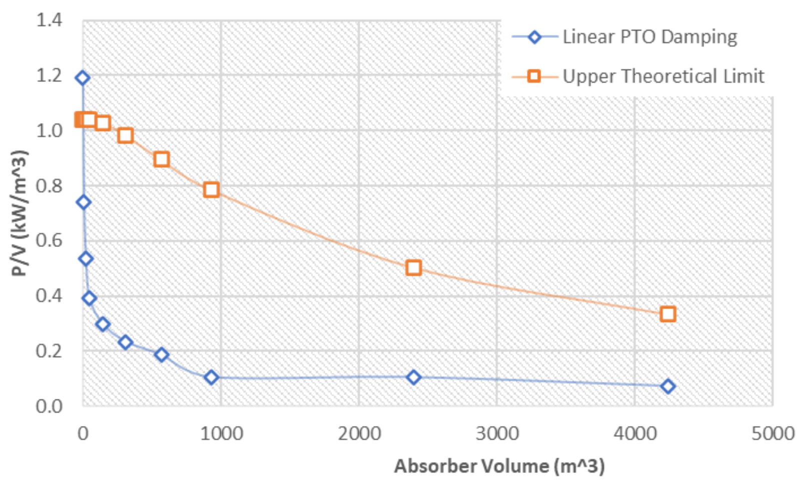

Figure 41 - P/V values for a range of different absorber volumes

The key to unlocking such theoretical P/V values lies in picking the right topology and applying optimal control that can impose constraints optimally. An example of such a system is the CorPower device, which uses a negative spring stiffness concept to reduce the effective spring stiffness of its WEC device. This allows it to tune its device to different sea states and broaden its resonance modes.

The second set of scenarios was evaluated for blue-economy applications, which were assumed to consist of a single WEC device providing power to an at-sea payload located on the seabed. Marine operational costs, including installation and O&M activities, drive the LCoE at this scale. We excluded permitting and environmental monitoring costs from this assessment as it remains unclear what requirements would be placed on such devices. We believe that eventually, such devices (especially if small) should be classified as vessels with a class-type approval similar to a small boat – making this cost contribution insignificant from an LCoE point of view. The following chart shows the relative LCoE for the two topologies studied.

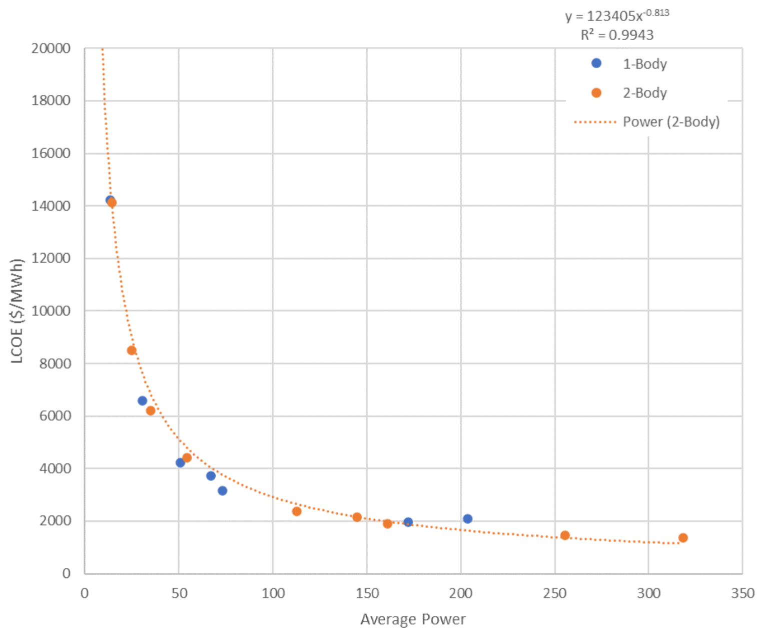

Figure 42 - LCoE vs Average Power for Blue Economy Applications

It shows that LCoE is mostly scale-dependent and that the topology has little effect on economic competitiveness. This is because at small scales, the LCoE is dominated by marine operational costs during the installation and O&M processes. This points to a need for Blue Economy WEC systems to be fully autonomous, eliminating the need for vessel intervention to provide competitive energy.

Our efforts identified several uncertainties:

- As designed, the proposed WEC has two major shortcomings that will require changes to the overall concept: (1) The fixed mass of the second body yields excessive motion amplitude in resonant conditions. This motion is difficult to suppress with the PTO system alone and will result in significant cost increases over the baseline estimates in this report. Moving to a variable reaction mass will enable better tuning to different wave periods and enable de-tuning in larger waves. (2) The current PTO envisions a fixed gearing ratio between the absorber buoy and the generator. Because optimal damping of the PTO varies by about an order of magnitude between different sea-states, this will result the generator operating in low-efficiency regimes for much of the time. Introducing a variable-speed transmission in the drivetrain would effectively address this issue.
- The performance of the 2-body topology will need to be studied further, specifically as it applies to imposing motion amplitude limits in an effective manner. Because heave motion limitations impose constraints on the relative motion between the two bodies and the absolute motion of the absorber buoy (against the water surface), this will require the development of an effective time-domain controls approach. The modeling efforts under this study impose constraints in an incomplete manner, which may have led to an overestimation of the performance of the 2-body topology.
- A point design of the system should be established at an appropriate and relevant scale that consistently addresses all the major structural and system integration issues. Such a design package

could be completed at a conceptual level, would improve cost prediction accuracy, and would improve design confidence.

A number of interesting R&D pathways were identified that could advance the Technology Performance Level of the current concept in a meaningful manner, including:

- Using a variable reaction mass combined with optimal control (MPC) could significantly improve the two-body performance and economic viability. A similar device was developed about 20 years ago by SeaVolt Technologies. Compared to that WEC topology, the current design would benefit from available MPC-based controls, which is critical to optimally solving the control system challenges of this WEC topology given the system's complex constraints.
- The current flywheel-based PTO topology relies on a flywheel operating at low rotational velocities – directly coupled to the rotational PTO. This creates a fundamental issue of having limited control over how the flywheel is engaged, resulting in marginal benefits and potentially challenging PTO dynamics. Furthermore, the low speed of the flywheel results in a required flywheel mass that is excessive to store any meaningful amount of energy. A simpler approach would be to move the electrical storage into the electrical domain and add it directly to the controller's DC bus.
- Alternative materials, including inflatable structures, could be leveraged to substantially improve device economics at the utility-scale and potentially make the system more portable and easier to transport at Blue Economy scales. An example is the NetBuoy concept, which was developed under a program funded by Wave Energy Scottland.
- At small Blue Economy scales, it makes sense to tune the device resonance to wind waves that have periods of 1-3s. These waves are consistently present in most deep-water offshore locations and are typically not reported in wave resource assessments. The shorter wave-periods would result in a much smaller reaction mass to tune the device and also naturally detune the system in larger waves, solving a key challenge related to de-tuning in these larger waves. We performed a rudimentary assessment for a location offshore of Oregon and found that capacity factors on the order of 50% should be attainable. This approach would enable a down-scale of the device and develop a seagoing prototype on a reduced budget.
- At Blue Economy application scales, the dominant cost drivers are related to marine operational costs. The only meaningful way to address the fundamental cost issues at this scale is to turn the 2-body WEC into a fully autonomous system that allows the system to transit to the deployment site and station-keep without a permanent anchor. This has been a focus of the Ocean Observing Prize competition and could be adopted to produce a prototype. Given the deep draft of the device, this would mean that it would have to be floated horizontally for transit to/from the deployment site to minimize drag during transit.

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