Post Access Report

Techno-Economic Assessment of AWS Waveswing

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TEAMER

Testing & Expertise for Marine Energy

Table of Contents

Executive Summary 3

1 INTRODUCTION TO THE PROJECT 7

2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS 7

2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED 7

2.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED 7

3 PROJECT OBJECTIVES 8

4 TEST FACILITY, EQUIPMENT, SOFTWARE, AND TECHNICAL EXPERTISE 8

5 TEST OR ANALYSIS ARTICLE DESCRIPTION 8

6 Work Plan 9

6.1 NUMERICAL MODEL DESCRIPTION 9

6.2 TEST AND ANALYSIS MATRIX AND SCHEDULE 11

6.3 SAFETY 13

6.4 CONTINGENCY PLANS 13

6.5 DATA MANAGEMENT, PROCESSING, AND ANALYSIS 13

6.5.1 Data Management 13

6.5.2 Data Processing 13

6.5.3 Data Analysis 13

7 Project Outcomes 16

7.1 RESULTS 16

7.1.1 Performance Modeling 16

7.1.2 Structural Design 19

7.1.3 Cost Modeling 21

7.1.4 LCoE Baseline Assessment of Waveswing 39

7.1.5 Waveswing Cost Reduction Pathways 50

7.1.6 LCoE Assessment of the Reference Point Absorber (RPA) 53

7.1.7 Cost Reduction Pathways of the Reference Point Absorber 64

7.2 Lesson Learned and Test Plan Deviation 66

8 Conclusion 67

9 Acknowledgements 70

EXECUTIVE SUMMARY

Background: The Wave Swing (www.awsocean.com), developed by AWS Ocean Energy, is a submerged pressure differential WEC device that has completed sea trials at EMEC in Scotland. The Waveswing is a highly efficient WEC topology that has won third place (out of 92 design teams) in the wave energy prize competition organized by the US Department of Energy and has since undergone significant further development culminating in the recent at-sea testing at EMEC.

The installation and testing at EMEC have shown that single-unit point absorbers are inherently expensive to build, deploy, and operate. They have also highlighted key operational issues that limit access to the device during extended periods during winter months. These critical issues are being addressed through the next evolution of AWS technology towards its multi-absorber platform.

The current work was motivated by the need to review and benchmark the technology's commercialization pathway and provide an understanding of key cost-reduction drivers.

Objectives: The primary objectives of the current scope of work are to benchmark the LCoE of the Waveswing device, identify cost-reduction pathways through design sensitivity studies, and compare the results against an actively tuned point absorber that employs a hydrostatic spring-compensation mechanism. This reference WEC benchmark is herein referred to as the Reference Point Absorber (RPA).

Work Carried Out: Re Vision started with a detailed review of the AWS R&D program to enable detailed implementation planning efforts. Subsequently, Re Vision engaged in a structured assessment process including the following:

- LCoE model to benchmark the current AWS configuration and the RPA at a 100MW plant scale
- A parametric performance model to model WEC performance for the Waveswing and the RPA
- Development of scalable performance and cost models
- Sensitivity studies to enable first-order design optimization
- Identify core LCoE cost-reduction pathways to enable the targeting of sensible technology development pathways

Key Challenges: Waveswing is a well-developed WEC topology, and the access to the data sets provided by AWS enabled the development of suitable cost functions. The key challenge in this work was to develop sensible models to enable plant-level cost-reduction pathways. We solved this issue by developing a parametrically driven techno-economic optimization model.

Key Deliverables: The key deliverables are documented in this report and associated data spreadsheet.

- Description of Methodology
- Baseline and sensitivity studies for Waveswing
- Baseline and sensitivity studies for RPA
- Cost-reduction pathways for both topologies

Key Results: The baseline was established to understand what the LCoE from a 100MW plant would be if it were constructed today. The Waveswing shows an LCoE at the 100MW scale of $306/MWh, while the reference point absorber has a slightly lower opening cost of $276/MWh. The following shows the Capex cost breakdown by cost center (left) and the contribution of these cost centers to the LCoE for the Waveswing device.

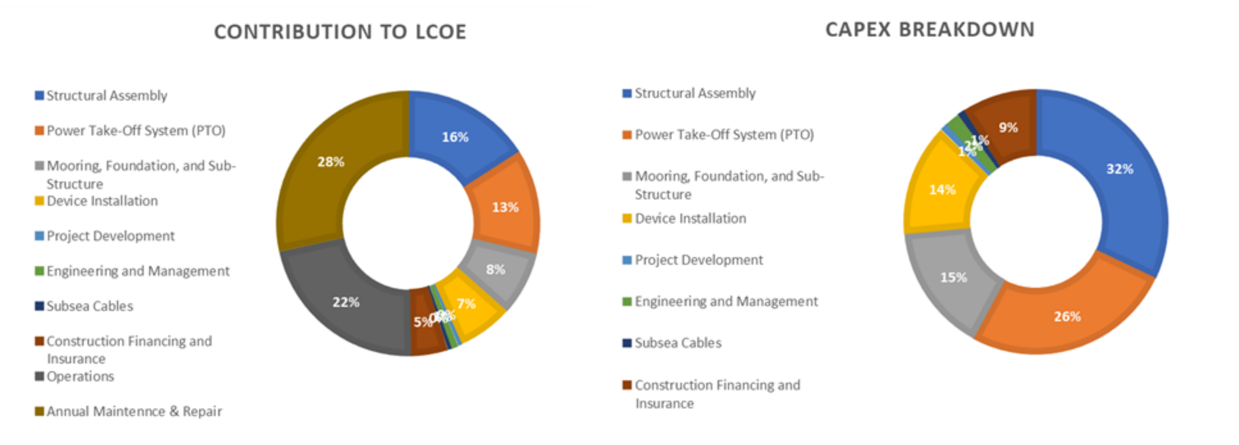


Figure 1 - 100MW Capex and LCoE by Cost Center for Waveswing

The Reference device shows a lower baseline LCoE due to a lower structural mass per unit of power. It also shows that the PTO significantly contributes to total cost. This is due to a more complex PTO that enables hydrostatic spring stiffness compensation.

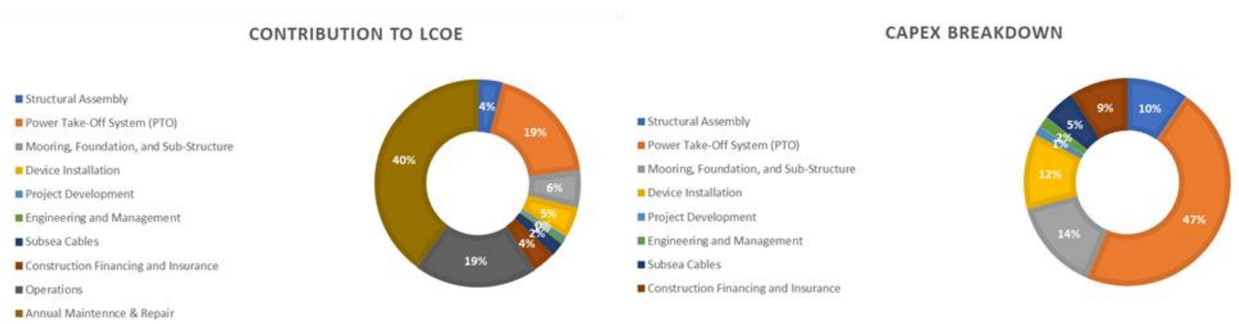


Figure 2 - 100MW Capex and LCoE by Cost Center for Reference Point Absorber

Key cost-reduction pathways were identified that could significantly improve WEC device economics, making it potentially competitive with current offshore wind. For the AWS device, this includes the following:

- **Multi-Absorber Platform:** Deploying multiple Waveswing devices onto a common platform provides key advantages, improving accessibility for O&M and substantially reducing this cost center. The annual O&M cost reduces from a baseline of 4.6% of Capex to 1.8% of Capex.
- **Reduced Subsea Volume:** The Waveswing baseline design evaluated is structurally less efficient than the RPA. This is because the device requires a passive volume to provide a low-inherent

spring stiffness to the subsea floater. Several approaches could reduce this volume by a factor of >2x over the baseline.

- **Low-Cost Manufacturing:** Robotically driven manufacturing processes could reduce structural cost by 2x over the baseline, which assumes manufacturing in a shipyard. A similar level of cost reduction could be attained by manufacturing in a country with low labor costs, such as China.
- **Optimal Control:** Currently, Waveswing has an onboard feedback control system. This yields power absorption values of about 65% of the upper theoretical limits. Using MPC-based optimal control, combined with a deterministic sea wave prediction (DSWP) system, this could be improved to > 85% of the theoretical upper limit.
- **Improved Reliability:** The baseline model assumed an annual O&M intervention cycle. This is consistent with what is being done in offshore wind. However, the experience with the Meygen tidal project showed that this intervention interval could be reduced to once every 4-5 years if the powertrain is designed for ultra-high reliability. Our cost-reduction assumption is that intervention cycles can be reduced to once every 4 years.
- **Reduced Insurance Rates:** The baseline assumption is that insurance rates will be 2% of Capex per annum. Mature commercial renewable energy projects (solar and wind) have insurance rates of < 0.5% of Capex. As the wave energy sector matures, we expect similar rates as well.

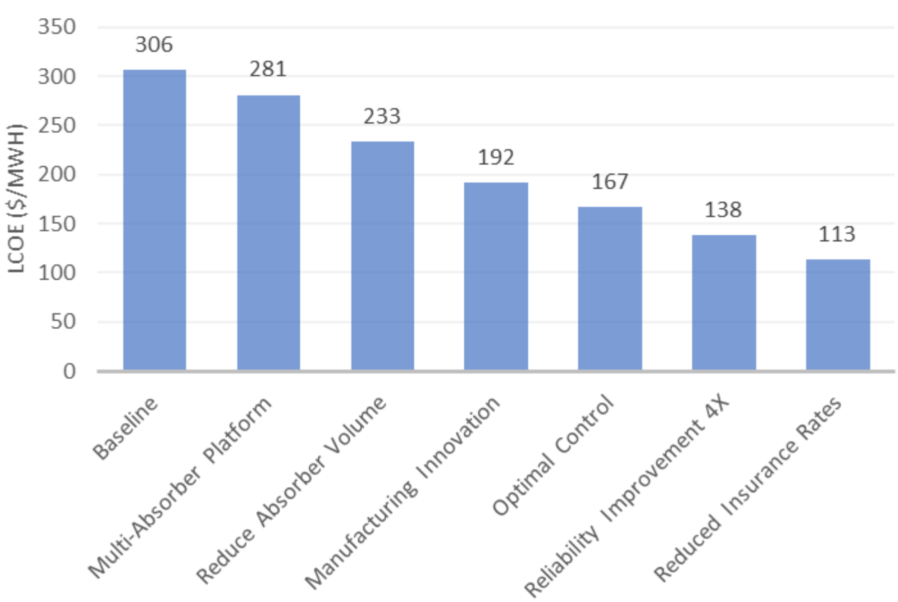


Figure 3 - LCoE Cost Reduction Pathway for Waveswing WEC

In comparison, the RPA has fewer technology-related levers to reduce LCoE, this reduces LCoE at commercial scale to about $127/MWh as shown in the following plot.

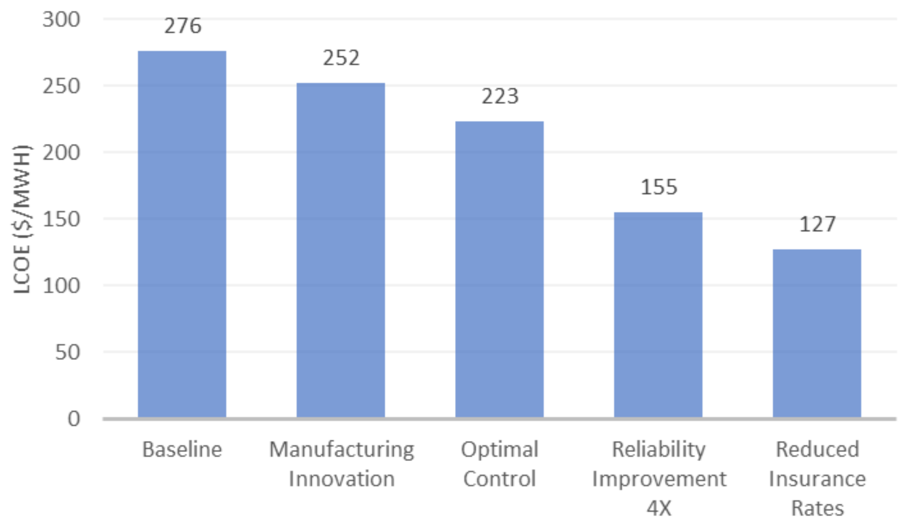


Figure 4 - Cost-reduction pathway for RPA

It is crucial to understand that the uncertainties in these models are still significant given the early stage of technological development and within the uncertainties in the analysis, both devices have similar commercial potential. Within the broader wave energy conversion space context, a technology development pathway that leads to an LCoE of < 15 cents/kWh is encouraging and competitive. However, more focused RD&D will be required to reduce the uncertainty in our predictions and clarify if such targets can be achieved using detailed engineering/design studies.

1 Introduction to the Project

The Wave Swing (www.awsocean.com) developed by AWS Ocean Energy is a submerged pressure differential WEC device presently going through sea trials at EMEC in Scotland. The Waveswing is a highly efficient WEC topology that has won third place (out of 92 design teams) in the wave energy prize competition organized by the US Department of Energy and has since undergone significant further development, culminating in the recent at-sea testing at EMEC.

The installation and testing at EMEC have shown that single-unit point absorbers are inherently expensive to build, deploy, and operate. If technology is to become economically competitive, it needs to achieve economies of scale across all lifecycle stages.

A techno-economic optimization of the entire envelope was carried out by studying various approaches to leverage economies of scale at the farm level. The metric used is the levelized cost of electricity (LCoE). Our objective was to benchmark the system's economics at utility scale (+100MW) and evaluate potential cost-reduction pathways. Our intended outcome was to identify and quantify the impacts of the key cost-reduction pathways for this technology. Since many of the scaling problems for AWS are not unique to this device topology, we hope to inform the broader industry in the process.

To support present commercialization efforts, Re Vision Consulting supported AWS with the development of a scalable techno-economic model that allows for the systems topology to be optimized at the wave-farm level. We utilized the same model to investigate design alternatives, alternative O&M strategies, and other LCOE reduction strategies.

2 Roles and Responsibilities of Project Participants

The team consisted of Re Vision Consulting, which conducted a parametrically driven techno-economic assessment, and AWS, which provided technical input data for the study.

2.1 Applicant Responsibilities and Tasks Performed

AWS provided Re Vision Consulting with design and performance assessment documents, enabling Re Vision to carry out its assessments. It also provided feedback and input on the direction of efforts.

2.2 Network Facility Responsibilities and Tasks Performed

Re Vision developed: (1) A baseline LCoE model to benchmark the current AWS configuration at 100MW scale, (2) Establish a baseline LCoE model for a generic point absorber including establishing a performance model, (3) develop a set of scalable performance and cost functions, (4) study innovative design alternatives, and (5) produce a final report.

3 PROJECT OBJECTIVES

The core objective was to identify cost-reduction pathways for this topology through a parametrically driven techno-economic model, with the primary goal of optimizing the overall design envelope. The key metric is the levelized cost of electricity at the farm level with an installed capacity of > 100MW.

The *expected outcome* was for us to successfully identify and quantify cost-reduction pathways that can inform the key focus areas for further RD&D efforts at AWS. The independently funded assessment of the AWS technology also provide a defensible cost and economic baseline that can be used in discussions with investors. We also provide a fully public-domain implementation of the analytical methods used for a point absorber, which can accelerate development within the broader community. Many lessons and innovation pathways are similar for a wide range of point absorbers, and lessons are applicable to the broader industry.

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 lead cost and economic assessment for a wide range of clients including: (1) The US Department of Energy, (2) 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 techno-economic analysis and optimization of marine energy systems is unique and will provide us with confidence as technology and market development activities advance.

5 TEST OR ANALYSIS ARTICLE DESCRIPTION

The Wave Swing (www.awsocean.com), developed by AWS Ocean Energy, is a submerged pressure differential Wave Energy Converter (WEC) device that is currently undergoing sea trials at EMEC in Scotland. The Waveswing is a highly efficient Wave Energy Converter (WEC) topology that won third place (out of 92 design teams) in the Wave Energy Prize competition organized by the US Department of Energy. It has since undergone significant further development, culminating in recent at-sea testing at EMEC.

The Wave Swing is a subsea pressure differential device that utilizes an internal gas-spring to enable a broad resonance bandwidth, resulting in high performance. The system is taught-moored (single point mooring) to an embedment plate anchor on the seabed. The PTO is an electro-hydraulic system that allows for power—smoothing on the minute timescale.

This system is benchmarked against a generic point-absorber architecture with negative spring stiffness, enabling highly efficient power capture without the need for reactive power. This device is considered structurally highly efficient and, as such, a relevant commercial benchmark.

Our Reference Point Absorber (RPA) device is a surface-piercing heaving point absorber that utilizes a taught-moored (single-point mooring) configuration. An embedment-plate anchor secures the device to the seabed. A key feature of the device is a PTO pre-tension gas cylinder that allows the PTO to generate power during the up- and downstroke and a set of pneumatic springs that are used to offset the buoy's hydrostatic spring stiffness.

6 WORK PLAN

6.1 NUMERICAL MODEL DESCRIPTION

The numerical models established consist of (1) A WEC-Sim model for the generic point absorber that is utilized to compute 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 for generic WEC device

A performance model was set up in WECSim, with the negative spring stiffness implemented at the Simulink level. A simplified optimal control strategy is implemented to enable the enforcement of end-stops. Concept-level designs were developed for the device structure to estimate structural quantities and associated costs. Parameters for negative spring stiffness terms and optimal damping were optimized for the overall design process.

The model relies on hydrodynamic coefficients obtained from Nemo and is complemented by quadratic viscous drag terms in the time domain. It allows us to compute the main structural loads (at connection points) and performance on a sea-state-by-sea-state basis.

The model allows for changes to be accommodated in a relatively straightforward way. This enables us to scale the device diameter and height of the cylinder relatively straightforwardly. The parametric scaling incorporates 6 different geometries, which is best modeled by re-running the existing model (including the geometry pre-processing in Nemoh). Performance is correlated with an analytical formulation that enables us to benchmark our performance rapidly.

Excel-based cost and economic model

The established model is purpose-built, leveraging its structure from the Reference Model Project cost assessment efforts carried out by ReVision Consulting. It contains a sub-model for the major subsystems, structured similarly to the reference model. All of the cost-models include an ability to scale the dimensions of the physical systems as follows:

1. Device Structural Components: Scalable parameters include buoy diameter and buoy height. It requires us to carry out a structural design at different sizes using a custom-built structural model.
2. Power Conversion System: This sub-system scales primarily to rated capacity of the PTO.
3. Subsea Cables and Infrastructure: This includes distance to shore and number of devices.
4. Installation and Commissioning: This scales to number of devices in the wave farm
5. Opex scales to number of devices as well.

Detailed (bottom-up) baseline cost models are developed to quantify these individual cost centers. Scaling functions are developed to quantify the scaling effects from the baseline. Performance is based on: (1) the scatter diagram for the chosen sites[1], (2) sea-state specific device performance, and (3) estimated losses. Uncertainties of the cost and performance estimates are estimated on a sub-system level, and its impact on LCoE is quantified using Monte Carlo simulations.

For the AWS machine, we utilize detailed engineering, performance, and cost data from the prototype build, as well as from past performance and cost scaling studies. For the generic point absorber, we develop our cost models.

Excel-based structural model

To estimate the amount of steel used for the structural components of this device, we 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 commonly used in ship design. To validate the model internally, develop a few validation points using the FEA model available within Solidworks Pro.

Key Metrics

Our core result metric is LCoE at utility scale and its sensitivity to device and farm-level design parameters. The majority of efforts is aimed at reducing the uncertainty and establishing credible cost estimates. For the open-source reference device, costs are publicly available. For the AWS device, we establish a 100MW-rated baseline plant deployed in an Oregon wave climate under task 1 of our efforts. This represents the current state-of-the-art commercial design point of the AWS machine and determines the LCoE baseline. All subsequent trade-offs are evaluated against that baseline. As such, it establishes how relevant a particular cost-reduction pathway is for the technology optimization process.

The following provides a high-level table of the major aspects and model interactions.

[1] California (Humboldt), Oregon (PacWave), Hawaii (WETS), Spain (BiMEP), and Scotland (EMEC).

Table 1 - 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

All units herein are metric unless otherwise indicated.

6.2 Test and Analysis Matrix and Schedule

The following tasks outline the tasks/scope agreed to with AWS. The level of effort estimates are provided assuming full-time work. Most of the efforts were spread out over a 9-month period (September 2023 – May 2024) and were carried out by Mirko Previsic. Only efforts by ReVision are indicated in this task breakdown. AWS participated in efforts, but these efforts are not listed as they are not supported by TEAMER funding.

Task 1 – Establish a *baseline configuration* based on the existing design with device-specific design parameters obtained from AWS. LCOE for this configuration is established at a commercial scale of 100MW. For this initial effort, we leverage AWS design, engineering, and performance data to develop an appropriate baseline LCOE model. The model is set up in Excel. As part of this task, we develop and refine a cost assessment of the device to a level suitable for subsequent parametrization.

Task 2 – Establish baseline for a generic heaving buoy point absorber. This concept design has lower fidelity than the AWS device, but it is informed by the at-sea testing experience from AWS from an operational perspective. Dimensional properties, weight breakdown, and PTO topology are taken from the CorPower WEC device as reported in the project information summary for their EMEC test-site report[2]. The report provides a weight breakdown that can serve as a starting point for estimating CAPEX. It is then refined using a concept-level design effort. Opex costs are estimated by establishing a bottom-up operational process model.

A performance model is set up in WECSim, with the negative spring stiffness implemented at the Simulink level. A simplified optimal control strategy is implemented to enable the enforcement of end-stops. Concept-level designs are carried out for the device structure to estimate structural quantities and related costs. A negative spring-stiffness term is introduced that mimics the behavior of the pneumatic piston cylinders in the CorePower design topology. The spring stiffness can be optimized by changing the pressure level inside the piston assembly. The net effect of this arrangement is a broadening of the resonance bandwidth. Both the spring-stiffness and the PTO damping term are iteratively optimized on a sea-state by sea-state basis to establish annual average performance values for this system. To establish an upper bound for the device performance, we utilize theoretical upper-performance bounds computed from point and volumetric limits for the device.

Task 3 – Develop *scalable cost and performance functions* to enable the model to be scaled in economically relevant dimensions. These dimensions include device size (diameter and height), water depth, wave resource, rated power, distance to shore, device spacing, and deployment scale. We develop independent device-specific functions for both devices, but many infrastructure cost functions are shared between the two devices.

Task 4 – *Study innovative design alternatives*. To understand the LcoE reduction potential of high-priority areas of innovation, we investigate the following cost-reduction pathways. This includes:

1. *Combining multiple absorbers into a single structure* to reduce device access requirements and related costs. This could reduce the per-device cost of items such as electrical connections and mooring systems, and some systems could be shared between units. It would also reduce access requirements.
2. *Scaling of absorber devices*. Larger-scale devices are going to become structurally less efficient, but building larger enables the sharing of fixed per unit costs (such as electrical connections and O&M). This is a trade-off that likely results in an optimal per device scale.
3. *Automation and robotics* for installation, inspection, operation and maintenance tasks. This includes: (1) automating external inspections using autonomous vehicles, (2) Purpose-built vessel for installation and O&M with various automation features, (3) Modularized access strategies whereby sub-systems can be rapidly swapped out using fully automated means.
4. *Optimal controls.* Comparing upper theoretical limits to the current device performance. We believe that the AWS device is close to its theoretical limits, but this is further investigated. Re Vision developed an analytical formulation that works for heaving absorbers in irregular sea-states that can significantly accelerate this sub-task.

[2] https://marine.gov.scot/sites/default/files/project_information_summary_10.pdf

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

Re Vision has signed a non-disclosure agreement with AWS and kept the datasets provided by AWS in confidence. We provide normalized LCOE data that shows the relative comparison of LCOE for the various trade-off studies performed. Data is shared in the report and a supporting Excel spreadsheet. We also provide a fully public-domain implementation of the analytical methods employed for a point absorber that can accelerate development within the broader community and disseminate the work as widely as possible. Data include comparative LCOE for single and multi-absorber WECs, with key cost influencers and required maintenance strategies. Data is shared in the post-access Teamer report and includes: (1) an appendix detailing the methodology, (2) an appendix with the normalized results for the AWS device, and (3) an appendix with the results of the generic point absorber. An excel model for the generic point absorber and normalized LCoE trends for the AWS is provided to support the final report.

The following table provides a list of data-sets and their format:

Dataset	Protection	Action	Location
Assessment Methodology	Public	Included in post access report	MHKDR
Normalized LCoE trend results	Public	Included in post access report	MHKDR
Generic point absorber results	Public	Included in post access report	MHKDR
Excel model with data tables and report plots	Public	Shared as Excel spreadsheet	MHKDR

6.5.2 Data Processing

Data is processed at Re Vision Consulting and includes various processing steps 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 also assign uncertainty ranges to each data point, which can subsequently be used in Monte Carlo simulations to quantify uncertainties.

Where possible and applicable, we compare the data with other cost datasets. This enables us to quantify uncertainties more accurately and assess their relative impact on the LCOE. Data is collected and analyzed in Excel, incorporating macros to automate data-processing routines and trade-off studies.

6.5.3 Data Analysis

Baseline design, performance, cost and economic assessments are established at the 100MW wave farm scale. These baselines provide a valuable understanding of critical cost drivers and offer some initial insight into cost-reduction pathways. Subsequent efforts are optimized based on these initial results. To understand the LCoE reduction potential of high-priority areas of innovation, we investigate the following cost-reduction pathways. This includes:

1. Combining multiple absorbers onto a single structure to reduce device access requirements and related costs. This could reduce the per device cost items such as electrical connections and mooring systems and some systems could be shared between units. It would also reduce access requirements.

2. Scaling of absorber devices. Larger-scale devices are going to become structurally less efficient, but building larger enables the sharing of fixed per unit costs (such as electrical connections and O&M). This is a trade-off that likely results in an optimal per device scale.

3. Automation and robotics for installation, inspection, operation and maintenance tasks. This includes: (1) automating external inspections using autonomous vehicles, (2) Purpose-built vessel for installation and O&M with various automation features, (3) Modularized access strategies whereby sub-systems can be rapidly swapped out using fully automated means.

4. Optimal controls. Comparing upper theoretical limits to the current device performance. We believe that the AWS device is close to its theoretical limits, but this is investigated. Re Vision developed an analytical formulation that works for heaving absorbers in irregular sea-states that can significantly accelerate this sub-task.

To keep our scope within budget and time-constraints, we utilize mostly first-order approaches to modeling (validated using testing data to confirm their usefulness). Specifically, we leverage the following tools/approaches:

Device performance/loads: We have found that the device performance can be modeled well with a 1-DoF model using frequency-dependent linear hydrodynamic parameters obtained from NEMO and a quadratic viscous damping term. The structural design is dominated by operational fatigue-driven loads, which can be assessed using our existing models and in combination with a cycle count and S-N curves be used to establish appropriate factors of safety.

Structural design: We utilize a low-fidelity structural design approach that leverages beam models for structural reinforcements and design-code-based approaches for skin thickness, corrosion allowance, and factors of safety. This allows us to rapidly evaluate the effect of different design dimensions on the amount of structural steel required.

Cost models: We build on AWS's experience, as well as Revisions' in-house experience in supporting a wide range of organizations. We update these models to reflect current costs using a combination of approaches including producer price indexes (PPI), discussions with manufacturers and updated price quotes. We also have in-house manufacturing process models that allow us to break down manufacturing costs of structures into material and labor costs and provide us insight into cost-sources and the related cost-reduction potential in manufacturing.

Economic Assessment: We utilize a Utility Generator (UG) Model to calculate a fixed charge rate based on levelized capital costs. Economic assumptions from the former DoE Reference Model effort ensure that results can be compared directly with those of other related efforts. To quantify uncertainties, we assign cost uncertainty ranges at the sub-system level and use Monte Carlo simulations to quantify LCoE uncertainty ranges at the plant level.

Up-scaling challenges: We are using validated numerical models to scale the device performance and loads. Assuming reasonable device spacing, performance degradation due to hydrodynamic array interactions is expected to be negligible in the context of other uncertainties present. Based on our experience, much larger uncertainties likely stem from the cost and economic assessment than from the performance assessment. Sub-system-level learning curves are employed for manufacturing at scale and operational processes are assessed at the target farm scale. All these uncertainties are captured using statistical approaches.

Resource Locations: 5 site locations are chosen, including EMEC, PMEC, WETS, Wavec, and a representative US east-coast site near Cape Hatteras. Their frequency distributions are incorporated into the performance assessment.

Price fluctuations over the past 2 years have been challenging to track, and we do not believe that it is realistic to try to capture them. Instead of trying to chase these price swings, we index data to before the pandemic. Costs over time should move gradually, and we believe that in hindsight, these price swings will be normalized. It is necessary to understand that these models – while trying to capture the economic reality of these technologies – do not need to be exact as of 2023. They need to provide a relative comparison to other technologies to establish competitiveness.

7 PROJECT OUTCOMES

7.1 RESULTS

This results section is broken into three different sections: (1) Device Performance Modeling, (2) Cost functions utilized (3) results for the AWS machine, (4) results for the generic point absorber, and (5) Cost reduction pathways. Two supporting spreadsheets provide the numerical data for all the plots generated in this report.

7.1.1 Performance Modeling

WaveSwing Performance—AWS provided performance data for different-sized machines generated using their in-house performance model, which was validated using wave tank and full-scale in-ocean data. AWS employs a causal control strategy that enforces PTO stroke limits while maximizing power. We used this performance as the baseline performance and were able to normalize the data set to the absorber's active stroke volume.

Passive Floater Volume - The WaveSwing requires a certain minimum floater height to yield a spring-stiffness that is soft-enough to allow the floater to move effectively. Because the entire volume is submersed and is required to withstand the pressure differential during wave actuation, the entire entrained volume contributes to the structural cost of the device. Similar to a ship, the cost of this sub-surface absorber is driven by its displaced volume and the design pressure differential across its hull. The total volume of the absorber device is typically about 3x of the active volume of the absorber. Because the passive floater volume contributes to structural and anchoring costs, an essential aspect of device optimization is minimizing that volume.

Load-Shedding – The amount of steel required is a strong function of the maximum design pressure under extreme wave conditions. The largest wave in a PM time series of wave elevations is about 2x the significant wave height. This results in extreme wave heights (peak to trough) encountered in Pacific or Atlantic wave conditions that are on the order of 24m – 30m. This results in sub-surface pressure differentials near the surface of +/- 120 – 150 kPa. This compares to an operational pressure differential during rated power conditions (at Hs=4m) of +/- 40 kPa, which means that the design pressure is about 3-4x the operational design pressure. As the floater moves, it compresses and decompresses the internal volume of the absorber. This, in turn, minimizes the pressure differential across the shell to some degree.

A vital issue to be considered when optimizing this WEC is minimizing the pressure differential in extreme waves. This can be accomplished through variable submergence of the absorber while internally compensating for the hydrostatic pressure. Submergence lowers that dynamic wave pressure while increasing the internal spring stiffness of the WEC. The combined effect of these measures enables an effective load-shedding mechanism in the WEC system that enables minimizing structural requirements on the absorber body. Alternative load-shedding mechanisms could be implemented whereby the passive volume of the absorber can be made active. There are several ways to implement that. However, the reduction of these measures is beyond the scope of the current study. This study assumes that such load-shedding is implemented effectively to enable a design pressure differential driven by the operational condition.

Upper-Performance Limits - Instead of performing time-domain control optimization on these topologies, the upper-performance limits were identified using point absorber theory adapted for irregular waves. This allows us to estimate the upper limits of power absorption by imposing point absorber and volumetric limits onto the device. This method was initially developed by Re Vision Consulting in 2017 under a controls optimization project, and the methodology was published in 2021[3].

Generic Point Absorber Performance – The single heaving point absorber studied was obtained from time-domain simulations that utilize hydrodynamic properties obtained from Nemoh. 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)
- A standard quadratic viscous drag coefficient of 0.3 was applied in the time domain.
- 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%.
- 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 2 - 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

For each device configuration, performance was optimized in the time domain by sweeping a velocity-dependent damping term. 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.

Site-Specific Performance Model

We followed a standard methodology to compute annual energy yield at prospective sites. The power conversion process steps used were as follows:

1. Compute sea-state dependent average power output for specific WEC configuration for both the lower limit using linear damping from the WECSim time-domain model and the upper limit using

[3] Previsic, M.; Karthikeyan, A.; Scruggs, J. A Comparative Study of Model Predictive Control and Optimal Causal Control for Heaving Point Absorbers. J. Mar. Sci. Eng. 2021, 9, 805. https://doi.org/10.3390/jmse9080805

optimal control from the analytical method. For the AWS WEC, performance was computed using their in-house performance model.

2. Apply losses, including powertrain efficiency and transmission efficiency.
3. Impose rated capacity to limit power generation in sea states where power exceeds the rated power. An iterative goal-seeking algorithm is used to adjust the rated capacity to yield a specific capacity factor target.
4. Reduce annual yield using the farm availability.

For the power conversion process, we used the following efficiency values.

Powertrain Efficiency: 80%
Transmission Efficiency: 98%
Farm Availability: 95%

Rated power was iteratively determined to yield a capacity factor target that approximates a techno-economic optimum for the technology – minimizing LCoE.

Scatter diagrams for the following sites were obtained to compute site-specific device performance. Data was obtained from the test-center websites for Oregon (PacWave), Hawaii (WETS), Spain (BiMEP), and Scotland (EMEC). Data for the California site was obtained from the US DoE Reference Model Project (RMP). Table 3 provides a summary of the sites assessed.

Table 3 - Summary of Sites for Performance Assessments

		Humboldt	**PacWave**	**WETS**	**BiMEP**	**EMEC**
		California	Oregon	Hawaii	Spain	Scotland
Average Power Density	kW/m	33.5	37.5	13.8	13.3	14.9
Average Hs	m	2.38	2.41	1.74	1.51	1.66
Average Te	s	9.25	9.68	8.09	7.82	7.48

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 seagoing vessels and was also utilized here. 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. It compares them against the upper theoretical limits that could be approached if optimal control is employed.

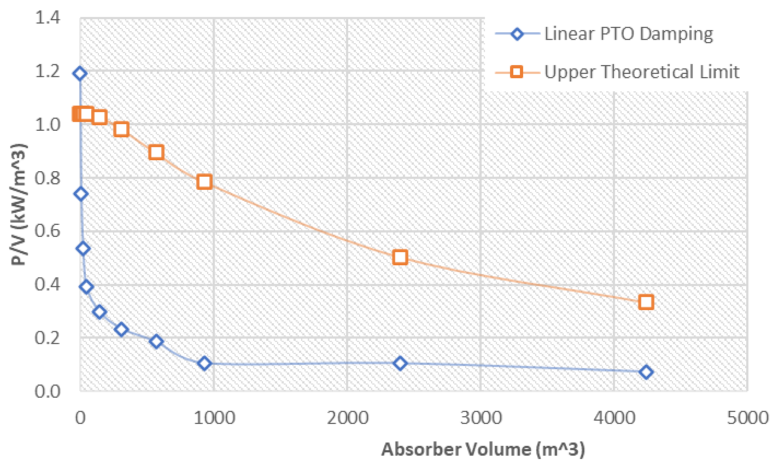


Figure 5 - P/V values for a range of different absorber volumes

It should be noted that this P/V metric is site-dependent and, as shown in the above chart, represents the 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.

7.1.2 Structural Design

The amount of structural steel used is a critical driver in the overall system's LCoE. Both the generic heaving point absorber and the Waveswing are cylindrical bodies with similar pressure rating requirements. As a result, a common method can be employed to estimate the amount of steel required to build these structures.

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.

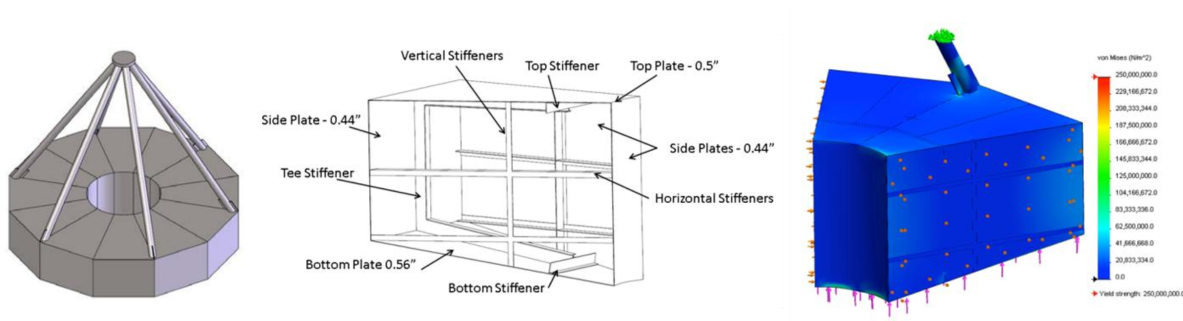


Figure 6 - Structural Design of Absorber buoy

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 unaccounted 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 significant differences in geometric shape, these different systems had mass/volume ratios within 25% of our design, providing us with a helpful level of certainty around our structural design efforts without having to engage in a detailed design effort.

The following chart shows the relationship between the structure's immersion depth and steel weight, normalized to kg of steel per m3 of submersed volume.

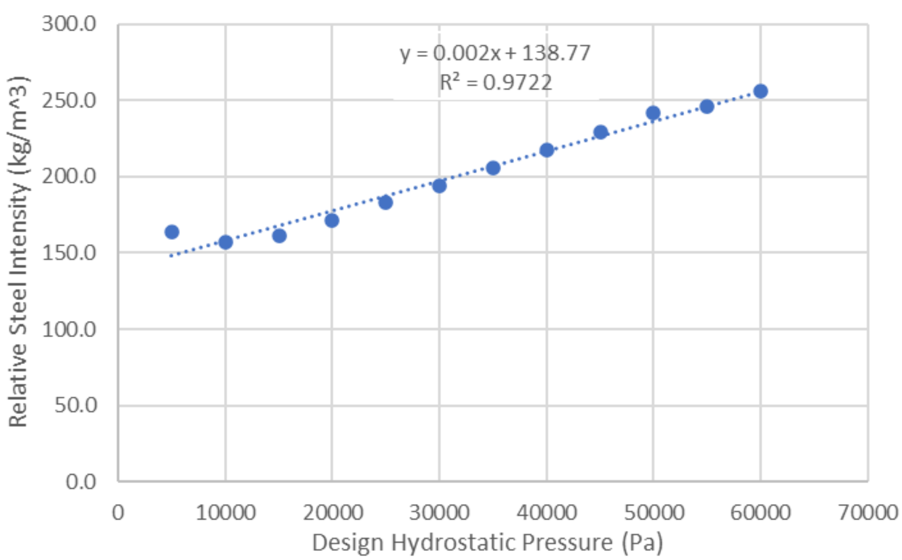


Figure 7 – Normalized steel weight as a function of barge height

The 10m diameter Waveswing baseline design provided by AWS came in at a design value of 262kg/m^3, corresponding to a design pressure of about 60kPa in our plot. The pressure differential of the Waveswing device in a fully contracted position (internal volume compressed) in a 100-year return wave with a wave amplitude of 12m is less than 80kPa, suggesting agreement between our in-house structural model and the Waveswing design. We used a design hydrostatic pressure assumption of 60kPa in the baseline assessment.

7.1.3 Cost Modeling

Cost Estimating Process

It is pretty common for early-stage innovators to underestimate costs because the design details required for an actual design are not yet understood at this stage, and the actual design complexity drives costs. Because of this, our approach was to reuse data from related, more mature efforts and scale these results in a consistent manner. The following shows a process example for the PTO subsystem.

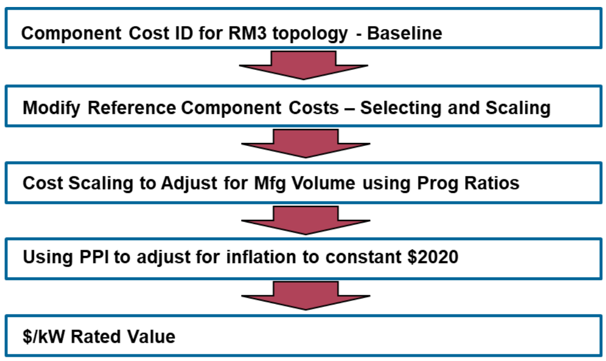


Figure 8 - Cost Estimation Process

Cost Breakdown Structure

The Cost Breakdown Structure (CBS) used for this project was directly adapted from the latest DoE LCoE guidance developed by NREL[4]. A few modifications were made to better reflect the requirements of this project, specifically this includes:

- We removed the project contingency budget as cost uncertainty. 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.
- The Assembly and installation cost category was subdivided into subsea cables and devices. This allowed us to conveniently separate the technology-specific and infrastructure costs.

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

Table 4 - Cost Breakdown Structure with Values for a Reference Case (irrelevant line items in the NREL Cost Breakdown Structure have been omitted)

		Cost			Economics		
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total
1.1	**Marine Energy Converter (MEC)**	**$ 556,612,019**	**$ 4,517,668**	**$ 5,566**	**$ 119**	**78%**	**49%**
1.1.1	Structural Assembly	$ 346,024,657	$ 2,808,463	$ 3,460	$ 74	49%	31%
1.1.2	Power Take-Off System (PTO)	$ 197,488,529	$ 1,602,890	$ 1,975	$ 42	28%	17%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 13,098,833	$ 106,315	$ 131	$ 3	2%	1%
1.2	**Balance of System (BOS)**	**$ 88,978,032**	**$ 722,178**	**$ 890**	**$ 19**	**13%**	**11%**
1.2.1	Project Development	$ 12,783,344	$ 103,754	$ 128	$ 3	2%	1%
1.2.2	Engineering and Management	$ 12,658,628	$ 102,742	$ 127	$ 3	2%	1%
1.2.3	Electrical Infrastructure	$ 32,089,645	$ 260,451	$ 321	$ 7	5%	3%
1.2.6	Assembly & Installation	$ 31,446,415	$ 255,231	$ 314	$ 7	4%	3%
1.2.6.1	*Device*	$ 21,035,175	$ 170,729	$ 210	$ 5	3%	2%
1.2.6.2	*Subsea Cables*	$ 10,411,239	$ 84,501	$ 104	$ 2	1%	1%
1.3	**Financial Costs**	**$ 64,559,005**	**$ 523,985**	**$ 646**	**$ 14**	**9%**	**6%**
1.3.2	Insurance During Construction	$ 12,911,801	$ 104,797	$ 129	$ 3	2%	1%
1.3.3	Construction Financing Costs	$ 51,647,204	$ 419,188	$ 516	$ 11	7%	5%
Total CAPEX		**$ 895,132,507**	**$ 7,265,225**	**$ 7,101**	**$ 152**	**100%**	**65%**
		Cost			Economics		
		$/Farm	$/WEC	$/kW	$/MWh	in %	
2.1	**Operations**	**$ 19,023,650**	**$ 154,403**	**$ 153**	**$ 58**	**64%**	**24%**
2.1.1	Environmental Monitoring	$ 1,121,000	$ 9,098	$ 11	$ 3	4%	1%
2.1.3	Insurance	$ 17,902,650	$ 145,304	$ 142	$ 55	61%	23%
2.2	**Maintenance**	**$ 10,542,517**	**$ 85,567**	**$ 105**	**$ 32**	**36%**	**13%**
Total OPEX		**$ 29,566,167**	**$ 239,970**	**$ 259**	**$ 91**	**100%**	**37%**
Plant LCoE $/MWh					**$ 243**		

Cost estimation – Generic Sub-Categories

For many system-level cost-centers, Reference Model 3[5] data was used, including appropriate scaling mechanisms to estimate 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 period created short-term price distortions that are difficult to capture and will not likely reflect longer-term trends. In a few years, we will be able to understand these impacts fully, but early indications are that some of these distortions are going back to historical norms in this post-pandemic period.

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

[5] https://energy.sandia.gov/programs/renewable-energy/water-power/projects/reference-model-project-rmp/

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

1.2.2 Engineering and Management—This is taken as 2% of total capital cost (excluding financial costs), which is consistent with utility-scale power plant construction projects.

1.2.3 Electrical Infrastructure – This includes the subsea cables, terminations, and connectors. However, this cost center does not include the flexible riser cable connecting the subsea array collector cable to the individual WEC devices. Instead, it is accommodated in the PTO cost. Substation and grid integration costs are also excluded from our calculation as these are highly site-specific costs that need to be evaluated on a case-by-case basis.

Our baseline case was based on an electrical collector/transmission design for a 100MW farm in the Pacific Northwest of the United States. The following baseline assumptions were made:

Table 5 - Electrical Collector and Transmission Assumptions

Electrical 3-Phase Voltage	36kV
Per Cable Capacity	25MW
Inter-Device Spacing	600m
# of Rows of Devices	2
Farm Distance to Shore	5km
Directional Drilling Distance	500m

The following illustration captures the overall layout arrangement for this baseline wave power plant.

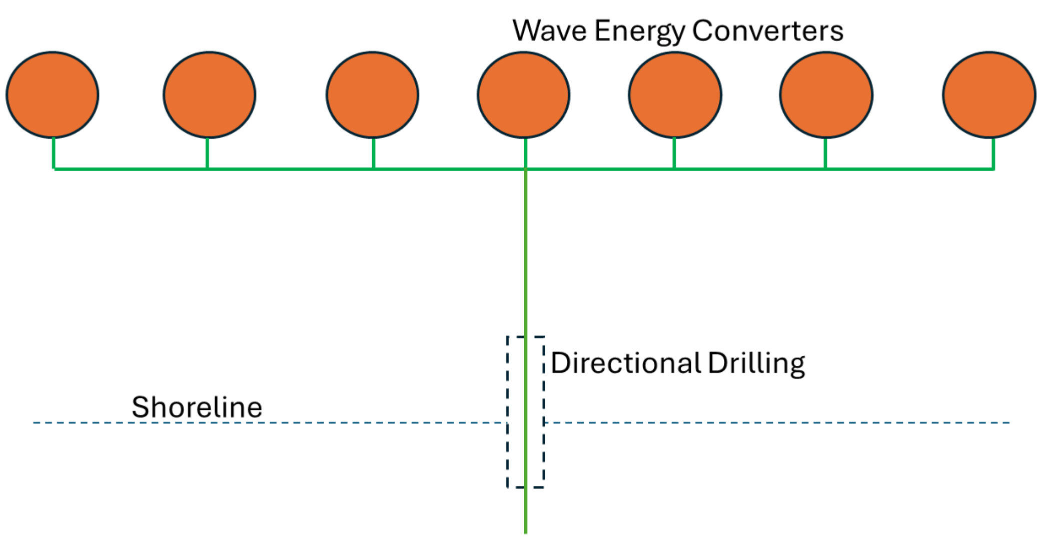


Figure 9 - Baseline Array Layout

This architecture scales well between a capacity of 25MW and 200MW. We conducted various sensitivity studies using our in-house subsea cable cost models to evaluate the influence of device-rated capacity and inter-device spacing. The results determined a subsea cable cost range of $250/kW to $372/kW with a median value of $321/kW, used in our parametric modeling efforts. Given the relatively small contribution of this cost center to LCoE, we decided that this was an adequate way of capturing this cost center.

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 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. For this task, we assumed that a cable-laying vessel, including cable burial equipment, would be mobilized to a nearby port, the cable loaded up, transit to the site, the surface lay of the cable, and subsequent burial using a waterjet-assisted plow. Cost estimates came in for a single unit at $1.5M, while for a 100-unit farm, it came in at $7.3M.

This cost center also includes the directional drilling of a conduit that transits the surf zone. This is the preferred method for crossing the shoreline with minimal environmental impacts. A 500m long directionally drilled conduit was included in the estimate. The costs came in at $670k for a single 8” ID conduit, rising to $1.5M for two 10” ID conduits required for the 100MW farm capacity.

Comparison to offshore wind: As a point of comparison, offshore wind farms have typical costs for subsea cabling of about $370/kW[6]. This includes array cable costs ($85/kW), Export Cable cost ($240/kW), and Cable accessories such as connectors, cable protection systems, buoyancy modules, and connectors ($53/kW). It should be pointed out that wind farms are typically located farther from shore, hence the large cost of the export cable, and have fewer turbines to interconnect (hence the lower array cable costs).

1.3 Financial Cost

This includes insurance during construction and construction financing costs. The construction financing rate default was set to 8%, and the insurance to 2%. This assumes that the marine construction operators cover liability insurance during construction. It should be noted that in typical utility generator (UG) models, construction financing is part of the Fixed Charge Rate (FCR).

1.3.1 Contingency Reserves

Contingency reserves are typically included in project costs. However, because these contingency reserves are not always used and are assigned based on specific project risks, they are omitted from this levelized cost analysis.

1.3.2 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.

[6] https://guidetofloatingoffshorewind.com/wind-farm-costs/

1.3.3 Insurance

Insurance is taken as a percentage of wave farm CAPEX. The default input is 2% of CAPEX per year, assuming reasonable commercial maturity. As a benchmark, insurance rates for in-ocean prototypes were at > 5%. Large-scale onshore solar[7] and wind projects have insurance rates of less than 0.5%, providing a suitable target rate assumption once the technology becomes commercially mature.

Cost estimation – Device-Specific Sub-Categories

AWS provided the following prototype device cost breakdown for a 425kW-rated machine, including component-level specifications. The baseline system design has the following specifications:

Floater Diameter	10m
Volume at Mid-Stroke	900m^3
Volume fully extended	1096m^3
PTO Stroke	5m
Floater Weight	97t
Silo Weight	190t
Total Weight	287t
Normalized Steel Weight	262kg/m^3

AWS provided the cost breakdown for the unit in UK pounds, which was converted to USD at an exchange rate of 1.2. The following provides a breakdown of the WEC system at a single-unit scale.

Table 6 - Single Unit Cost Provided by AWS

	Cost	$/kW	in %
Floater	859,616.59	2,022.63	23%
Silo	1,584,766.84	3,728.86	42%
Seal	226,535.40	533.02	6%
Bearings	151,367.04	356.16	4%
PTO	542,280.00	1,275.95	14%
End-stop & survival lock	395,667.12	930.98	11%
Total	3,760,232.99	8,847.61	100%

To understand these cost categories better, the following assumptions are essential to understand:

- The floater weighs 106t, and steel manufacturing costs (including paint) account for 82% of the cost. The manufacturing cost is $6680/t, assuming manufacturing in a UK facility.
- The silo weighs 190t, and steel manufacturing costs (including paint) account for 95% of the cost. The manufacturing cost is $8340/t.

[7] Insuring Solar Photovoltaics: Challenges and Possible Solutions, NREL Technical Report, 2010

- The 4 x 5m stroke dual-acting hydraulic cylinders bear 2/3 of the PTO cost. They weigh 5000kg a piece and cost $18/kg. The remainder includes the fixed displacement hydraulic motors, generators, and miscellaneous items.

Scaling the initial cost of $8,847/kW to a 100MW manufacturing volume, assuming a learning rate of 15% is typical for these types of manufacturing processes, we end up with a cost of about $2,400/kW. This provides a valuable benchmark, but scaling from a single unit scale to a reasonable manufacturing volume is sensitive to the learning rate applied. The following sections utilize an analogous cost-estimating approach to understand these cost structures better. We also break down the cost using our original CBS.

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 $/tonne value. Values for $/t are largely a function of manufacturing complexity. They can range from $1,500/t for simple pile-type structures that can be robotically welded to > $10,000/ton for more complex shapes and small-scale production. The WaveSwing device will undergo a construction process that can be automated mainly due to its serial production nature. To establish a competitive benchmark for steel construction, we examined barge construction costs, as these are mature processes that leverage low-cost locations and a high level of process automation. To understand barge construction costs, we obtained cost estimates for new barge construction from a construction yard in the US (Illinois) that builds hopper barges for transporting goods on inland waterways, as well as a boat builder in China that specializes in building offshore barges. Rolled mild steel plates and I-beams used in the construction of barges from the steel mill cost $600-$1000 per ton. The manufacturing process, including cutting, assembly, welding, and painting, is the dominant cost of creating the finished product at low volumes, which is typical in shipyards. Labor costs tend to dominate that process, but facilities such as dry docks can add significant overhead costs if they are not carefully managed. Low-cost manufacturing facilities for barges tend to be inland with river access, where labor costs are cheap and facilities can load batches of devices onto an offshore barge for direct tow to the deployment site.

Cost data was obtained for a standard barge that measures 61m x 10.7m x 3.2m. The construction cost was < $1,200 per ton for China (fall 2024) and $4,170 for US-based construction. It should be noted that significant tariffs apply to imports of manufactured steel products in most European and US-based locations, and projects may need to adhere to a “buy America” or “buy Europe” policy to qualify for renewable energy tax incentives. The current steel import tax from China is set at 25%.

Considering a 25% tax on China-built steel and an additional 10% for transportation, the barge built in China remains the lowest-cost option at $1,560 per metric ton of steel. Depending on the jurisdiction and available tax credits, these costs may or may not be attainable for a specific project.

It was also instructive to note that the amount of steel used for these barges ranged from 110 kg/m³ to 160 kg/m³. However, offshore barges that feature thicker plate materials and reinforcements can reach densities of up to > 200 kg/m³. These values align well with our structural model and provide an additional method for validating embedded steel requirements for these systems.

A third resource reviewed is the RM3 efforts, where Re Vision Consulting 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. The manufacturing cost for this was $3,060 per ton, assuming a manufacturing volume of 100 units in the United States.

We assumed US-based steel manufacturing costs for the cost-modeling efforts with the following assumptions.

- Steel Construction Cost at 100-unit mfg scale: $2,750/t
- Steel Construction Cost at single unit: $4,500/t
- The above assumptions resulted in a progress ratio between 1 and 100 devices of 90%.
- Producer Price Index (PPI): Steel product mfg from purchased steel. NAICS code: 3312.

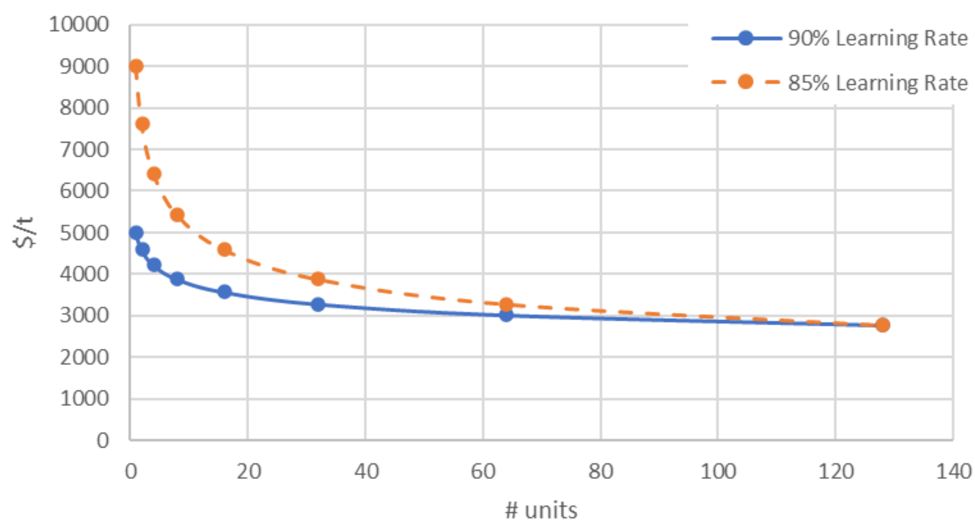


Figure 10 - Comparison of Learning Rates for Steel Manufacturing

Over time, there is an opportunity to build manufacturing facilities that increasingly automate processes. This automation will make the product less dependent on labor and make manufacturing costs competitive with China in developed nations. The above assumptions are aggressive, especially at the single unit scale. However given that our focus is on utility-scale LCoE projections, we find them adequate.

1.1.2 Power Take Off System (PTO)

AWS Supplied Cost - As designed by AWS, the PTO topology consists of a hydraulic cylinder connected to a generator over a fixed displacement pump. The prototype used electric heater elements to dissipate the electrical energy on the device. This cost element at the prototype stage came in at $1,276/kW. Comparing this to our estimates for a geared direct-drive powertrain, the system replaces the front-end (excluding grid integration) of the powertrain, estimated at $1,390/kW, showing good agreement between different powertrain approaches. The four double-acting cylinders used to convert primary motion into hydraulic pressure are the most significant contributors to the cost of the low-speed portion of the powertrain. They each weigh about 5t and cost about $18/kg.

Additional elements of the PTO include a shock absorber to enable end-stop protection and a braking system. Using hydraulics and appropriate redundancies in the design, these protective mechanisms can likely be incorporated into a production system's hydraulic PTO system (cylinder and appropriate cut-off valves). As such, they are excluded from this cost estimate as they represent the required safety equipment for prototyping.

Other elements of the PTO include (1) a large-diameter rolling seal that seals the silo from the moving floater and (2) linear bearings to guide the relative movement of the two components. AWS estimated these components to be $890/kW for the prototype system. However, significant cost reductions are likely possible as these are bespoke components.

The total PTO cost for the AWS Waveswing includes the cost of elements required for grid interconnection.

Table 7 - WaveSwing PTO Cost Breakdown

	1-Unit Cost $/kW	100-Unit Cost $/kW	Learning Rate
Hydraulic PTO (Mechanical to Electrical)	$1,276	$908	0.9
Power Converter	$657	$465	0.95
Step-up Transformer	$84	$60	0.95
Riser Cable	$432	$307	0.95
Bearings and Supports	$356	$253	0.95
Rolling Seal Assembly	$533	$265	0.9
Total	$3,335	$2,257	

Pelamis Powertrain Cost Cross-Check – While Pelamis has a different PTO topology, it did use a hydraulic primary stage with added hydraulic energy storage. Powertrain cost estimates[8] came in at £800 - £1100, which, converted to USD in 2014 (when these quotes were likely obtained), yields $1280 to $1760 per kW of rated (continuous) power.

Analogous Direct-Drive Study - We decided to undertake an analogous costing study using components readily available in the wind industry. The topology consists of a geared bidirectional PTO system that directly connects to a generator. A rack-and-pinion system converts the high-force linear motion into rotary motion. Energy storage is achieved by incorporating battery or ultracapacitor storage on the DC bus of the frequency converter, which is connected to the generator. The following diagram shows a schematic of the overall system.

[8] PTO System Cost Metrics, Quotient Report produced under contract to Wave Energy Scotland, 2016

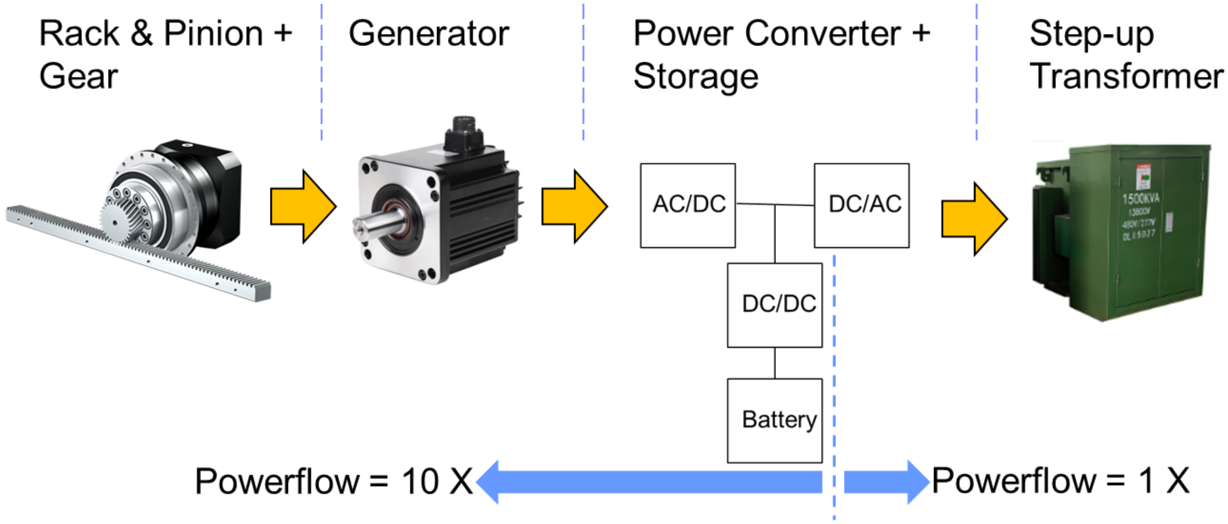


Figure 11 -Direct-Drive PTO Topology

The wind-turbine analogue - Although the Waveswing device is not a wind turbine, many of its components share similarities. It would be beneficial from a cost, economic, and design maturity perspective to tap into this existing supply chain. The maturity of the supply chain also provides a solid basis for cost estimation, thereby reducing commercial risks. The following table provides a cost breakdown of an MW-class wind turbine, including details on the cost components of the powertrain.

Table 8 - Wind-turbine Powertrain Component Cost[9]

Component			**$/kW**
Rotor Blades	20%		$ 268
Tower	25%		$ 335
Nacelle Components	35%		$ 150
Pitch & Yaw Bearings	2%		$ 27
Generator	3%		$ 40
Power Converter	4%		$ 54
Gearbox	11%		$ 147
Balance of Plant	24%		$ 319
Sum	**100%**		**$ 1,340**

The following table isolates the cost breakdown of components that are similar to our WEC device.

[9] Derived from https://www.windpowerengineering.com/understanding-costs-for-large-wind-turbine-drivetrains/

Table 9 - Cost Breakdown of PTO Components in a MW class wind turbine

Component				$/kW
Nacelle Components		25%		$ 150
Generator		23%		$ 134
Power Converter		27%		$ 161
Gearbox		25%		$ 147
Sum		**100%**		**$ 592**

WEC PTO Differentiation – Several key differences need to be captured in our conceptual design and cost assessment, including:

1. Peak-to-average power flow in the input stage of a WEC device is about 10:1. Most WEC devices advancing to some level of commercial maturity reduce that ratio somewhat. This means that some of the powertrain components need to be oversized to accommodate that power flow, which increases their cost.
2. Power flow variability will require short-term energy storage on the timescale of a few wave periods to enable continuous power flow to the grid. Typically, such energy storage will be on the order of 30 s to 5 minutes, depending on the acceptability of variability on the power grid and the number of devices in the wave farm. Having many devices in a wave farm spread over broad spatial scales provides an opportunity to smooth out variability using farm-level WEC device control.
3. Specialty components are not present in wind turbines. For the current design, this includes the rack-and-pinion system that converts the linear motion into rotary motion and the energy storage system that provides short-term storage for the energy flow.

Performing a detailed bottom-up cost assessment of the powertrain would require a detailed full-scale optimized powertrain design, which was not available at the time of this study. This leads us to adopt an analogous cost-estimating method for the powertrain. We made the following assumptions:

1. Rack and Pinion System—converting linear into rotary motion. Absent a detailed design, we assumed that the cost of this system is equal to the gearbox cost.
2. Gearbox—increasing rotational speed to generator speed. The cost of gearboxes scales linearly with the input torque. Some gearing is already accommodated within the rack-and-pinion system, and we would expect that an optimized PTO system will include some control to limit peak torque levels. We assumed that the cost of the gearbox increases by a factor of 3 over the wind turbine baseline.
3. Generator – converting high-speed (~3600rpm) rotary motion to variable AC electrical power. The peak power flow is about 10X of the equivalent wind machine. However, given the intermittent nature of the power flow and that many components are thermally limited, these generator components do not need to increase in size by 10x. Based on in-house conceptual design work, we assumed that cost increases by 3x compared to a wind turbine.
4. Power-converter. The power converter requires a custom topology, albeit the individual sub-components are common in wind turbines. We have discussed this application with ABB and Siemens applications engineers to better understand the re-use of these components and sub-systems. The power-conversion topology can be subdivided into the following elements:

a. AC/DC converter - converts the variable AC power from the generator into DC power. Current control in this stage allows for control over the torque on the generator, which needs to be impedance-matched to maximize power absorption from the waves. In addition to maximizing power, the control objectives can include force and power flow objectives, resulting in reduced structural loads and improved commercial viability. This converter's solid-state electronics used for pulse width modulation is rated for peak current flow. We assume that the cost of this stage will be 6x that of a wind turbine AC/DC power converter. We also assume that the front-end AC/DC converter makes up half of the overall wind turbine converter system cost.
b. DC/DC converter - converts the variable DC voltage on the DC bus of the energy converter into the constant voltage/current required by the battery pack or ultra-capacitor bank. Control can be used to optimize the voltage levels on the DC bus and improve longevity in the battery pack. While in theory, we could couple a battery pack directly to the DC-bus, this would limit the voltage range on the DC-bus, which imposes limits on the rotational speed of the generator. Because the power train needs to accommodate highly dynamic power flows, this is an important feature of the overall system. For this study, we assume that this power-conversion stage is half of the AC/DC converter stage.
c. Energy storage – stores electrical energy to smooth electrical power output. We assume that energy storage includes about 2 minutes of storage at rated capacity. So, we need 120kWs (30Wh) of energy storage for each kW of capacity. A 1MW system would require about 30kWh of short-term battery storage. The many cycles experienced by the battery system over its lifetime will likely require optimized chemistry, optimized charge/discharge control logic, and limiting the discharge depth. Energy storage systems used in off-grid solar applications are on the order of $1000/kWh, costing $30/kW (0.03kWh x $1000) of PTO power. Because of the likely need to limit discharge depth in the energy storage system, we assume that the net cost increases by 3x to $90/kW of rated capacity.
d. DC/AC converter – converting the variable DC voltage into grid-compliant AC power at a nominal voltage of 690V. This stage can provide grid services (such as power-facto control) that, in some cases, can add economic value to the power on the grid. This converter only sees the average power delivered to the grid, so the cost equals that of a wind turbine converter stage. We assume that the DC/AC conversion stage is 50% of a typical wind turbine converter cost.

5. Nacelle Components—This includes mounting systems (such as the bedplate) and enclosures. We assume that these costs are equal to the cost of a wind turbine powertrain.

In addition to the main components, we need to account for the cost of the step-up transformer, grid-interface disconnect and safety, and cabling to the interconnection point. For a MW-class on-shore wind turbines (2MW scale), this cost comes in at $78/kW[10]. Our central estimate for the transformer cost came in at $60/kW.

[10] NREL 2.8MW Reference Wind Turbine https://www.nrel.gov/docs/fy22osti/81209.pdf

Table 10 - PTO Cost Breakdown at 100-unit mfg scale for direct-drive PTO

Component		**$/kW**
Nacelle Components	7%	$ 150
Rack & Pinion	22%	$ 442
Gearbox	22%	$ 442
Generator	6%	$ 121
Power Converter	23%	$ 465
AC/DC Stage	*13%*	*$ 268*
DC/DC Stage	*4%*	*$ 80*
Energy Storage	*4%*	*$ 90*
DC/AC Stage	*1%*	*$ 27*
Step-Up Transformer	3%	$ 60
Riser Cable	6%	$ 125
Assembly & Testing	10%	$ 201
Sum	**100%**	**$ 2,006**

Dynamic riser cable cost estimates varied significantly depending on suppliers. While the cable cost is relatively straightforward, many of the components required to enable a lazy S configuration were considered bespoke components. At the 15MW offshore wind turbine scale, an optimization study showed costs of $280k—$320k per riser cable. However, adjusting for a water depth of 60m revealed the following cost profile.

Table 11 - Dynamic Riser Cable Cost for 15MW Floating Offshore Wind Turbine

Baseline Model			
	Water Depth	60	m
	Cable Length	135	m
	Cable Voltage	66	kV
	Cross Section	240	mm^2
	Power Rating	15	MW
	Cable Cost	€ 420	/m
	Total Cable	€ 56,700	
	Bend Stiffener	€ 80,000	/unit
	Buoyancy Floats	€ 3,650	/unit
	Dry-Mate Connector	$ 52,000	
	# of Buoyancy Modules	10	
Cost Estimate		€ 225,200	
Currency Conversion		1.05	
USD		$ 236,460	

Normalized, this results in a cost of only $12/kW capacity. At smaller scales, this relative cost does increase, albeit the cost becomes very design dependent. A report[11] on the Pelamis WEC riser cable cost, which operated at 11kV (rated capacity per device 750kW), provided the inputs to a cost model at a smaller scale.

Table 12 - Dynamic Riser Cable Cost for 750kW Machine in 60m Water Depth – Production Scale 100-Units

Model Inputs			
	Water Depth	60	m
	Cable Length	135	m
	Cable Voltage	11	kV
	Cable Capacity	750	kVA
	Cable Cost	180	/m
	Total Cable	£ 10,800	
	Bend Stiffener Cost	£ 24,000	
	15 Buoyancy Modules	£ 9,000	
	15 Cable Ballasts	£ 6,000	
	Cable Touchdown Riggir	£ 8,000	
	Wet Mate Connector	£ 15,000	
Total		£ 72,800	
Currency Conversion		1.25	
USD		$ 91,000	

The above two values provide for a cost-correlation function that can be applied on a per-device basis and scales to the connections rated capacity.

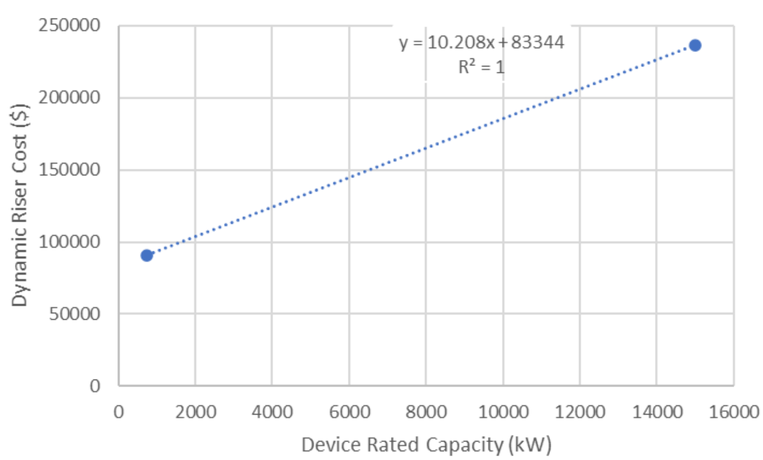


Figure 12 - Riser Cable Cost Correlation Function

[11] Moorings & Connection Systems Cost Metrics, Quotient under Contract to Wave Energy Scotland, 2016

A key issue in connecting many small WEC devices to the grid is the need for a hub to connect them to a common transmission line to shore. This will likely require a subsea hub that enables electrical fault protection, appropriate electrical connectors, and a step-up transformer. The cost for this subsea electrical infrastructure is poorly understood and is a key techno-economic risk when connecting smaller WEC units. For this assessment, the sub-system's cost is neglected because AWS's primary approach is to address this challenge through its multi-absorber platform that enables an electrical infrastructure similar to offshore wind turbines.

The above values would not be achievable for a prototype system and assume a somewhat mature supply chain. Given our ability to tap into the existing supply chain, we believe these values can be attained at a production scale of 100 units.

Reference Model PTO Cost - As a point of comparison, the WEC Reference Model 3 cost[12] for the hydraulic PTO developed by Re Vision Consulting under contract to the US Department of Energy arrived at $1,443 per kW at a production scale of 100 units ($2013). The PPI for generators and motors increased only slightly between 2013 and our 2020 reference year by 8.5%, leading to a reference cost value of $1,566/kW. However, between 2020 and 2024, we saw an increase in that PPI of 43%. It is unclear how much this trend will reverse over the coming years. Increasing automation in manufacturing processes can significantly reduce these costs as increasing robotic automation occurs despite increasing labor costs. The RM3 topology is similar to the Waveswing topology in the prototype device. In retrospect, this estimate likely did not include sufficient contingencies for mechanical support systems such as linear bearings and other items.

RPA PTO Cost – A detailed PTO design effort for this system was beyond our current scope of work. The RPA has a more complex PTO system than the AWS machine and needs to includes the following additional sub-systems:

1. A tidal compensation system that allows the system to adjust its position in the water column optimally. This is envisioned as a slowly adjusting winch mechanism, similar to the AWS machine.
2. A negative spring-system mechanism that reduces the hydrostatic spring stiffness of the point absorber, resulting in a broad resonance bandwidth and enabling optimal power capture without any reactive power in the powertrain. This can be achieved with pneumatic springs that are geometrically aligned in a manner that allows it to offset the absorber buoys hydrostatic spring stiffness.
3. A pneumatic force compensation system that ensures that the system is immersed at 50% and enables the operation of the PTO in two directions. It leverages a large gas-spring system always to keep the mooring system under tension.

We performed some rudimentary scaling of these gas-spring components and ended up accounting for the cost of these sub-systems by doubling the cost of the low-speed primary power conversion stage in our parametric techno-economic model.

[12] Previsic, M. Reference Model 3 LCoE Model, Developed under contract to the US Department of Energy, 2013

Generalized PTO Model—To generalize the PTO cost model, we separated it into 4 stages that embody logical functionalities in the power conversion process. Values were normalized to $/kW to enable subsequent scaling.

Resonance Tuning Stage: This stage includes components that enable the machine's resonance tuning. For the AWS machine, this consists only of a rolling seal assembly. For the RPA, this includes the pneumatic spring required to keep the system operating at pre-tension and the pneumatic springs required to enable spring-stiffness compensation. Because design efforts for the resonance tuning stage for the RPA machine were beyond the scope of this study, we assumed it would double the low-speed stage of the powertrain.

Low-Speed Stage: The low-speed stage of the powertrain converts the low-speed linear motion to the high-speed rotational motion of the generator. For the Waveswing, that includes linear motion guides and a hydraulic power conversion system. The RPA device includes linear motion guides and a rack-and-pinion system.

High-Speed Stage: The high-speed stage includes the electric generator, the power converter, and short-term energy storage to absorb power peaks.

Grid Integration: This includes a step-up transformer and electrical isolation equipment.

Table 13 - WEC PTO Cost Comparison Summary ($/rated electrical output kW)

	Power Conversion Stage				
	Resonance Tuning	Low-Speed	High-Speed	Grid Integration	**Total**
Waveswing	$ 265	$ 1,040	$ 586	$ 60	**$ 1,951**
Active Point Aborber	$ 1,034	$ 1,034	$ 586	$ 60	**$ 2,714**
Passive Point Absorber	$ -	$ 1,560	$ 586	$ 60	**$ 2,206**
Direct-Drive Analogue	$ -	$ 1,034	$ 586	$ 60	**$ 1,680**
MW Class Wind Turbine	$ -	$ 324	$ 94	$ 60	**$ 478**

1.1.3 Mooring, Foundation, and Sub-Structure

The mooring system of the Waveswing consists of a single taught leg. Because of the large underwater volume, mooring forces are significant. The system consists of (1) A high-capacity tether, (2) a winch system to control submersion depth, and (3) a high-capacity uplift plate anchor.

Anchor. High-capacity embedment plate anchors are well understood from offshore oil & gas and offshore wind. Typical anchoring efficacies are on the order of 25 for large-capacity plate embedment anchors installed in clay. That means that for each ton of steel in the embedment plate, we get 25 tons of anchor holding capacity (depending on soil and embedment depth). A common type of anchor in this class is the suction embedment plate anchor (SEPLA), where the plate is driven into the ground using the suction pressure of a large diameter follower pile. Once the plate is at the target embedment depth, the follower is removed and rotated in the soil (keyed) to establish its vertical holding capacity. Due to the large forces required to key the anchor, these systems are typically limited to a holding capacity of < 700t due to the limitations of the anchor handling vessel to exert the required forces to key the plate.

Table 14 - SEPLA Anchor Cost (excluding install)

Design Load (incl. factor of safety)	12.5MN
SEPLA Weight to Capacity Ratio	1:25

Anchor Steel Weight	50.1 t
Anchor Cost (1-unit)	$5k/t
Learning Rate	0.95
Anchor Cost (100-Units)	$3,546/t

Tether. The vertical tether is assumed to be a steel cable with suitable coatings and protective layers for costing purposes. The reference design cost for the WaveSwing is listed below.

Table 15 - Tether Cost (excluding install)

Design Load (incl. factor of safety)	12.5MN
Tether Weight	56t
Mooring Line Cost (1-unit)	$6k/t
Learning Rate	0.95
Mooring Line Cost (100-units)	$4,255/t

Winch System. The winch system used to control the depth of the machine will require a high-force, low-speed system. A slow-moving hydraulic winch system would be well-suited for this. AWS has developed concept designs for such a system, but these were insufficiently detailed to perform a detailed cost analysis. To account for this sub-system (present in the RPA and AWS system), we decided to include a multiplier of 1.5 in the tether cost. This correlated well with an in-house concept design for a similar system, but significant uncertainties remain.

1.2.6.1 Assembly & Installation

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

Assembly: Assembly and pre-deployment testing will be carried out at the factory. This process includes (1) PTO assembly and testing, (2) Sub-system integration into the main hull, and (3) testing before shipping. The total cost for these activities is estimated at 10% of the device's CAPEX.

Anchor Installation: Our analysis assumed an AHATS DP-2 class vessel would be mobilized from the Gulf of Mexico region and used for the mooring installation in the Pacific Northwest. The same mobilization assumption was used for all wave climates considered. The SEPLA installation process cost is dominated by the ship time required for the embedment process. We assumed that the maximum capacity per anchor is limited to 500t of force to stay well within vessel limits to key the system and be able to choose among a larger pool of available AHATS vessels.

Device Installation: The device would be connected to its mooring system and commissioned using the same workboat/custom service vessel that will be used for O&M activities. At the reference 100MW farm scale, it is likely that such a vessel would be custom-built and O&M activities of the WEC technology. This will likely be a small catamaran with DP-2 thrusters enabling efficient operation.

Subsea Cable Installation: A cable installation vessel and support tug boats will need to be mobilized to the deployment site for these activities.

It should be noted that design refinements around the electrical infrastructure and moorings should enable most repairs to be carried out from a small custom-built catamaran adapted for mooring installation and device deployment/repair. These are aspects that are beyond the current scope of work.

2.2 Maintenance

Maintenance costs include marine operations, repair labor, and replacement parts.

Marine Operations: Under contract to Wave Energy Scottland (WES), AWS developed a detailed marine operational model that compared its multi-unit platform O&M cost to O&M activities carried out on a single unit (baseline).

The baseline model assumes an annual retrieval and re-deployment cycle every year. Maintenance would be carried out at dockside in protected waters. Every 10-years the device would have to be recovered to shore for a more extensive overhaul. An AHATS class vessel would be utilized for these marine operations with a day-rate of £25k.

The model for the multi-absorber platform would enable most O&M activities to be carried out onboard the WEC, and personnel would be shuttled between shore and the deployment site using a crew boat. This addresses two main core issues: (1) accessing a set of shared equipment in a common space significantly reduces time spent on O&M activities, and (2) the stability of a stable offshore structure, enables on-site maintenance.

The results showed that the multi-absorber platform would reduce O&M costs from £53,044 ($63,652) to £18,830 ($22,596) per device and year. We used these numbers as inputs to our costing model. At a 100MW scale, these annual costs would represent a reduction from $183/kW-yr to about $53/kW-yr for the AWS machine. We used the same model for the point absorber, although this system does not benefit from the multi-absorber economies of scale.

Additional cost reductions could be achieved through automation and leveraging unmanned vehicle technologies. Specifically, this would include:

1. The current model for the single-unit deployment/recovery process is conservative and assumes the use of an AHATS class vessel. The experience by Pelamis showed that if the mooring and electrical interfaces are properly designed, a much smaller (and cheaper) vessel could be utilized. A small multi-cat could serve that purpose and reduce the day rate from about $30k to < $10k.
2. Outside visual inspection tasks include the hull, the rolling seal, the depth-control winch, the tether to the seabed, and the riser cable. Currently, such operations are performed using ROVs, which require a vessel to operate from and an operator/pilot. This type of operation could be automated using a small AUV.
3. Above-water visual inspection can be done from a drone using a combination of Lidar and cameras.
4. Outside cleaning of biofouling. Especially around the rolling seal and any other moving assemblies. Several methods can be adapted from the shipping industry, including (1) cleaning using ROV's that utilize high-pressure water jets or rotating brushes, (2) laser radiation to damage the cell of micro-

organisms without damaging the hull coating, and (3) recovery of the equipment and pressure wash and re-coat the hull. To the greatest extent possible, autonomous technology should be utilized to minimize the costs of these activities. A hull-cleaning ROV asset could be operated from an autonomous USV that would provide the power for the cleaning process and enable remote access to an operator on shore.
5. Inside inspection tasks, including PTO system, water ingress, linear guides and bearings, sensors, hydraulic components, and electrical components. A small crawler-type robot could remotely inspect sub-systems and components inside the hull. This crawler could attach with magnets to the hull and provide a great level of visual access. Additional sensor suites could be utilized to enable inspection tasks such as ultrasonic, laser, and vibration.

The objective would be to leverage robotic and remote interventions to the extent possible to identify issues fully and early on. This will enable precise targeting of intervention cycles. It will also allow early identification of problems, which can be addressed during regular maintenance cycles and enable much more frequent monitoring and inspection.

Finally, there is an opportunity to extend intervention intervals. Re-Vision has worked on tidal projects with feasible design targets for 4-year O&M intervention cycles (reduced from annual), and Meygen actually achieved 7 years of operation without intervention. It is also worth noting that CorPower assumes a 5-year intervention cycle once the technology is mature with minimal repair costs due to failures. Our baseline case assumes an annual intervention cycle.

Replacement Parts: Subsystems were assigned a failure rate based on some common assumptions. This allowed us to compute an annual replacement part cost based on their CAPEX. The following failure rate assumptions were made.

Table 16 - MTBF Assumptions

SubSystem	MTBF
PTO	5%
Structural	2%
Mooring	2%
Electrical	2%

Comparison to Wind: It is interesting to note that O&M costs account for about a third of the lifecycle cost of wind farms[13]. Onshore wind has an annual O&M cost range of $15 - $27 per kW, while offshore wind farms have a range of $40 - $60 per kW. It is interesting to note that the O&M estimates for AWS's multi-absorber platform are within the range of current offshore wind O&M costs.

Economic Model

The economic model used a Utility Generator (UG) methodology with a fixed charge rate of 7%. This is the default assumption DoE makes for technology comparisons, but it is essential to understand that this rate

[13] Hammond, Rob and Aubryn Cooperman. 2022. Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT). Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-83712.

will be a function of project risks. For an early adopter of technology, these rates are likely much higher. Sensitivity studies carried out do capture the impact of these rates.

7.1.4 LCoE Baseline Assessment of Waveswing

LCoE for the Waveswing device was baseline on a 100MW WEC array deployed off the Oregon coast. The assessment starts by optimizing machine dimensions and machine capacity factor by minimizing LCoE. Sensitivity studies are carried out to identify key cost drivers and subsequently are brought together in a cost-reduction pathway that shows the impact of different cost-reduction measures on an optimized system.

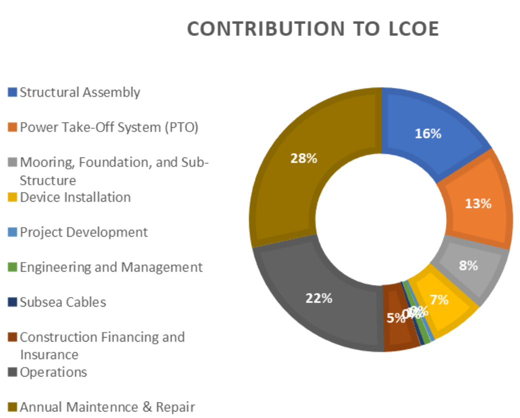
Table 17 - Wave Farm Specifications

Wave Resource			
	Reference Location	Oregon PacWave	
	Average Te	9.7	s
	Average Hs	2.4	m
	Average Power Density	37.5	kW/m
Wave Farm			
	# of WECs	272	
	Farm Rated Capacity	100	MW
	Water Depth	60	m
	Transmission Distance	5000	m
WEC Specifications			
	Diameter	12	m
	Active Stroke	5	m
	Max Volume	1572	m^3
	Structural Steel Weight	407	tonnes
	Structural Efficiency	259	kg/m^3
Device Performance			
	Rated Power	368	kW
	Capacity Factor	60%	
	Availability	95%	
	PTO Efficiency	80%	
	Transmission Efficiency	98%	
	Average Absorbed Power	299	kW
	Average Electric Power	221	kW
	Annual Electric Energy	1801	MWh/year
	# of US Households	110	
	P/V Actual	0.53	kW/m^3
	P/V Theoretical Limit	0.81	kW/m^3
Economic Inputs			
	Fixed Charge Rate	7%	
	Construction Financing Rate	8%	
	Insurance Rate	2%	of Capex / year
	O&M	2.9%	of Capex / year

The Cost Breakdown Structure (CBS) was computed based on the parametric cost model described in earlier sections. The following table shows the projected CBS breakdown.

Table 18 - CBS for Baseline AWS Wave Farm at 100MW scale

		Cost			Economics		
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total
1.1	**Marine Energy Converter (MEC)**	**$ 731,338,954**	**$ 2,689,788**	**$ 7,313**	**$ 105**	**$ 1**	**34%**
1.1.1	Structural Assembly	$ 318,450,849	$ 1,171,229	$ 3,185	$ 46	28%	15%
1.1.2	Power Take-Off System (PTO)	$ 257,020,820	$ 945,296	$ 2,570	$ 37	23%	12%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 155,867,284	$ 573,264	$ 1,559	$ 22	14%	7%
1.2	**Balance of System (BOS)**	**$ 172,751,788**	**$ 635,363**	**$ 1,728**	**$ 44**	**15%**	**14%**
1.2.1	Project Development	$ 9,769,692	$ 35,932	$ 98	$ 1	1%	0%
1.2.2	Engineering and Management	$ 17,727,269	$ 65,199	$ 177	$ 3	2%	1%
1.2.3	Electrical Infrastructure	$ 9,228,751	$ 33,942	$ 92	$ 1	1%	0%
1.2.6	Assembly & Installation	$ 136,026,076	$ 500,290	$ 1,360	$ 19	12%	6%
1.2.6.1	*Device*	$ 117,143,404	$ 430,841	$ 1,171	$ 17	10%	5%
1.2.6.2	*Subsea Cables*	$ 18,882,672	$ 69,448	$ 189	$ 3	2%	1%
1.3	**Financial Costs**	**$ 90,409,074**	**$ 332,515**	**$ 904**	**$ 13**	**8%**	**4%**
1.3.2	Insurance During Construction	$ 18,081,815	$ 66,503	$ 181	$ 3	2%	1%
1.3.3	Construction Financing Costs	$ 72,327,259	$ 266,012	$ 723	$ 10	6%	3%
Total CAPEX		**$ 1,393,686,754**	**$ 5,125,834**	**$ 9,945**	**$ 162**	**88%**	**53%**
		Cost			Economics		
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total
2.1	**Operations**	**$ 30,640,769**	**$ 112,694**	**$ 227**	**$ 63**	**43%**	**20%**
2.1.1	Environmental Monitoring	$ 2,767,034	$ 10,177	$ 28	$ 6	4%	2%
2.1.3	Insurance	$ 27,873,735	$ 102,517	$ 199	$ 57	40%	19%
2.2	**Maintenance**	**$ 39,828,617**	**$ 146,485**	**$ 398**	**$ 81**	**57%**	**27%**
Total OPEX		**$ 70,469,386**	**$ 259,179**	**$ 625**	**$ 144**	**100%**	**47%**
$/MWh					**$ 306**		



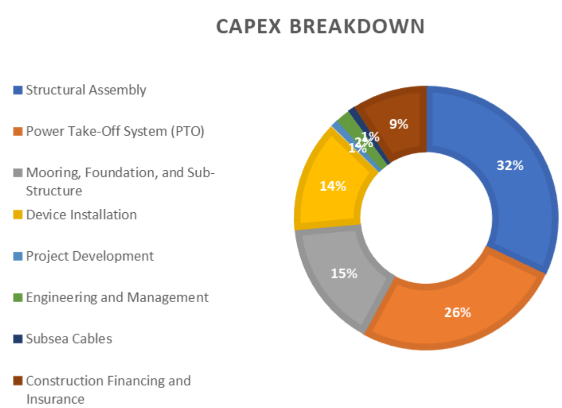


Figure 13 – LcoE and CAPEX among major categories for 100MW plant

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:

- Device Active Volume
- Device Passive Volume
- Wave Power Absorption
- Design Pressure of the Absorber

- Plant Scale
- Machine Capacity Factor
- Fixed Charge Rate
- PTO Power Conversion Efficiency
- Plant Availability
- Wave Resource Location
- Plant Availability
- Structural Cost
- PTO Cost
- Mooring Cost
- Installation Cost
- O&M Cost
- Insurance Cost
- Plant Efficiency
- Deployment Location

Device Active Volume—The Waveswing is an effective absorber that operates at an average of 60%- 70% of the theoretical upper limits for a point absorber as computed by the point absorber and volumetric limits. In general, smaller devices produce more power per unit of active volume than larger devices because theoretical limits start to impede power production. This means that scalability has its limits from a techno-economic perspective. The following plot shows the annual average power produced from each m^3 of active device volume, comparing the theoretical upper limit of a heaving point absorber against the AWS machine and a point absorber with a power take-off adjusted on a sea-state by sea-state basis only. It shows diminishing productivity with increasing absorber volume, which makes larger devices less attractive from an economic point of view.

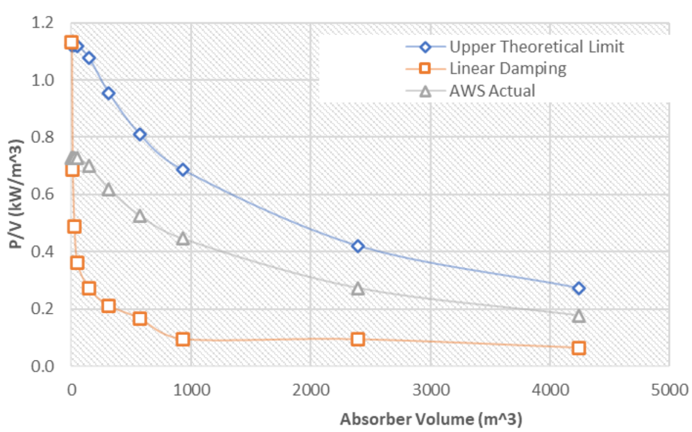


Figure 14 - Power production comparison

An economically optimal size is found with an active volume of about 475m^3.

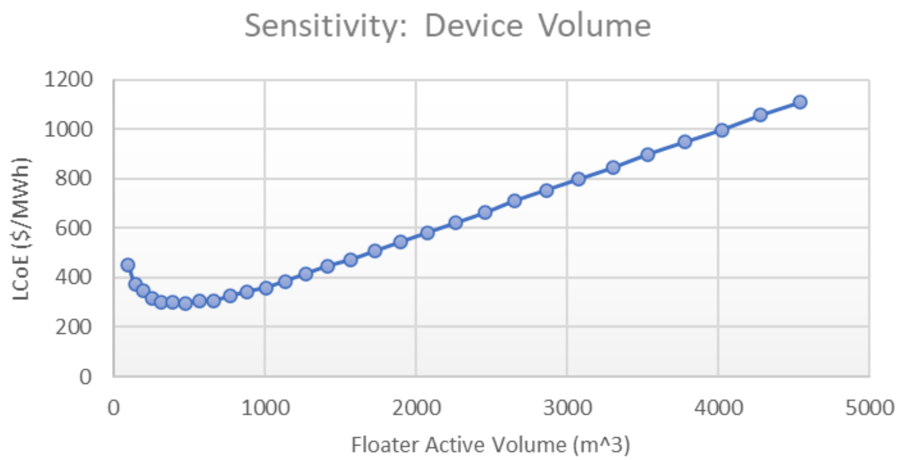


Figure 15 – LcoE vs. device active volume

450m^3 of active absorber volume represents an active floater with a stroke of 5m and a diameter of 11m. Smaller sizes are un-economic (despite improved relative power production) due to the fixed cost for each unit deployed.

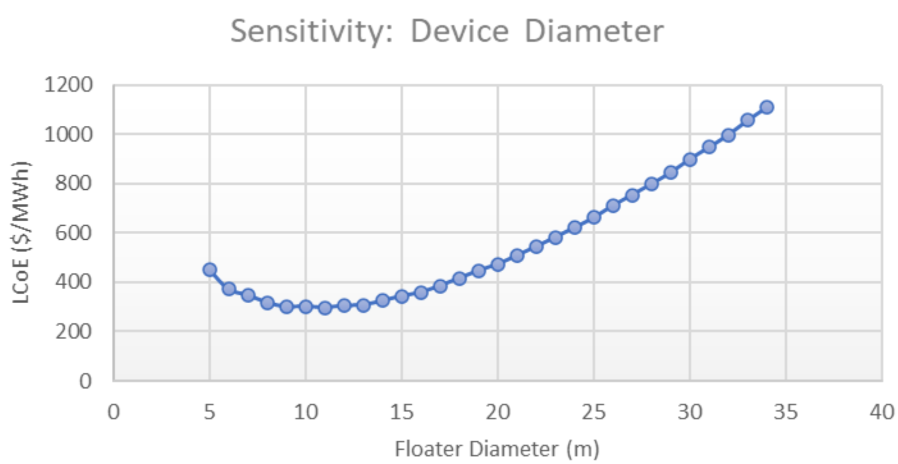


Figure 16 - Floater diameter vs. LCoE using a fixed stroke of 5m.

To enable a low-enough spring stiffness in the absorber and enable resonance across a broad bandwidth, additional volume is required in the absorber that is passive. The baseline design had an active-to-passive volume ratio of 1:1.78. This passive volume has an impact on device structural cost as well as mooring costs, as it increases the mooring forces required to submerse that volume.

A comparison of peak forces acting on the PTO with the maximum buoyancy forces shows that the buoyancy forces are about 5x higher than the PTO forces. This means that we could aim to reduce entrained volume by a factor of 5x. The following trade-off shows the trade-off between the passive volume multiplier and LCoE.

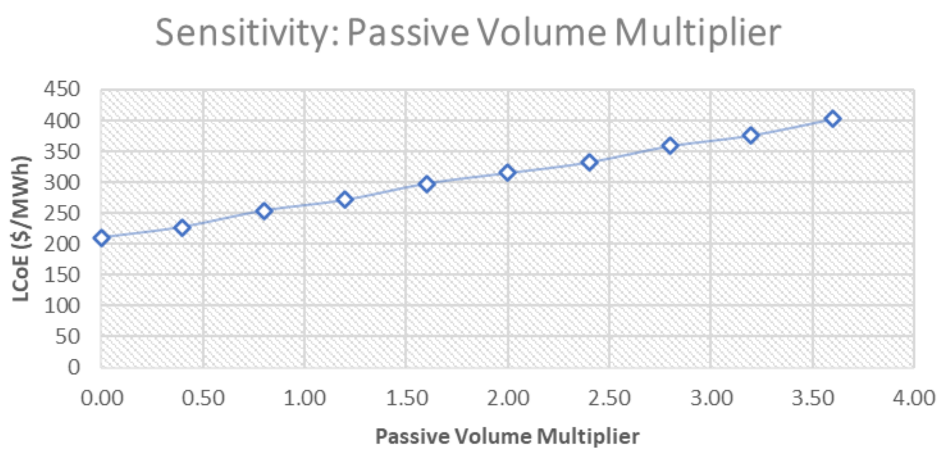


Figure 17 - Passive Volume Multiplier vs. LCoE.

Wave Power Absorption Efficiency - Currently, the Waveswing in average absorbs 65% of its theoretical potential given by point absorber and volumetric limits. Active control such as MPC using feed-forward control, leveraging a deterministic sea wave prediction system (DSWP), could further improve WEC power production. We would consider 85% as a useful target for active control that could reduce LCoE.

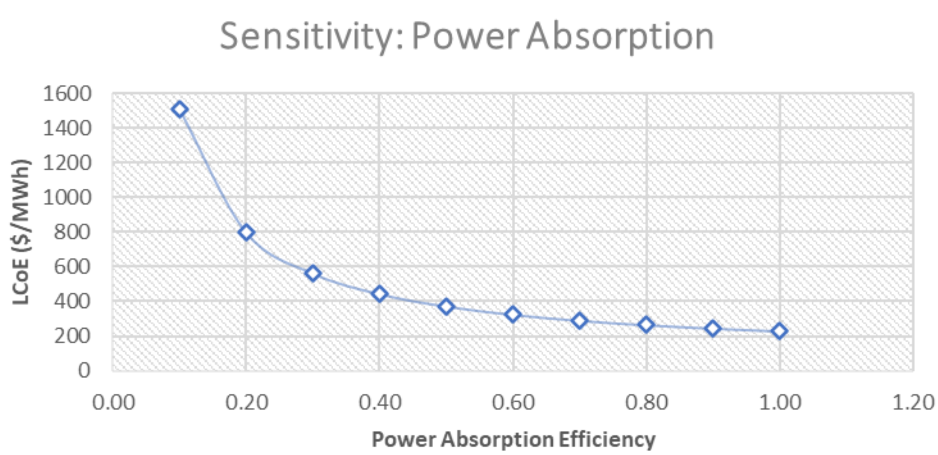


Figure 18 - LCoE vs power absorption efficiency

Plant Scale - A second key consideration is the plant scale. To run this study, we used the LCoE optimized device dimension to identify and scale the plant by increasing the number of machines in the wave farm. At the plant level, economy of scale is driven by shared infrastructure components such as subsea cables, O&M vessel costs, and installation vessel mobilization costs. Larger plant scales also benefit from lower system costs due to the learning rates embedded in volume manufacturing.

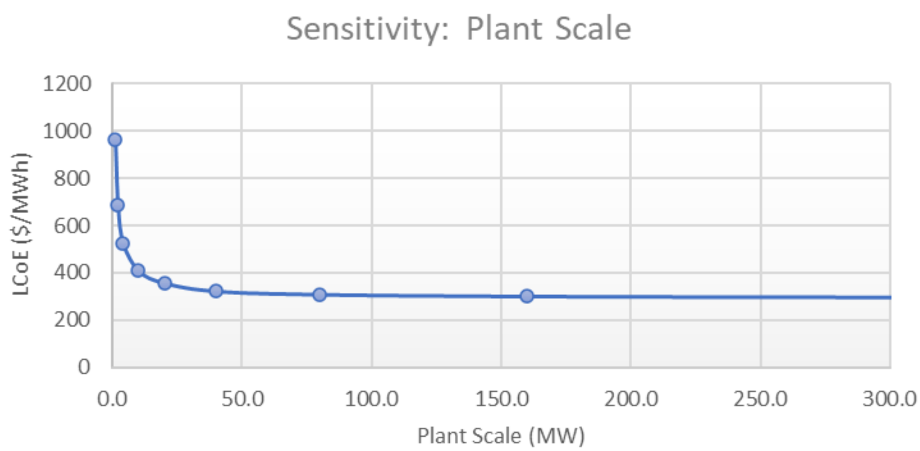


Figure 19 - LCoE Sensitivity to Plant Scale

Capacity Factor - The capacity factor is an indirect metric representing this powertrain's average utilization. An optimum economic rating will weigh the powertrain cost against the other costs in the plant. As shown below, optimal economics is achieved at a capacity factor of about 60%.

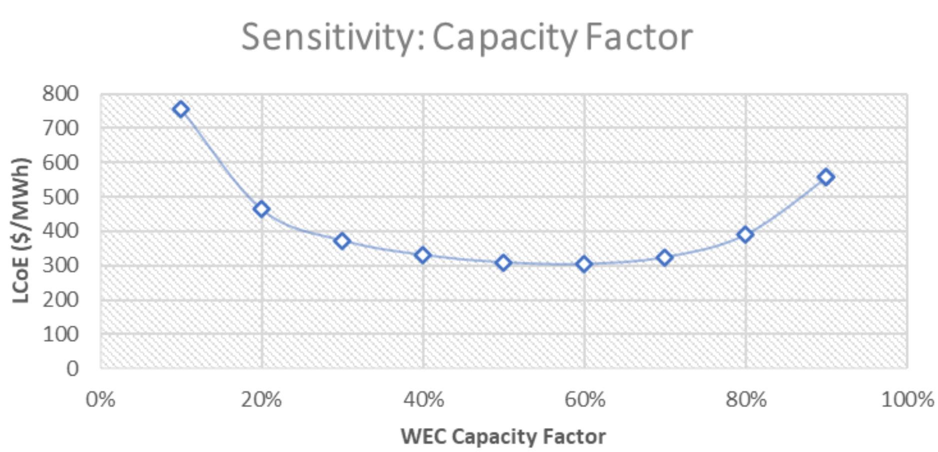


Figure 20 - LCoE Sensitivity to Capacity Factor

PTO Efficiency and Plant Availability—Other performance-related parameters that have a critical impact on LCoE include the PTO power conversion efficiency and plant availability, or its related parameter, the average plant downtime, which is related to reliability.

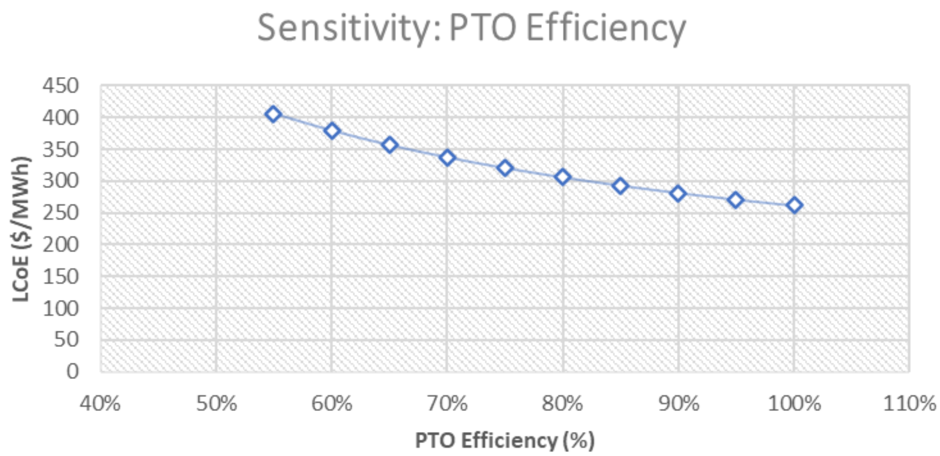


Figure 21 – LcoE Sensitivity to PTO Efficiency

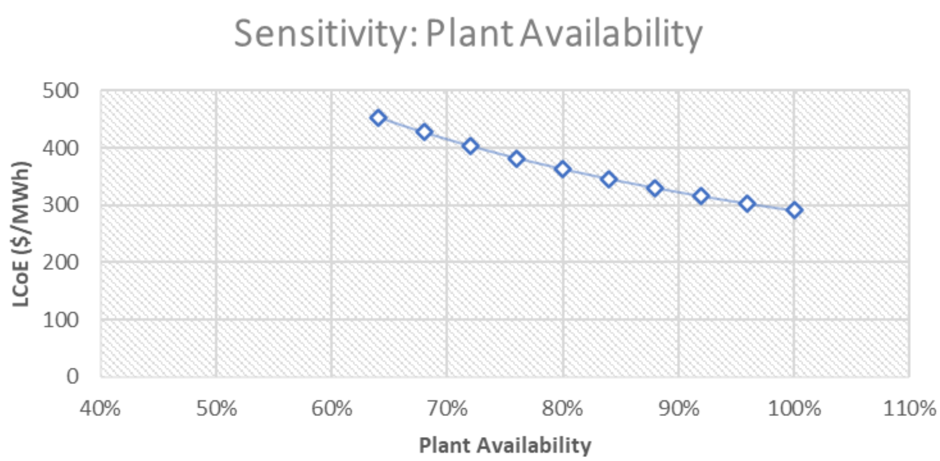


Figure 22 – LcoE Sensitivity to Plant Availability

Wave Resource—The wave energy resource strongly affects the amount of energy captured and, hence, the related LCoE. Only the wave resource is varied for this trade off. The following plot compares five different locations.

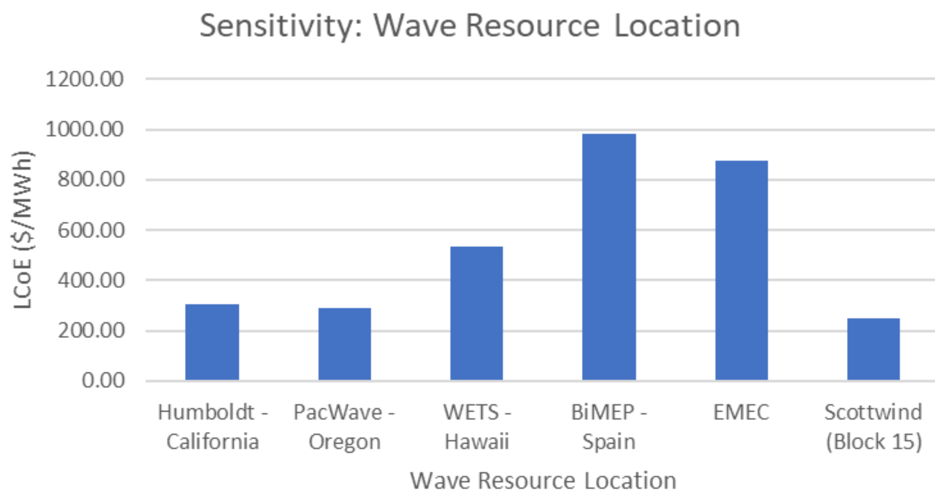


Figure 23 - LCoE Sensitivity to Wave Energy Resource

Steel Manufacturing Cost—Not surprisingly, WEC economics is very sensitive to the device's structural cost. Our current baseline utilizes a US-based steel manufacturing cost model, which projects $2879/t at a 100-unit production volume. However, the automation of manufacturing processes and/or the utilization of low-cost manufacturing locations (i.e., China) could significantly reduce that cost. A cost-reduction potential of 50% should be attainable, and we obtained quotes for barges in China for less than $ 1,400/t.

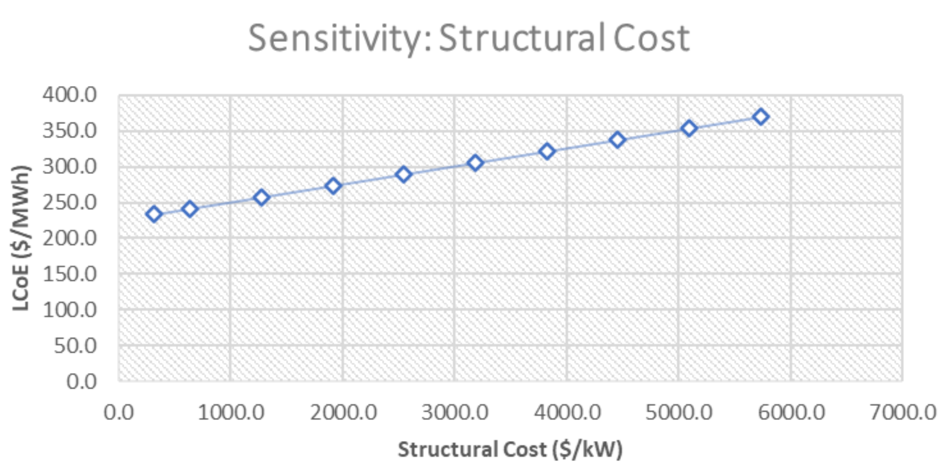


Figure 24 - LCoE vs. Structural Steel Mfg Cost

PTO Cost—The baseline PTO cost at a manufacturing volume of 100 units is projected to be $2,570/kW. This cost includes a low-speed hydraulic stage, a high-speed electric stage, power electronics to provide grid-compliant power, a riser cable, and a variable-depth winch system.

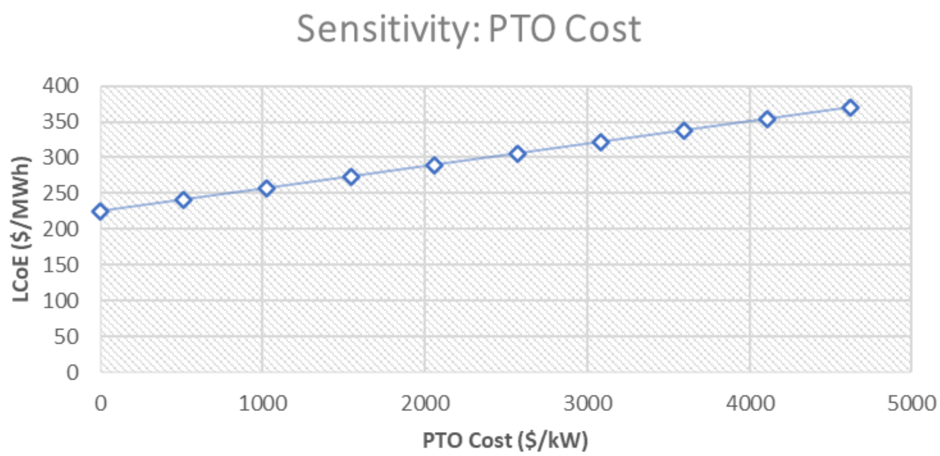
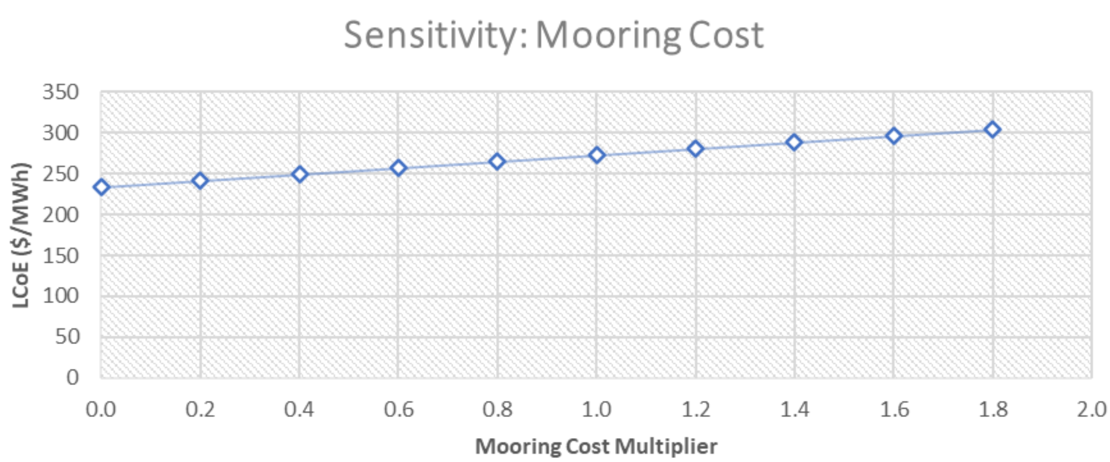


Figure 25 - LCoE Sensitivity to PTO Capex

Mooring Cost – The mooring includes a suction embedment plate anchor (SEPLA) and a vertical tether connecting the anchor to the device hull over a winch system. This cost-center excludes the installation activities.



O&M, Installation, and Insurance Cost - Other key cost drivers affecting the LCoE include the installation, O&M, and insurance rates. The installation cost baseline was explicitly computed for this device and includes assumptions on equipment day rates and installation process timelines. Given the early-stage nature of the current design, O&M and insurance costs were estimated parametrically.

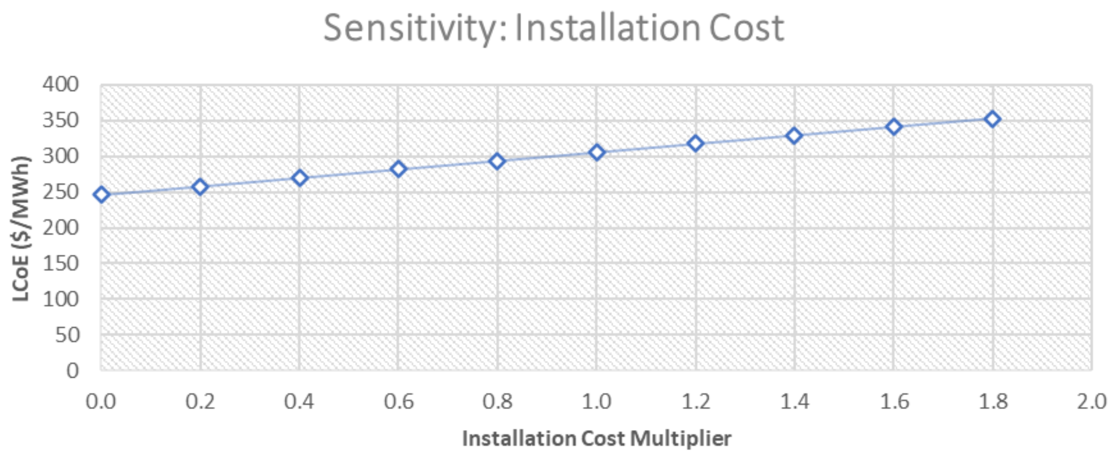


Figure 26 - LCoE Sensitivity to Installation Cost

Significant uncertainties remain in respect to O&M. The baseline assumes an annual recovery/redeployment of the device using an AHATS class vessel with a day-rate of about $30k. We also assume failure rates consistent with building the first 100MW plant. Going from an AHATS class vessel to a smaller multi-cat could reduce marine operational cost by a factor of 4 and intervention cycles could be pushed to 5-years.

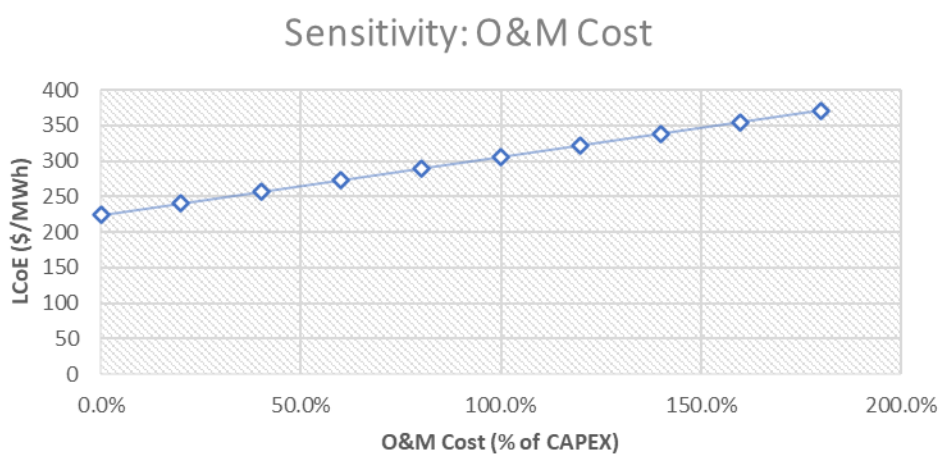


Figure 27 - LCoE Sensitivity to O&M Cost

The baseline insurance rate is assumed to be 2% of Capex. This is consistent with large offshore projects. Prototype systems have seen insurance rates of > 6%, while mature commercial wind and solar projects have insurance rates of < 0.5%.

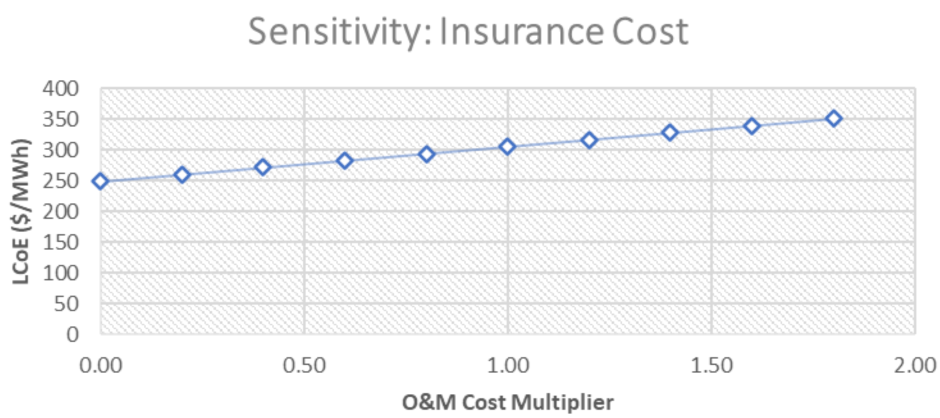


Figure 28 - LCoE Sensitivity to Insurance Cost

Fixed Charge Rate - The fixed charge rate (FCR) in utility economic models represents a version of the weighted average cost of capital, including ROI on debt and equity of the project, as well as tax rates. It allows us to annualize the plant Capex. The Reference Model Efforts by the US Department of Energy assumed a fixed FCR of 7% which is consistent with how the DoE assesses its entire portfolio of generation technologies. It is important, however, to point out that this rate is a direct function of the perceived overall risks of the project. The first plants will likely have much higher rates with rates likely being on the order of 10%-12%. The following plot shows the sensitivity of FCR to LCoE for the baseline plant.

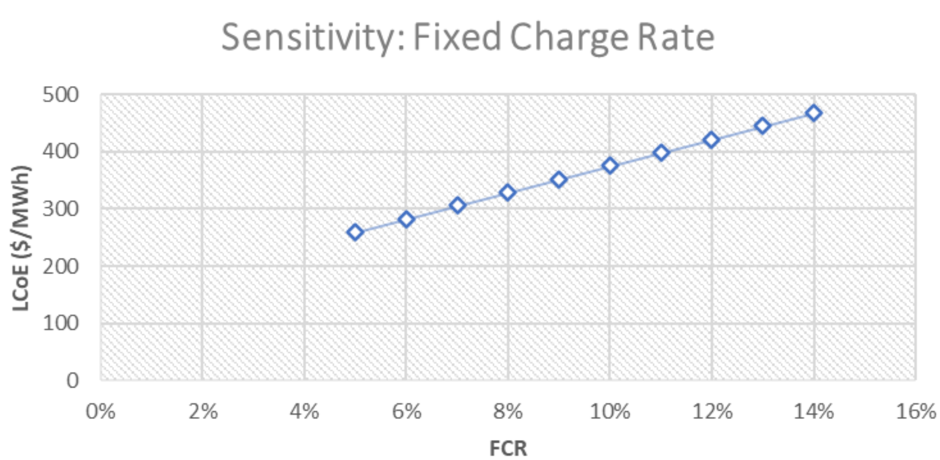


Figure 29 - LCoE Sensitivity to Fixed Charge Rate

7.1.5 Waveswing Cost Reduction Pathways

A key benefit of a macroeconomic study such as this one is to combine the critical cost-reduction pathways and develop a high-level strategy that can lead to an improved device envelope. The key question to be answered is: what LCoE level could be achieved if we successfully commercialize the technology and implement key cost-reduction measures? In the technology development process, we would envision the following measures to improve techno-economic viability:

1. *Combine multiple absorbers into a single platform:* This would provide a number of benefits, including improved accessibility during winter months, enabling maintenance activities to be carried out onboard the platform – reducing marine operational costs, and reducing subsea cabling complexity and cost.
   Proposed R&D: Concept-level design and subscale validation of motions and loads.

2. *Reduce absorber volume:* Reduce the total volume of the absorber structure through a combination of shape optimization and spring-stiffness adaptation. Initial assessments suggest a volume reduction potential of 2-5 is attainable using different approaches. For modeling purposes, a reduction of 2x is assumed.
   Proposed R&D: Numerical trade-off studies combined with wave tank validation.

3. *Structural cost:* Serial production automation, such as robotic welding and modularization of absorber structures, could reduce the cost of manufactured steel by more than 50% over the current baseline. The equivalent level of cost reduction could be achieved by manufacturing the steel structures in a low-cost country such as China. There are additional opportunities to be explored by leveraging alternate materials such as concrete and FRP that could enable significant cost savings.
   Proposed R&D: Design for manufacturing including (1) investigation of alternate materials such as concrete and RFP, (2) design of process automation in mfg process.

4. *Performance Improvement:* Power capture is presently at 65% of the theoretical limit on average. This is achieved using a feedback control algorithm. A significant improvement is possible using MPC control and deterministic sea wave prediction (DSWP) to near its theoretical upper limits. A key advantage of the AWS approach is that these limits can be attained without having to rely on reactive power flows, which is inherently challenging (and costly) to implement. We assume an improvement to a conservative 85% over the baseline.
   Proposed R&D: Study application of MPC in the numerical domain. At-sea validation of DSWP and controls to retire implementation risks.

5. *O&M costs* can be reduced by a factor of 4 from about 4% of Capex per year to < 1% of Capex per year through (1) reducing operational interventions from 1x per year to 1x every 4 years, and (2) increased reliability in the powertrain, resulting in reduced replacement costs. Most of the improvements can be achieved by simply improving the reliability of the powertrain and increasing the intervention interval.

Proposed R&D: Detailed PTO design focusing on reducing intervention intervals and reliability—accelerated testing of critical components and sub-systems. Incrementally automating at-sea operational procedures to enable low-cost access arrangements.

6. *Insurance costs* can be lowered from 2% of Capex/yr to 0.5% of Capex/yr. This aligns with mature onshore wind or solar farms and requires mature technology with a proven track record. This is likely a function of the design maturity of components and subsystems and cumulative deployment experience that demonstrates reliability over several years.
   Proposed R&D: None. This reduction is a direct result of commercial maturity.

Table 19 - Cost Reduction Pathway

	LCoE	Relative Improvement
Baseline	306	
Multi-Absorber Platform	281	8%
Reduce Absorber Volume	233	17%
Manufacturing Innovation	192	18%
Optimal Control	167	13%
Reliability Improvement 4X	138	17%
Reduced Insurance Rates	113	18%

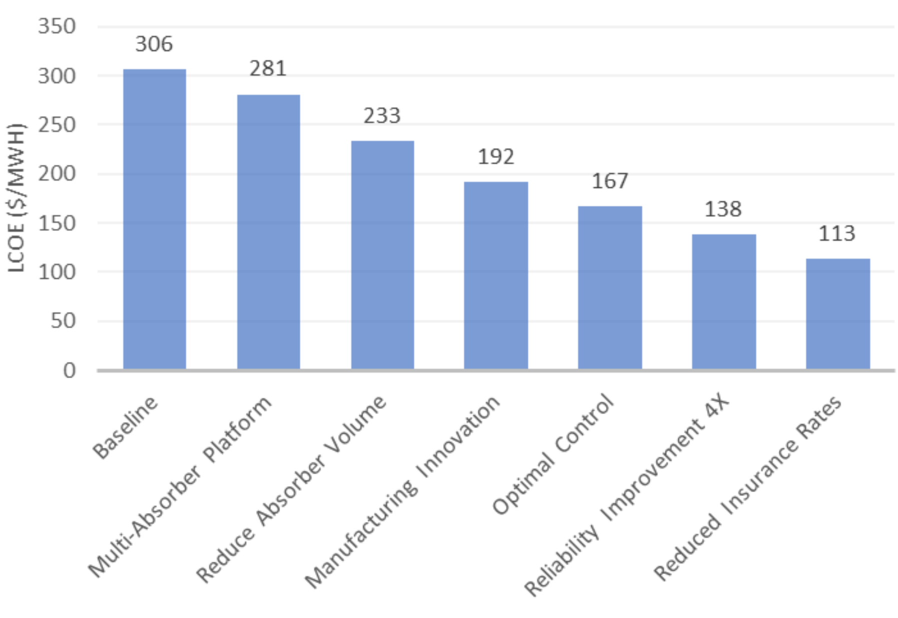


Figure 30 - Cost Reduction Pathway for AWS Waveswing

An optimized plant has a cost-breakdown structure that will look very different from the baseline. As shown below, the WEC device components comprise 68% of Capex and 54% of LCoE. Further design studies could enable potential cost-reduction pathways in the PTO design.

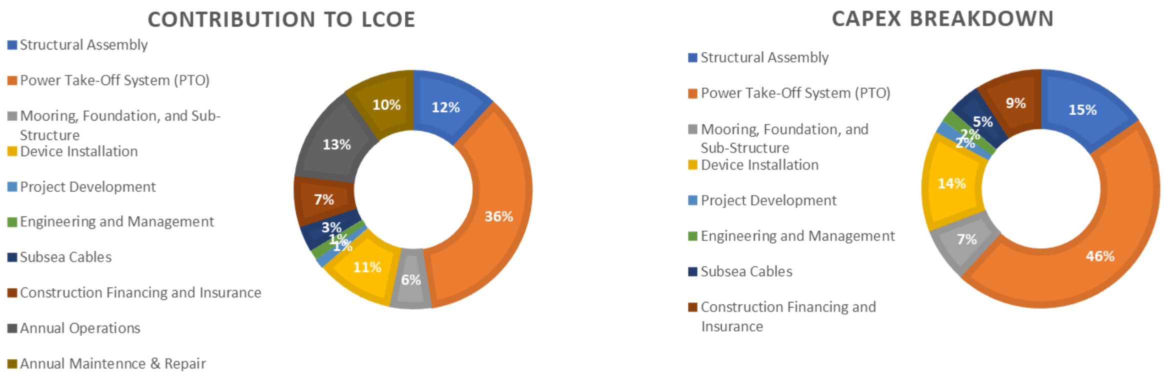


Figure 31 - LCoE and Capex Breakdown of Optimized 100MW Waveswing Plant.

7.1.6 LCoE Assessment of the Reference Point Absorber (RPA)

The following baseline outputs and trade-off studies were completed to provide an understanding of the impact different design decisions have on the LCoE. The following baseline study was carried out on a 100MW plant near shore with a wave energy resource near the PacWave site in Oregon. The device considered is a heaving point absorber assumed to achieve the theoretically possible power absorption computed from its active volume. It leverages a negative spring-stiffness compensation mechanism similar to the Corpower device combined with optimal feed-forward control such as MPC informed by a deterministic sea wave prediction system to achieve this.

The system must always provide excess buoyancy to remain upright and account for structural and PTO system weight. Fundamental scaling exercises performed by Re Vision showed that the active power-producing volume would be reduced by about 30% if these effects were accounted for. This effectively reduces the upper theoretical limit by 30% due to its passive volume.

To make the comparison fair, we assumed that using present-day feed-back control, the machine would produce 65% of its theoretical limit (using an on-board feedback controller), which would be raised to 85% of its limit using optimal MPC control. The cost-reduction pathway outlines the cost-reduction potential of these innovations.

It is essential to understand that this benchmarking baseline does not represent the actual CorPower machine design but is merely an exercise to identify upper techno-economic limits for a heaving point absorber with this topology. The two topologies ' cost functions were the same to enable an apples-to-apples comparison.

The assessment starts by optimizing machine dimensions and machine capacity factor by minimizing LCoE. Sensitivity studies are carried out to identify key cost drivers and subsequently are brought together in a cost-reduction pathway that shows the impact of different cost-reduction measures on an optimized system.

Table 20 - Wave Farm Specifications

Wave Resource			
	Reference Location	Oregon PacWave	
	Average Te	9.7	s
	Average Hs	2.4	m
	Average Power Density	37.5	kW/m
Wave Farm			
	# of WECs	491	
	Farm Rated Capacity	100.0	MW
	Water Depth	60	m
	Transmission Distance	5000	m
WEC Specifications			
	Diameter	11	m
	Buoy Height	3.3	m
	Volume	314	m^3
	Structural Steel Weight	54	tonnes
	Structural Efficiency	172	kg/m^3
Device Performance			
	Rated Power	204	kW
	Capacity Factor	60%	
	Availability	95%	
	PTO Efficiency	80%	
	Transmission Efficiency	98%	
	Average Absorbed Power	153	kW
	Average Electric Power	122	kW
	Annual Electric Energy	997	MWh/year
	# of US Households	94	
	P/V Actual	0.49	kW/m^3
	P/V Theoretical Limit		kW/m^3
Economic Inputs			
	Fixed Charge Rate	7%	
	Construction Financing Rate	8%	
	Insurance Rate	2%	of Capex / year
	O&M	4.7%	of Capex / year

The Cost Breakdown Structure (CBS) was computed based on the parametric cost model described in earlier sections. The following table shows the projected CBS breakdown.

Table 21 - CBS for Baseline RPA Wave Farm at 100MW scale

		Cost			Economics		
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total
1.1	**Marine Energy Converter (MEC)**	**$ 556,451,312**	**$ 1,133,622**	**$ 5,565**	**$ 80**	**71%**	**29%**
1.1.1	Structural Assembly	$ 76,130,056	$ 155,095	$ 761	$ 11	10%	4%
1.1.2	Power Take-Off System (PTO)	$ 366,525,052	$ 746,697	$ 3,665	$ 52	47%	19%
1.1.3	Mooring, Foundation, and Sub-Structure	$ 113,796,204	$ 231,830	$ 1,138	$ 16	14%	6%
1.2	**Balance of System (BOS)**	**$ 157,820,118**	**$ 321,517**	**$ 1,578**	**$ 23**	**20%**	**15%**
1.2.1	Project Development	$ 10,484,304	$ 21,359	$ 105	$ 1	1%	1%
1.2.2	Engineering and Management	$ 14,005,322	$ 28,532	$ 140	$ 2	2%	1%
1.2.3	Electrical Infrastructure	$ 9,228,751	$ 18,801	$ 92	$ 1	1%	0%
1.2.6	Assembly & Installation	$ 124,101,741	$ 252,824	$ 1,241	$ 18	16%	6%
1.2.6.1	*Device*	$ 92,610,341	$ 188,669	$ 926	$ 13	12%	5%
1.2.6.2	*Subsea Cables*	$ 31,491,400	$ 64,155	$ 315	$ 5	4%	2%
1.3	**Financial Costs**	**$ 71,427,143**	**$ 145,514**	**$ 714**	**$ 10**	**9%**	**4%**
1.3.2	Insurance During Construction	$ 14,285,429	$ 29,103	$ 143	$ 2	2%	1%
1.3.3	Construction Financing Costs	$ 57,141,714	$ 116,411	$ 571	$ 8	7%	3%
Total CAPEX		**$ 1,139,047,575**	**$ 2,320,507**	**$ 7,857**	**$ 112**	**100%**	**47%**
		Cost			**Economics**		
		$/Farm	$/WEC	$/kW	$/MWh	in %	in % Total
2.1	**Operations**	**$ 25,987,790**	**$ 52,943**	**$ 189**	**$ 53**	**32%**	**19%**
2.1.1	Environmental Monitoring	$ 3,206,839	$ 6,533	$ 32	$ 7	4%	2%
2.1.3	Insurance	$ 22,780,951	$ 46,410	$ 157	$ 47	28%	17%
2.2	**Maintenance**	**$ 53,998,924**	**$ 110,008**	**$ 540**	**$ 110**	**68%**	**40%**
Total OPEX		**$ 79,986,714**	**$ 162,952**	**$ 729**	**$ 163**	**100%**	**59%**
$/MWh					**$ 276**		

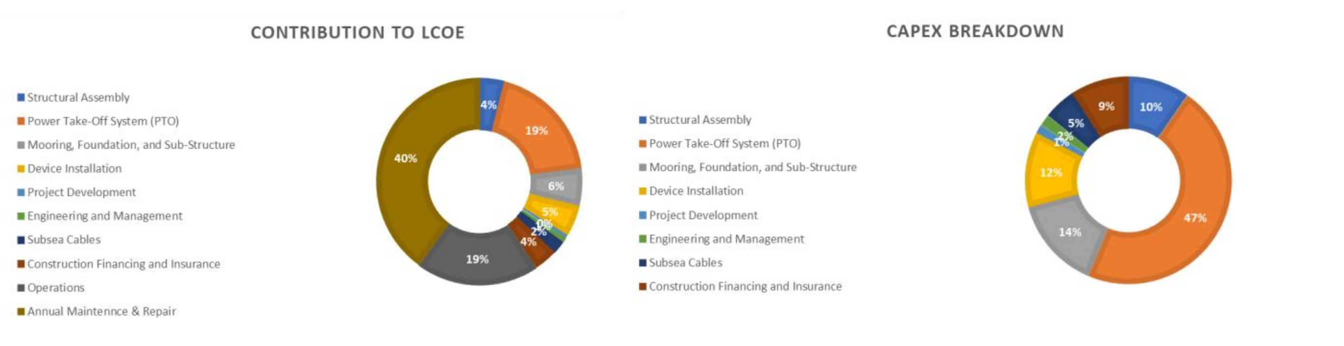


Figure 32 – LCoE and CAPEX among major categories for 100MW plant

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

- Device Active Volume
- Wave Power Absorption
- Design Pressure of the Absorber
- Plant Scale
- Machine Capacity Factor

- Fixed Charge Rate
- PTO Power Conversion Efficiency
- Plant Availability
- Wave Resource Location
- Plant Availability
- Structural Cost
- PTO Cost
- Mooring Cost
- Installation Cost
- O&M Cost
- Insurance Cost
- Plant Efficiency
- Deployment Location

Device Active Volume—The RPA is an effective absorber that operates at an average of 60%- 70% of the theoretical upper limits for a point absorber as computed by the point absorber and volumetric limits. Because of the PBAs pneumatic spring stiffness compensation, this can be achieved without having to resort to reactive powerflow, which is challenging to implement in practice. The baseline power aborption assumes that only feedback control is implemented. Further upside is expected with an MPC based control system, informed by a deterministic sea wave prediction system (DSWP).

In general, smaller devices produce more power per unit of active volume than larger devices because theoretical limits start to impede power production. This means that scalability has its limits from a techno-economic perspective. The following plot shows the annual average power produced from each m^3 of active device volume, comparing the theoretical upper limit of a heaving point absorber against the AWS machine and a point absorber with a power take-off adjusted on a sea-state by sea-state basis only. It shows diminishing productivity with increasing absorber volume, which makes larger devices less attractive from an economic point of view.

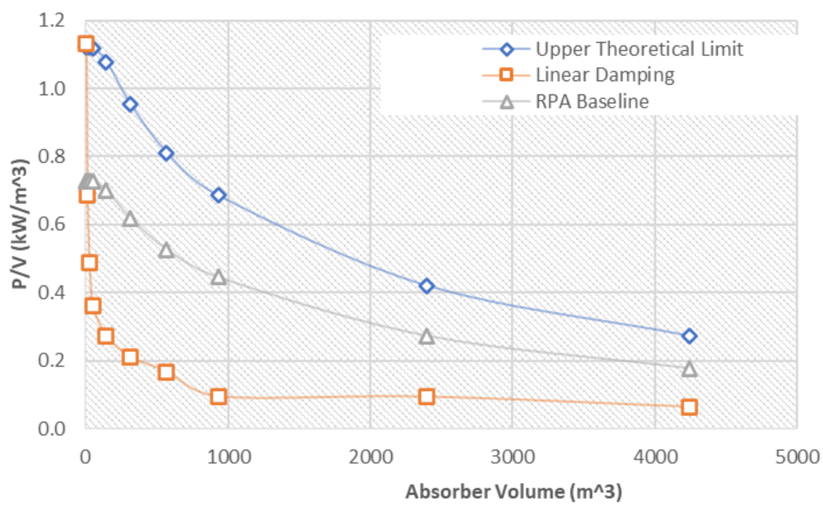


Figure 33 - Power production comparison

An economically optimal size is found with an active volume of about 310m^3. Smaller sizes are un-economic (despite improved relative power production) due to the fixed cost for each unit deployed. Larger units have reduced structural efficiency due to point absorber effects.

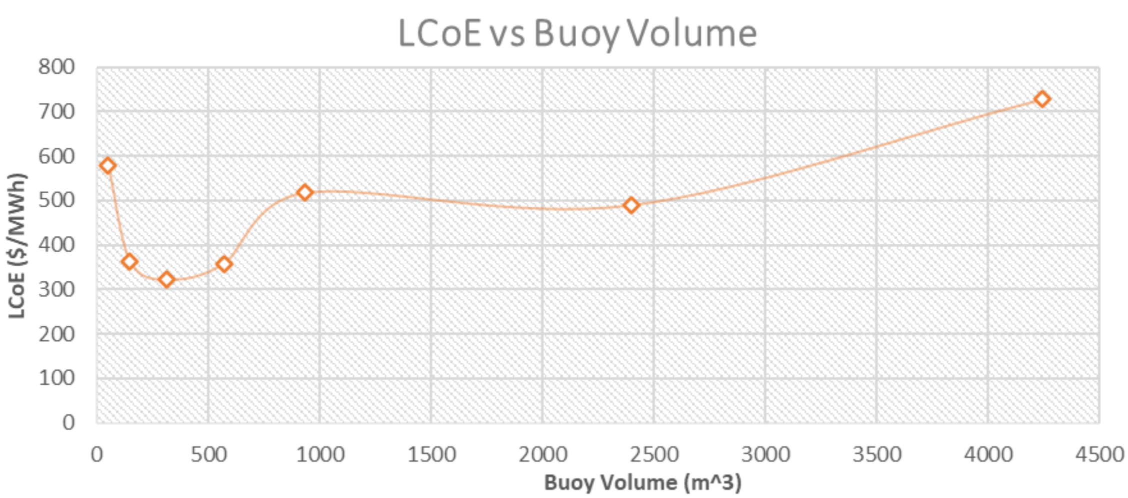


Figure 34 – LcoE vs. device active volume

Plant Scale - To run this study, we used the LCoE-optimized device dimension to identify and scale the plant by increasing the number of machines in the wave farm. At the plant level, the economy of scale is driven by shared infrastructure components such as subsea cables, O&M vessel costs, and installation vessel mobilization costs. Larger plant scales also benefit from lower system costs due to the learning rates embedded in volume manufacturing.

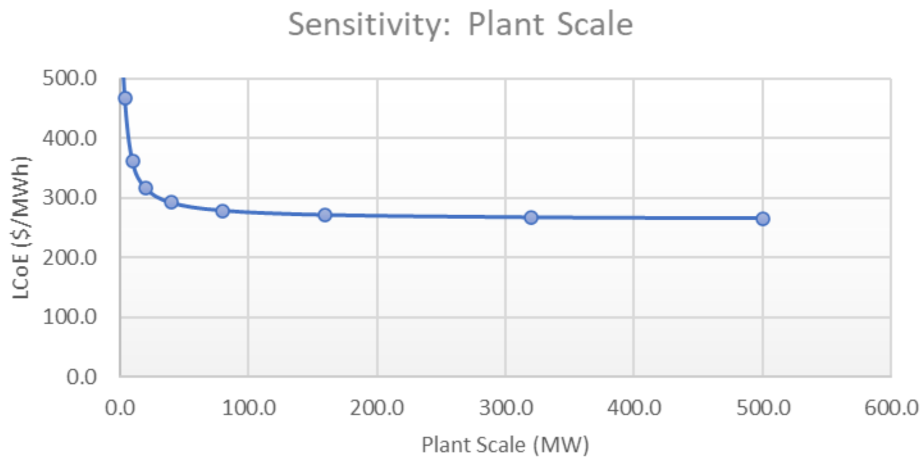


Figure 35 - LCoE Sensitivity to Plant Scale

Capacity Factor - The capacity factor is an indirect metric representing this powertrain's average utilization. An optimum economic rating will weigh the powertrain cost against the other costs in the plant. As shown below, optimal economics is achieved at a capacity factor of about 70%.

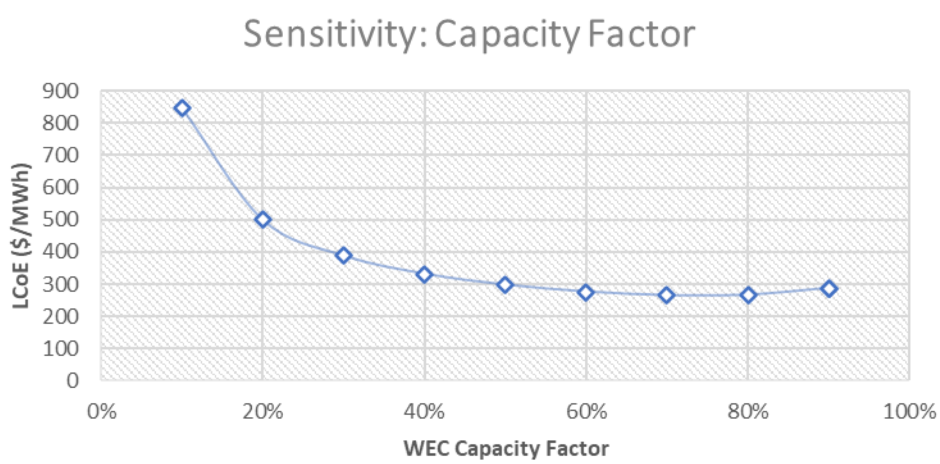


Figure 36 - LCoE Sensitivity to Capacity Factor

PTO Efficiency and Plant Availability—Other performance-related parameters that have a critical impact on LCoE include the PTO power conversion efficiency and plant availability, or its related parameter, the average plant downtime, which is related to reliability.

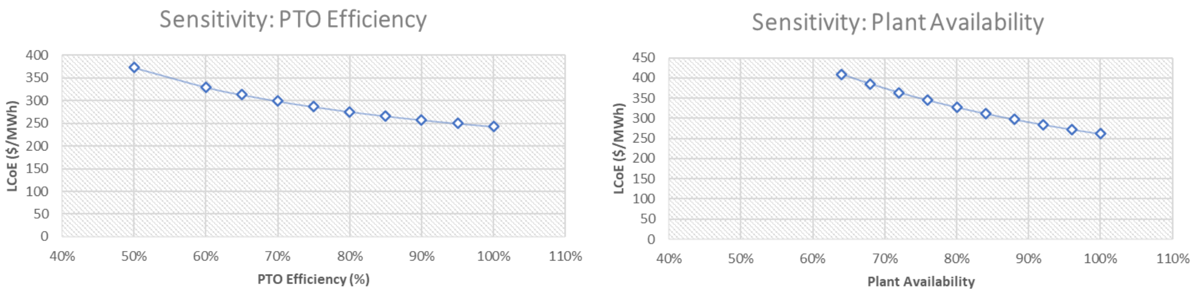


Figure 37 – LcoE Sensitivity to PTO Efficiency and Plant Availability

Wave Resource—The wave energy resource strongly affects the amount of energy captured and, hence, the related LCoE. Only the performance impact is evaluated. Cost profiles due to mobilization distance etc. stayed consistent with the baseline. The following plot compares five different locations.

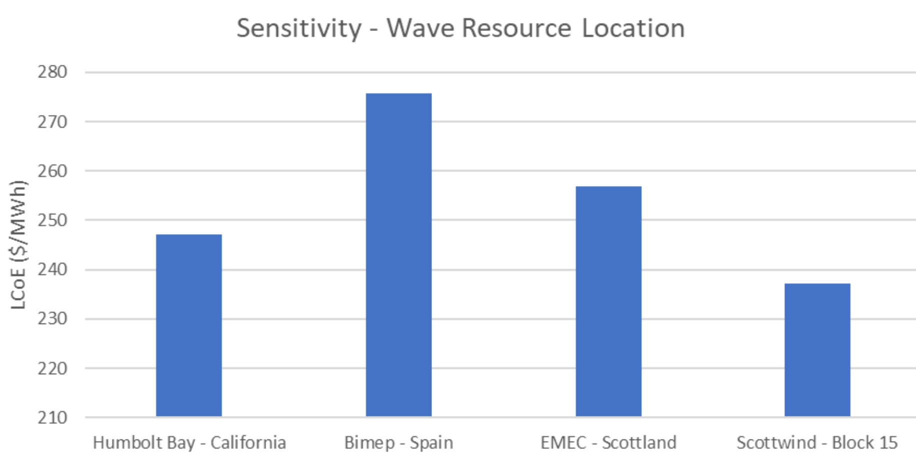


Figure 38 - LCoE Sensitivity to Wave Energy Resource

Steel Manufacturing Cost—Not surprisingly, WEC economics is very sensitive to the device's structural cost. Our current baseline utilizes a US-based steel manufacturing cost model, which projects $2879/t at 100 unit production volume. However, the automation of manufacturing processes and/or the utilization of low-cost manufacturing locations (i.e. China), could significantly reduce that cost. A cost-reduction potential of 50% should be attainable and we obtained quotes for barges in China for < 1,400/t.

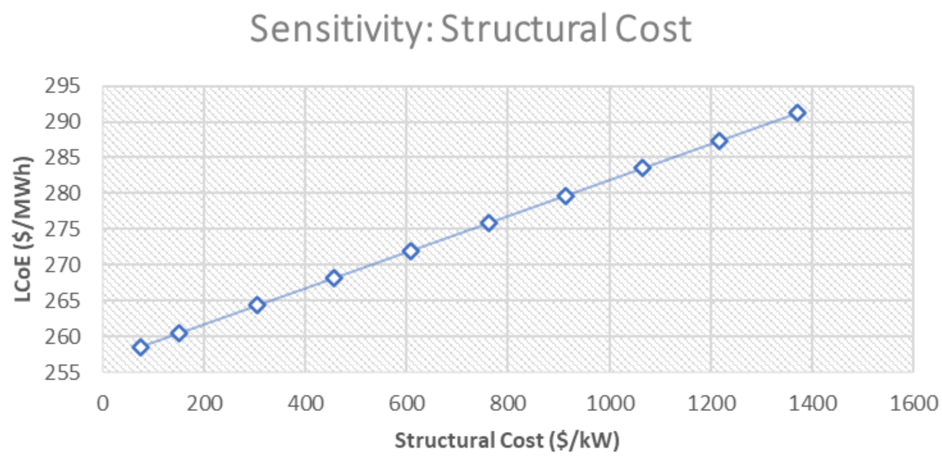


Figure 39 - LCoE vs. Structural Steel Mfg Cost

PTO Cost—The baseline PTO cost at a manufacturing volume of 100 units is projected to be $2,570/kW. This cost includes a low-speed hydraulic stage, a high-speed electric stage, power electronics to provide grid-compliant power, a riser cable, and a variable-depth winch system.

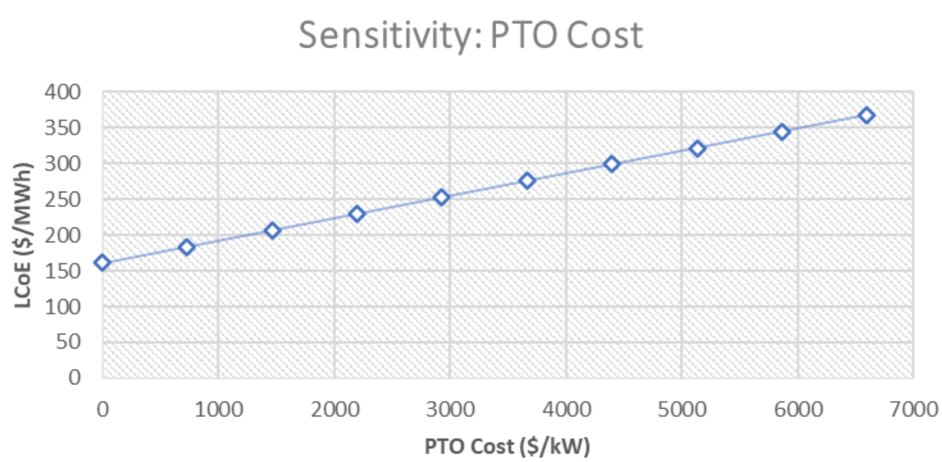
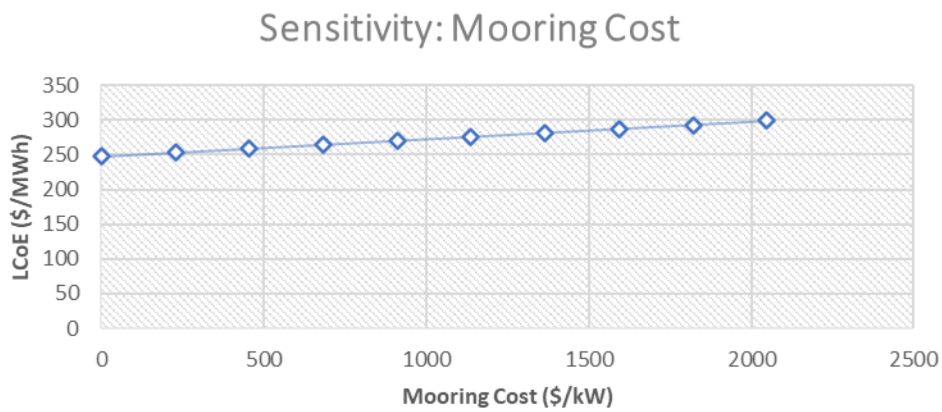


Figure 40 - LCoE Sensitivity to PTO Capex

Mooring Cost – The mooring includes a suction embedment plate anchor (SEPLA) and a vertical tether connecting the anchor to the device hull over a winch system. This cost-center excludes the installation activities.



O&M, Installation, and Insurance Cost - Other key cost drivers affecting the LCoE include the installation, O&M, and insurance rates. The installation cost baseline was explicitly computed for this device and includes assumptions on equipment day rates and installation process timelines. Given the early-stage nature of the current design, O&M and insurance costs were estimated parametrically.

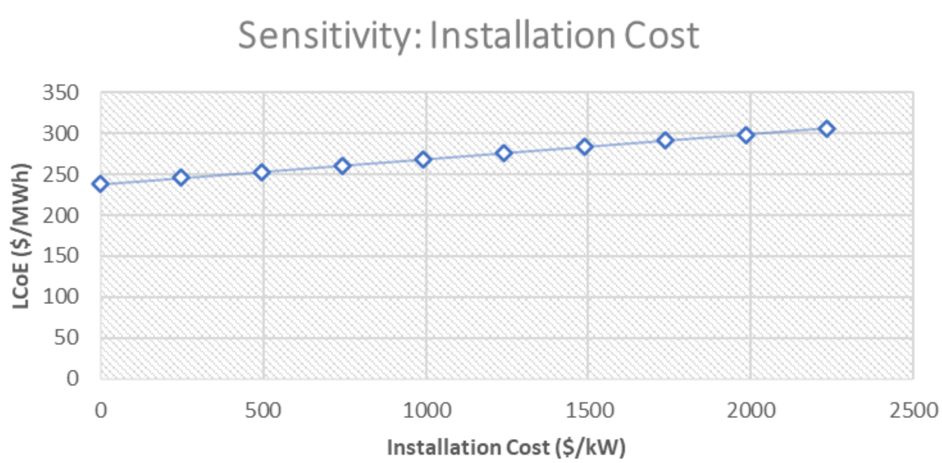


Figure 41 - LCoE Sensitivity to Installation Cost

Significant uncertainties remain in respect to O&M. The baseline assumes an annual recovery/redeployment of the device using an AHATS class vessel with a day-rate of about $30k. We also assume failure rates consistent with building the first 100MW plant. Going from an AHATS class vessel to a smaller multi-cat could reduce marine operational cost by a factor of 4 and intervention cycles could be pushed to 5-years.

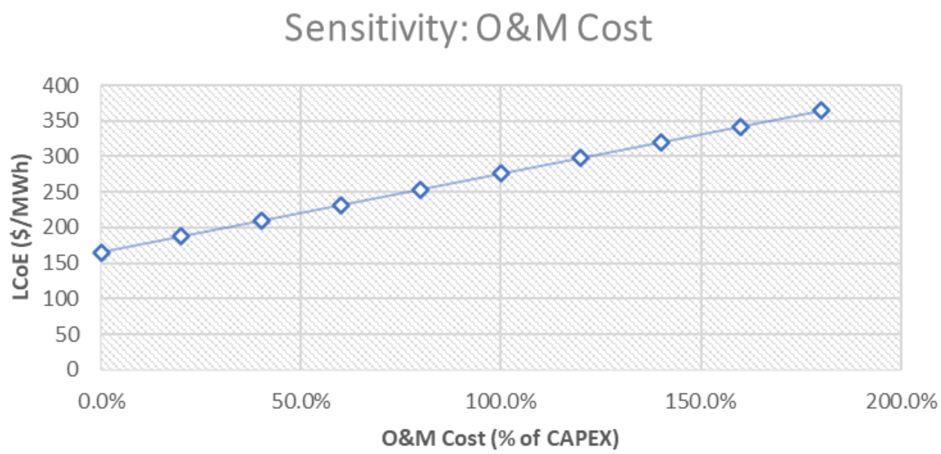


Figure 42 - LCoE Sensitivity to O&M Cost

The baseline insurance rate is assumed to be 2% of Capex. This is consistent with large offshore projects. Prototype systems have seen insurance rates of > 6%, while mature commercial wind and solar projects have insurance rates of < 0.5%.

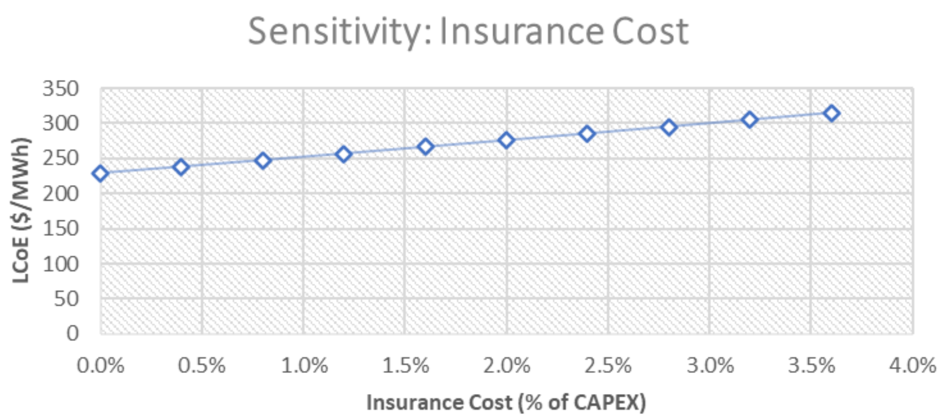


Figure 43 - LCoE Sensitivity to Insurance Cost

Fixed Charge Rate - The fixed charge rate (FCR) in utility economic models represents a version of the weighted average cost of capital, including ROI on debt and equity of the project, as well as tax rates. It allows us to annualize the plant Capex. The Reference Model Efforts by the US Department of Energy assumed a fixed FCR of 7% which is consistent with how the DoE assesses its entire portfolio of generation technologies. It is important, however, to point out that this rate is a direct function of the perceived overall risks of the project. The first plants will likely have much higher rates with rates likely being on the order of 10%-12%. The following plot shows the sensitivity of FCR to LCoE for the baseline plant.

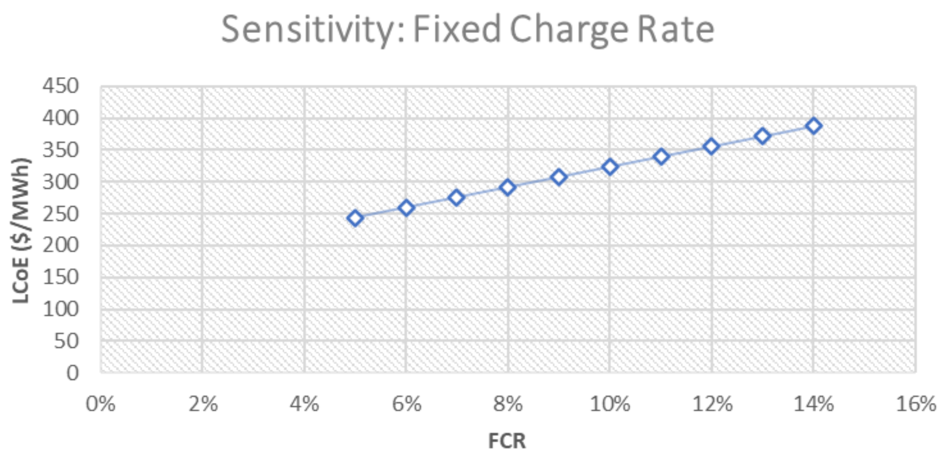


Figure 44 - LCoE Sensitivity to Fixed Charge Rate

7.1.7 Cost Reduction Pathways of the Reference Point Absorber

A key benefit of a macroeconomic study such as this one is to combine the critical cost-reduction pathways and develop a high-level strategy that can lead to an improved device envelope. The key question to be answered is: what LCoE level could be achieved if we successfully commercialize the technology and implement key cost-reduction measures? In the technology development process, we would envision the following measures to improve techno-economic viability:

1. *Structural cost:* Serial production automation, such as robotic welding and modularization of absorber structures, could reduce the cost of manufactured steel by more than 50% over the current baseline. The equivalent level of cost reduction could be achieved by manufacturing the steel structures in a low-cost country such as China. There are additional opportunities to be explored by leveraging alternate materials such as concrete and FRP that could enable significant cost savings.
   Proposed R&D: Design for manufacturing including (1) investigation of alternate materials such as concrete and RFP, (2) design of process automation in mfg process.

2. *Performance Improvement:* Power capture is presently at 65% of the theoretical limit on average. This is achieved using a feedback control algorithm. A significant improvement is possible using MPC control and deterministic sea wave prediction (DSWP) to near its theoretical upper limits. A key advantage of the AWS approach is that these limits can be attained without having to rely on reactive power flows, which is inherently challenging (and costly) to implement. We assume an improvement to a conservative 85% over the baseline.
   Proposed R&D: Study application of MPC in the numerical domain. At-sea validation of DSWP and controls to retire implementation risks.

3. *O&M costs* can be reduced by a factor of 4 from about 4% of Capex per year to < 1% of Capex per year through (1) reducing operational interventions from 1x per year to 1x every 4 years, and (2) increased reliability in the powertrain, resulting in reduced replacement costs. Most of the improvements can be achieved by simply improving the reliability of the powertrain and increasing the intervention interval.
   Proposed R&D: Detailed PTO design focusing on reducing intervention intervals and reliability—accelerated testing of critical components and sub-systems. Incrementally automating at-sea operational procedures to enable low-cost access arrangements.

4. *Insurance costs* can be lowered from 2% of Capex/yr to 0.5% of Capex/yr. This aligns with mature onshore wind or solar farms and requires mature technology with a proven track record. This is likely a function of the design maturity of components and subsystems and cumulative deployment experience that demonstrates reliability over several years.
   Proposed R&D: None. This reduction is a direct result of commercial maturity.

Table 22 - Cost Reduction Pathway

	LCoE	in %
Baseline	276	
Manufacturing Innovation	252	9%
Optimal Control	223	12%
Reliability Improvement 4X	155	30%
Reduced Insurance Rates	127	18%

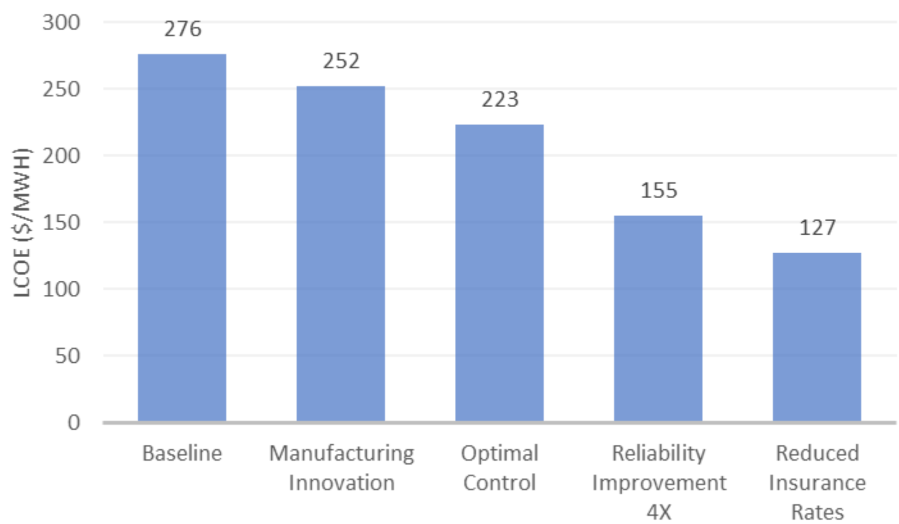


Figure 45 - Cost Reduction Pathway for AWS Waveswing

An optimized plant's cost breakdown structure will be very different from the baseline. As shown below, the PTO becomes the key cost driver. Further studies should be undertaken to reduce cost uncertainties around this sub-system.

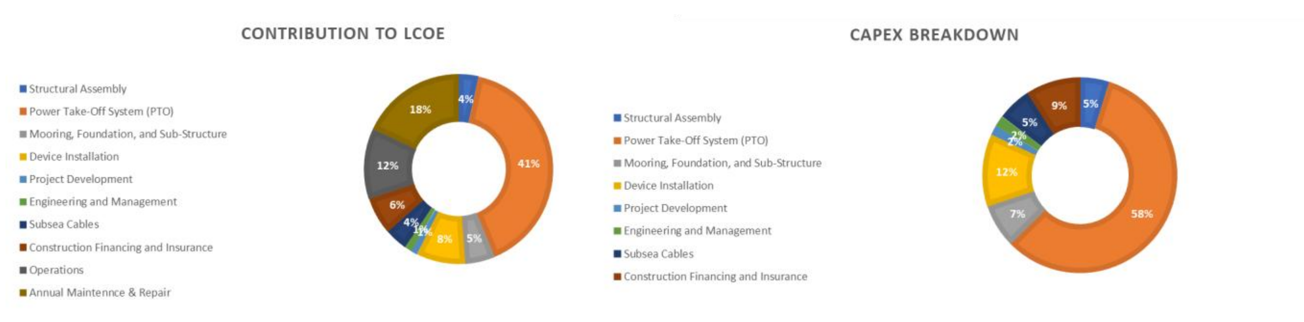


Figure 46 - LCoE and Capex Breakdown of Optimized 100MW Waveswing Plant.

7.2 Lesson Learned and Test Plan Deviation

Our overarching objective for this work was to develop a suitable cost/economic model that would allow the device manufacturer to refine and optimize their technology toward commercialization. However, our approach needed to be adapted in a few areas.

Optimal Controls Modeling of RPA — Time-domain modeling of the RPA system was successful using linear damping. However, because the system employs a spring-stiffness compensation mechanism, resulting in a low net hydrostatic stiffness, it becomes a highly dynamic system, and enforcing motion constraints becomes critical. To address this issue optimally would require a controls optimization scope of work that was beyond our planned scope of work. As a result, we used the time-domain model to identify lower performance bounds for the RPA device. To identify upper performance bounds, we relied on an analytical solution based on the limits of point absorbers and volumetric absorbers. The method was initially developed under a DoE-sponsored controls optimization study[14]. When comparing the modeling to the actual performance achieved by the Waveswing device (during wave tank and in-ocean validation), which features an optimally tuned feedback control strategy, we found that the device absorbed power consistently at 65% of the theoretically identified limit in each sea state. In the absence of a fully-fledged control optimization study, we utilized this model as a realistically achievable performance benchmark for these two WEC topologies using an optimal feedback controller.

It is worth noting that our in-house studies of similar topologies suggest that optimal MPC-based control can potentially reach the theoretical upper limit; however, it remains to be seen how much reactive power is required to achieve this for the two topologies explored in this study. Further study is required to identify the potential performance upside that can be achieved using optimal control. In this study, we addressed this uncertainty through sensitivity analyses of WEC device performance. In the economic context, performance uncertainty is no different than any other design or commercial uncertainty.

Cost-Reduction Pathways—We entered the project with a set of assumptions about how costs would be most optimally reduced. The results uncovered many new and interesting pathways that were not originally anticipated. We adapted our sensitivity studies in light of these findings.

The above-listed adaptations are pretty normal for a project of this type. We produced results that added value to the device developer's development process by focusing on the objectives.

A key lesson learned is that many task details had to change during the overall project execution. This highlights the challenge of comprehending all the design details and their implications for optimal project execution before undertaking the effort. A reasonable amount of flexibility is required in the overall process to ensure optimal outcomes.

[14] Previsic, M.; Karthikeyan, A.; Scruggs, J. A Comparative Study of Model Predictive Control and Optimal Causal Control for Heaving Point Absorbers. J. Mar. Sci. Eng. 2021, 9, 805. https://doi.org/10.3390/jmse9080805

8 CONCLUSION

The baseline was established to understand what the LCoE from a 100MW plant would be if it were constructed today. The Waveswing shows an LCoE at the 100MW scale of $306/MWh, while the reference point absorber has a slightly lower opening cost of $276/MWh. The following shows the Capex cost breakdown by cost center (left) and the contribution of these cost centers to the LCoE for the Waveswing device.

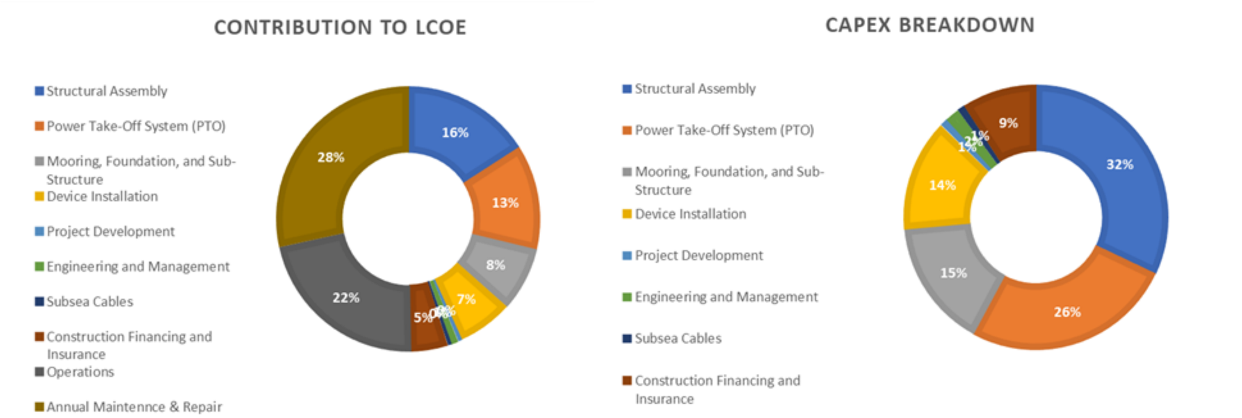


Figure 47 - 100MW Capex and LCoE by Cost Center for Waveswing

The Reference device shows a lower baseline LCoE due to a lower structural mass per unit of power. It also shows that the PTO significantly contributes to total cost. This is due to a more complex PTO that enables hydrostatic spring stiffness compensation.

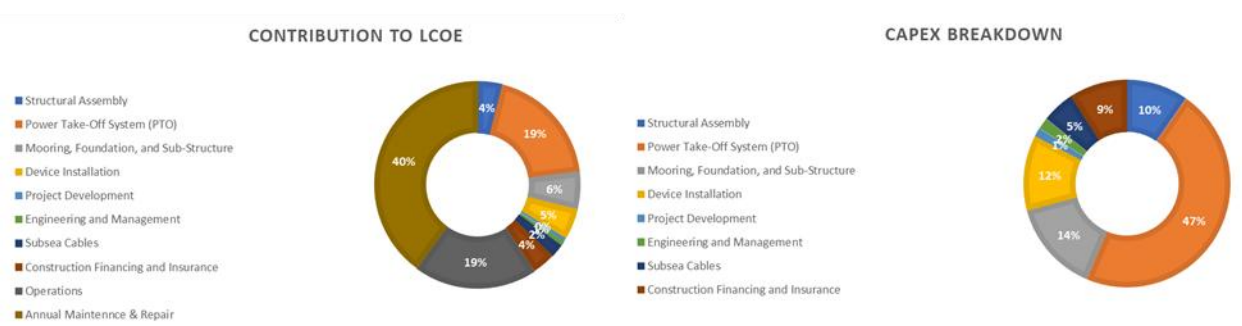


Figure 48 - 100MW Capex and LCoE by Cost Center for Reference Point Absorber

Key cost-reduction pathways were identified that could significantly improve WEC device economics, making it potentially competitive with current offshore wind. For the AWS device, this includes the following:

- **Multi-Absorber Platform:** Deploying multiple Waveswing devices onto a common platform provides key advantages, improving accessibility for O&M and substantially reducing this cost center. The annual O&M cost reduces from a baseline of 4.6% of Capex to 1.8% of Capex.

- **Reduced Subsea Volume:** The Waveswing baseline design evaluated is structurally less efficient than the RPA. This is because the device requires a passive volume to provide a low-inherent spring stiffness to the subsea floater. Several approaches could reduce this volume by a factor of >2x over the baseline.
- **Low-Cost Manufacturing:** Robotically driven manufacturing processes could reduce structural cost by 2x over the baseline, which assumes manufacturing in a shipyard. A similar level of cost reduction could be attained by manufacturing in a country with low labor costs, such as China.
- **Optimal Control:** Currently, Waveswing has an onboard feedback control system. This yields power absorption values of about 65% of the upper theoretical limits. Using MPC-based optimal control, combined with a deterministic sea wave prediction (DSWP) system, this could be improved to > 85% of the theoretical upper limit.
- **Improved Reliability:** The baseline model assumed an annual O&M intervention cycle. This is consistent with what is being done in offshore wind. However, the experience with the Meygen tidal project showed that this intervention interval could be reduced to once every 4-5 years if the powertrain is designed for ultra-high reliability. Our cost-reduction assumption is that intervention cycles can be reduced to once every 4 years.
- **Reduced Insurance Rates:** The baseline assumption is that insurance rates will be 2% of Capex per annum. Mature commercial renewable energy projects (solar and wind) have insurance rates of < 0.5% of Capex. As the wave energy sector matures, we expect similar rates as well.

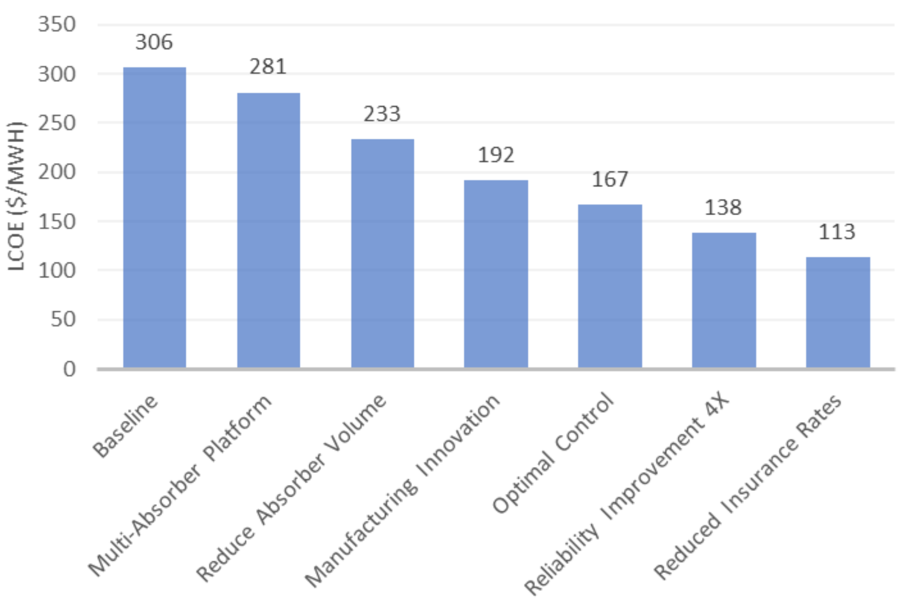


Figure 49 - LCoE Cost Reduction Pathway for Waveswing WEC

In comparison, the RPA has fewer technology-related levers to reduce LCoE, this reduces LCoE at commercial scale to about $127/MWh as shown in the following plot.

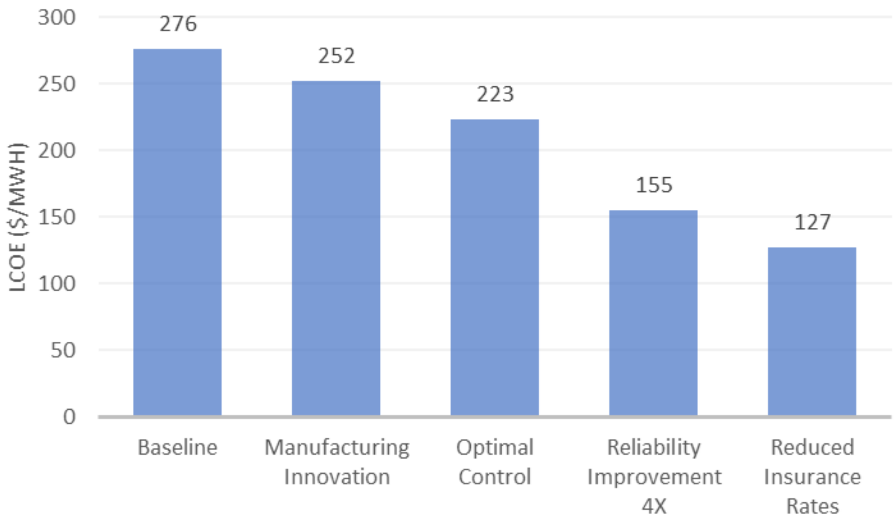


Figure 50 - Cost-reduction pathway for RPA

It is crucial to understand that the uncertainties in these models are still significant given the early stage of technological development and within the broader context both devices have similar commercial potential. Within the broader wave energy conversion space context, a technology development pathway that leads to an LCoE of < 15 cents/kWh is encouraging and competitive. However, more focused RD&D will be required to reduce the uncertainty in our predictions and clarify if such targets can be achieved using detailed engineering/design studies.

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9 ACKNOWLEDGEMENTS

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