Test Post Access Report

Techno-Economic Optimization of SurgeWEC Device

Awardee: Resolute Marine Energy

Awardee point of contact: Marcus Gay

Facility: Re Vision Consulting

Facility point of contact: Mirko Previsic

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EXECUTIVE SUMMARY

Resolute Marine Energy (RME) has developed a unique technology that harnesses ocean wave energy to produce fresh water. Commercially this technology is called Wave2OTM. A typical commercial application for a Wave2OTM Plant may comprise a plurality of Wave2OTM Trains, each rated for nominal permeate production of 500 m3/day at the rated sea conditions. The current body of work was carried out on their GEN 1.5 product generation.

The energy from ocean waves is captured using RME's Wave Energy Converter (WEC), dampened to smooth out pressure variations, and transferred to feed a Reverse Osmosis (RO) desalination unit to produce fresh water. The RO reject brine passes through an Energy Recovery Unit (ERU) to conserve energy to the feed water. A portion of the wave energy is used to drive a hydraulic generator to produce power which can be used to power the rest of the Facility.

During this project, we created a plant-level parametrically driven cost and economic model that allowed us to study key technical parameters of Resolute Marine Energy's wave powered desalination system. The model was developed by leveraging previous design and cost assessment efforts at RME, organizing and normalizing data-sets and augmenting data and models where required.

Key parameters studied included both WEC level factors (such as PTO rating and WEC size) and plant level considerations (such as distance to shore, mobilization distance and financing assumptions). The key metric considered during this project was the levelized cost of water. A total of eleven sensitivity studies were carried out to help understand design drivers. Because many design considerations remain at an early stage of development, uncertainty levels were estimated at the sub-system level and evaluated in the global context using statistical methods.

Key findings of the study included:

- While estimating of cost and economics at a plant level requires attention to a significant number of considerations, identifying dominant cost-centers allowed us to focus on a small number of key cost drivers.
- Working with lifecycle cost of different components as opposed to just capital cost is critical in quantifying the relative importance of sub-system cost. For example, we found that while piled foundations in rock are inherently structurally efficient, their cost is dominated by installation requirements.
- The PTO system includes volumetric displacement pumps and hydraulic accumulators to smooth the pulsating flow from the individual flaps. These systems are cost-drivers and further work could help in establishing cost-reduction pathways for alternate PTO configurations.
- The baseline device design relies on a piled foundation. These piles are costly to install due to the need of lift-barges to support the installation process. Alternative foundations should be evaluated to study their viability.
- Site Development cost – Because these systems are not utility scale, site development costs play an important role. These costs could be lowered through rapid site-assessment tools including: (1) wave resource assessment, (2) automated environmental assessments and characterizations.

Our objectives were fully met during this initial cost and economic characterization and will allow RME to focus resources on technological pathways that can significantly reduce the cost of water from these wave powered desalination systems. The high-level nature and budget constraints of this study did not allow us to deep-dive into specific engineering aspects of this system and further work is required to refine many aspects of this assessment.

1 INTRODUCTION TO THE PROJECT

Resolute Marine Energy (RME) has developed a unique technology that harnesses ocean wave energy to produce fresh water. Commercially this technology is called Wave2OTM. A typical commercial application for a Wave2OTM Plant may comprise a plurality of Wave2OTM Trains, each rated for nominal permeate production of 500 m3/day at the rated sea conditions. The current body of work was carried out on their GEN 1.5 product generation.

To better understand the company's product development pathway and be able to optimize the product to prospective customer sites, it is critical to develop the modeling capabilities to be able to optimize the flap to target site conditions and parametrically explore the design space. To do so, we seek assistance in developing a parametrically scalable cost and economic model. This will allow us to adapt/optimize our system to different target sites considered for development, support early market exploration opportunities and study what-of scenarios to evaluate product development pathways. RME seeks to develop a scalable cost model that will allow to evaluate the following effects:

1. Scale of flap device on levelized cost of water
2. Economies of scale in manufacturing and deployment
3. Cost impact of site conditions including; water depth, distance to shore, distance to port, and wave conditions

The model will be used to evaluate the sensitivity of water cost to these critical driving parameters. This will allow us to understand the economic impacts of design choices early-on in the development process and support our marketing efforts by providing a screening tool for the different sites under investigation.

2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

The applicant will provide access to relevant design, cost and performance data sets developed during the development of their SurgeWEC technology. It will further provide access to key personnel to clarify data sets and provide feedback on questions by the network facility.

2.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED

The network facility will assimilate cost and performance data into a uniform assessment framework and augment them with complimentary data points established for related efforts. It will then develop scalable cost and performance models for these systems to enable the integration into a techno-economic modeling tool.

3 PROJECT OBJECTIVES

RME has developed a bottoms-up cost and economic model for it's wave powered desalination product, which has evolved through a number of evolutions. To better understand the company's product development pathway and be able to optimize the product to prospective customer sites, it is critical to develop the modeling capabilities to be able to optimize the flap to target site conditions and parametrically explore the design space. To do so, we seek assistance in developing a parametrically scalable cost and economic model. This will allow us to adapt/optimize our system to different target sites considered for development, support early market exploration opportunities and study what-of scenarios to evaluate product development pathways. RME seeks to develop a scalable cost model that will allow to evaluate the following effects:

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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 the techno-economic analysis and optimization of marine energy systems is unique and will provide us with confidence moving forward on our technology and market development activities.

5 TEST OR ANALYSIS ARTICLE DESCRIPTION

Resolute Marine Energy (RME) is developing a shallow water surge WEC device that is used to pressurize seawater used in a desalination system on-shore. The focus of the costing model will be on the WEC device, foundation and PTO as well as related installation, operation and maintenance processes.

6 WORK PLAN

6.1 NUMERICAL MODEL DESCRIPTION

The model to be stablished will be purpose-built, but will leverage it's structure from the Reference Model Project cost assessment efforts carried out by Re Vision Consulting. We will incorporate the following capabilities:

- Parametric sweep of key variables
- Monte Carlo simulation using excel macro functions

Cost-functions developed consist largely of curve fits carried out in excel and/or Matlab. The modeling complexity is at a low order.

6.2 TEST AND ANALYSIS MATRIX AND SCHEDULE

The following tasks outline the tasks/scope agreed to with RME. The level of effort estimates are provided assuming full-time work. Most of efforts will spread out over a 3 month period (September – December 2021) and will be carried out by Mirko Previsic.

Task 1: Establish costing baselines using data provided by RME
Level of Effort: 1 week
- Review cost models provided by RME and underlying engineering basis for models
- Engineering studies on different sized flaps currently underway by RME by june/july this summer.

Task 2: Refine cost estimates
Level of effort: 1.5 weeks
- Identify areas of uncertainty
- Fill gaps in the cost analysis through analogous costing studies
- Adjust costing data using PPI adjustments and normalize estimates to a common date basis

Task 3: Determine cost-scaling functions for major scaling parameters
Level of effort: 1 weeks
- Establish major scaling functions
- Document scaling functions in Spreadsheet format for RME internal review

Task 4: Build/test an integrated excel model to enable parametrically driven techno-economic analysis
Level of Effort: 2 weeks
- Parametrically-driven performance model
- Parametrically-driven Cost model
- LCOW model
- Uncertainty analysis functionality (MonteCarlo or similar)

Task 5: Report to Teamer Board

Level of Effort: 1 week

Task 6: Internal Review by RME of teamer report
A report will be provided to RME by early December for review.

6.3 SAFETY

The work to be carried out does not require any physical model testing and is largely desktop work.

6.4 CONTINGENCY PLANS

We do not have any contingency plans.

6.5 DATA MANAGEMENT, PROCESSING, AND ANALYSIS

6.5.1 Data Management

Cost data will be supplied by Resolute Marine Energy. Because this is commercially sensitive data, covered under a Nondisclosure agreement between RME and ReVision, we will not be able to share this data. There are several efforts underway by RME that will provide inputs to ReVisions project. These efforts are scheduled to complete by late June and we will likely delay efforts until these data-sets are in place.

We will provide results of the analysis in non-dimensional form. Data will be shared in excel format with associated tables and will show the relative impact of design parameters on the levelized cost of electricity.

6.5.2 Data Processing

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

Where possible and applicable, we will compare the data against other cost data-sets. This will allow us to further quantify uncertainties and evaluate the relative impact of the uncertainty on the levelized cost of water.

6.5.3 Data Analysis

The type of analysis carried out will depend largely on the actual data supplied. The relative economic trade-off studies will likely include:

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

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

7 PROJECT OUTCOMES

7.1 RESULTS

Cost and economic models were developed in a manner that allowed us to vary key technical parameters and study the impacts on the levelized cost of water. Our cost assessments relied largely on work previously completed at Resolute Marine Energy (RME) and subject to a Nondisclosure agreement between RME and Re Vision Consulting. To protect, the confidentiality, we are presenting results in a non-dimensional format as described in the agreed-upon technical scope. The technical data and presented figures are provided in an excel spreadsheet to provide transparency into the methods and comply with Teamer Requirements. The following sections outline results of our studies.

<u>Baseline Cost Model</u>

Building directly on RME's efforts, a baseline cost and economic assessment was carried out. The baseline is an RO system that is powered exclusively using wave energy with an average daily fresh-water output of 4000m^3.

Several steps of quality control and data normalization were used to ensure that cost-baselines reflected costs in 2019. Specifically, this included: (1) Adjusting material and labor cost of main components to a common year using producer price index (PPI) data, and (2) adjusting for manufacturing volumes using learning curves. Learning curve progress ratios were obtained from previous efforts under the Reference model program that produced detailed manufacturing models for manufacturing scales with 1-100 units.

Uncertainties in the cost estimates were assigned at the sub-system level in accordance with guidance developed by the Electric Power Research Institute (EPRI) that specifies likely cost uncertainty ranges based on the level of detail in the assessment and the technology development status for energy projects.

COST ESTIMATE RATING	A MATURE	B COMMERCIAL	C DEMONSTRATION	D PILOT	E CONCEPTUAL (IDEA OR LAB)
A. Actual	0	-	-	-	-
B. Detailed	-5 to +5	-10 to +10	-15 to +20	-	-
C. Preliminary	-10 to +10	-15 to +15	-20 to +20	-25 to +30	-30 to +50
D. Simplified	-15 to +15	-20 to +20	-25 to +30	-30 to +30	-30 to +80
E. Goal	-	-30 to +70	-30 to +80	-30 to +100	-30 to +200

Figure 1 - Cost uncertainty estimate ratings (Source: EPRI Technical Assessment Guide)

A standardized cost breakdown structure (CBS) was used to establish and track system and sub-system costs. The CBS is presented below and provides a breakdown that is suitable to capture all the major design elements from a wave energy perspective. It builds directly on the structure established previously by RME.

000	**Project Development**
001	Permitting and Environmental Compliance
002	Site Assessment
003	Project Design, Engineering and Management
100	**Inlet Structure**
200	**WEC Array**
300	**WECs A&B**
301	Prime Mover
302	Power Take Off
303	Foundation
304	Sensors
400	**Offshore Hydraulics**
500	**Onshore Hydraulics**
600	**House Power**
700	**Desalination**
800	**Balance of Plant**
900	**SCADA**
1000	**Installation**
1001	Site Access, Port & Staging
1002	Assembly & Installation
1002.1	Foundation Installation
1002.2	Pipeline Installation
1002.3	Device Installation & Comissioning
1003	**Other Infrastructure**

O&M categories were classified in a similar manner, reflecting the categories established by the Reference Model Project (RMP).

2001	Insurance
2002	Environmental Monitoring and Regulatory Compliance
2003	Marine Operations
2004	Shoreside Operations
2005	Replacement Parts
2006	Consumables

The following breakdown provides the normalized CAPEX and OPEX cost contributions and their relative contributions after levelizing cost using a Fixed Charge Rate (FCR) of 7%.

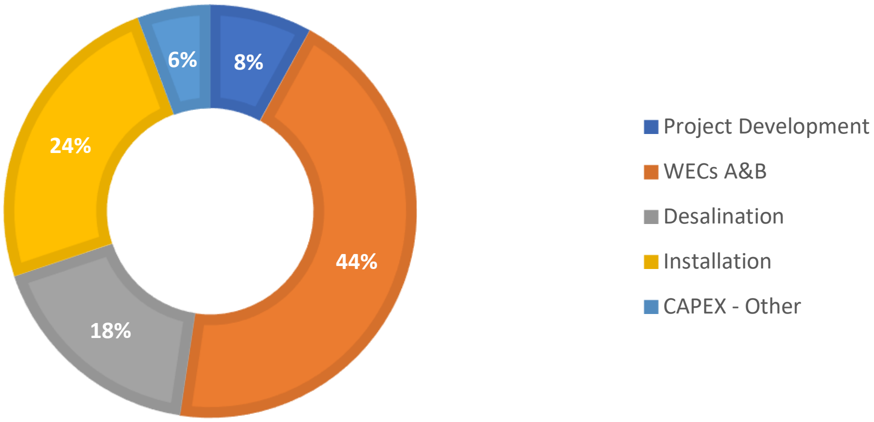

Figure 2 - Baseline CAPEX for 4000m^3 System

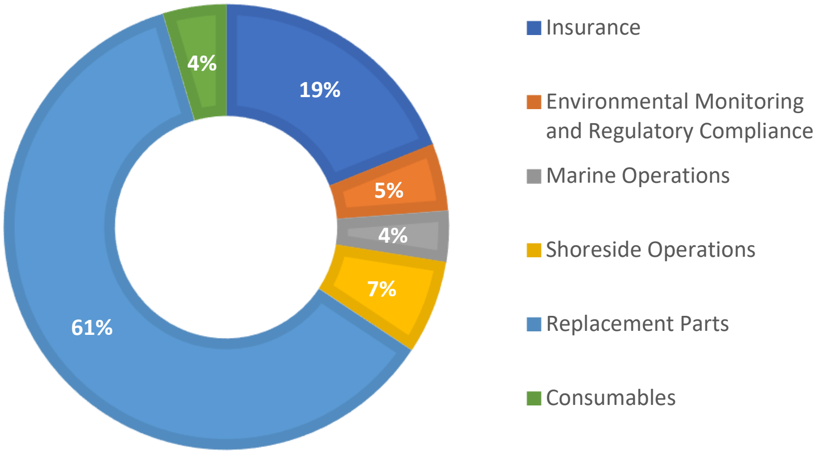

Figure 3 - Baseline OPEX for 4000m^3 System

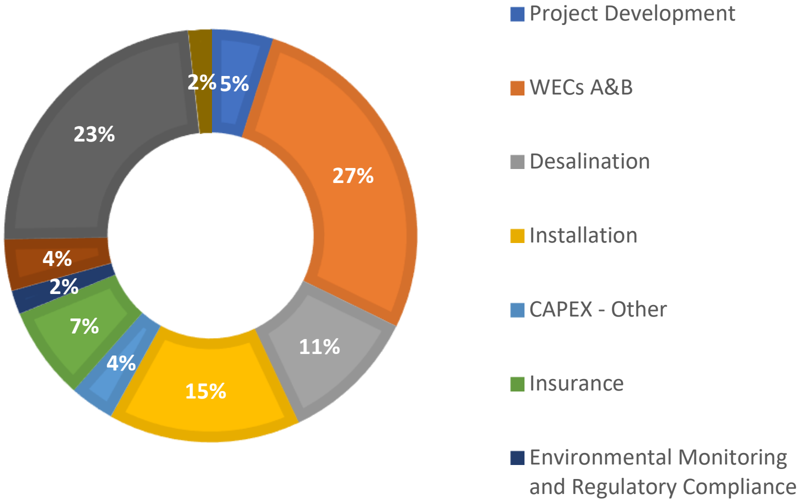

Figure 4 - LCoW Contribution for Baseline System

Uncertainties were characterized on the sub-system level based on design-detail provided and development stage. Most of the uncertainties were characterized at -30% and +80% in accordance with established uncertainty ranges by the Electric Power Research Institute (EPRI) for similar types of projects. Based on these uncertainties, a Monte Carlo Simulation was run to establish the likely embedded uncertainty in our outcomes. It showed the resulting uncertainty range is on the order of +/- 20%.

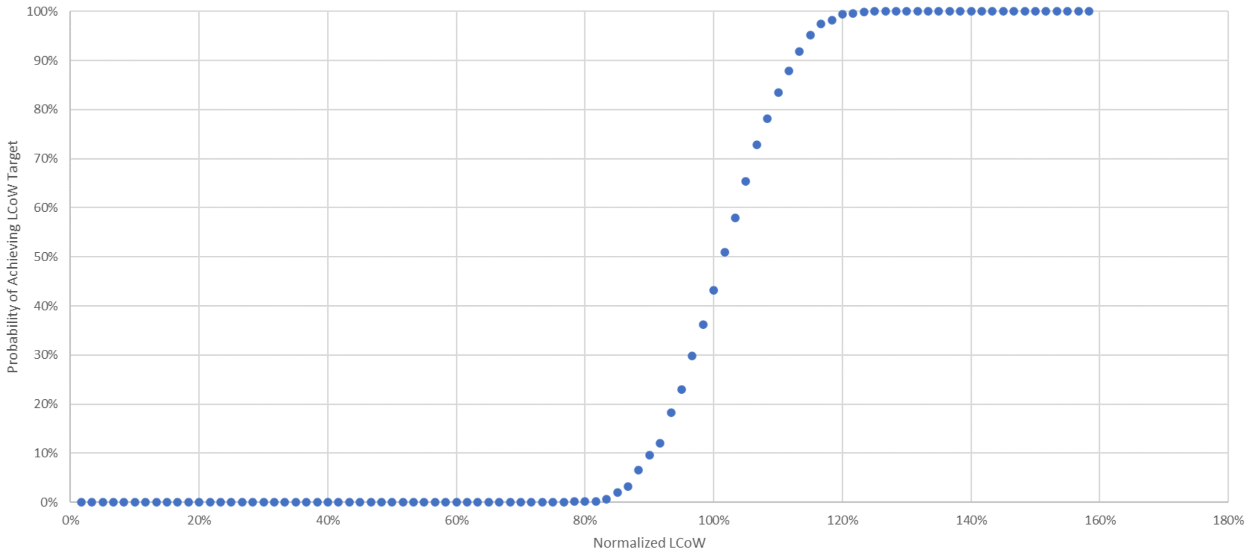

Figure 5 - LCoW Uncertainty Characterization using a Monte Carlo Simulation

Tradeoff 1 – Capacity Factor

Electricity-producing WEC devices typically achieve lowest LCoE numbers if the capacity factor is at about 30%. In desalination systems, the fundamental cost-balance shifts. The cost to produce a m^3 of water is significantly higher than the cost for producing the energy by itself. As a result, the optimal capacity factor is significantly higher. We studied this issue by sweeping the rated plant capacity and plotting capacity factor against LCoW. All subsequent trade-offs include a routine to optimize the capacity factor for each data-point produced by minimizing LCoW.

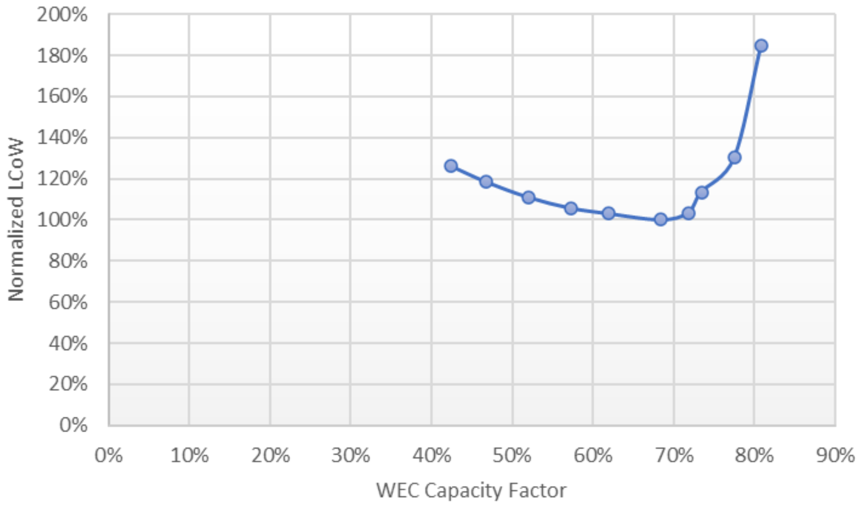

Figure 6 - Capacity Factor vs. Normalized LCOW

Tradeoff 2 – Plant Distance to Shore

The further offshore the plant is located, the more expensive it becomes due to the additional subsea pipelines required and increase in transmission losses. Because these flaps sit in relatively shallow water (<9m) water depth, the likely distance to shore is likely going to be < 1000m.

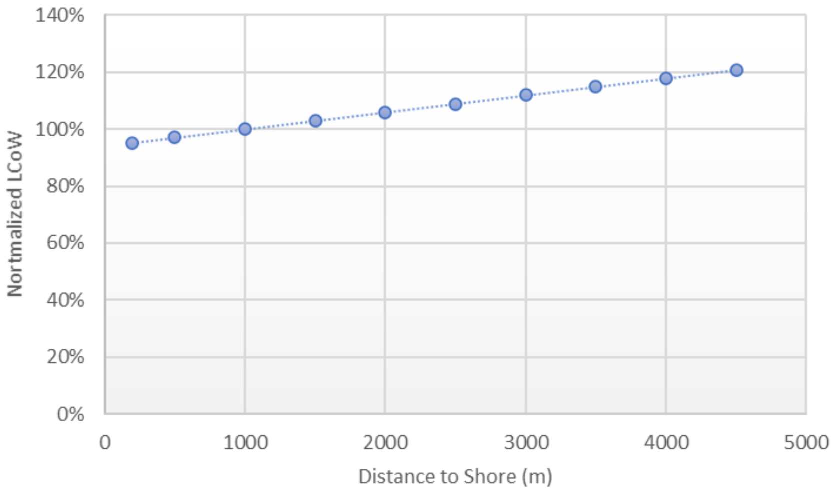

Figure 7 – Distance to Shore vs. Normalized LCOW

Tradeoff 3 – Mobilization Distance

To install the foundation and transport all the equipment to the target site, the mobilization distance to a major port is crucial. The key impact of distance is that it increases the mobilization distance for jackup barges and pile driving equipment. It was found that this is not a dominant driver and the default assumption is that equipment would need to be mobilized from 2000km away.

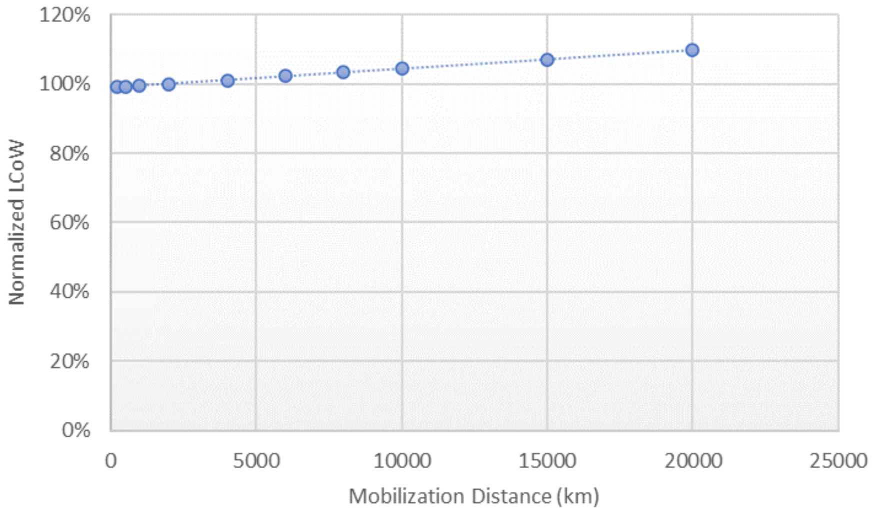

Figure 8 – Mobilization Distance vs. Normalized LCOW

Tradeoff 4 – Flap Width

Economies of scale in the flap size (height and width) largely come from the foundation cost being shared across more cross-sectional area. In addition, costs for installation and maintenance increase for smaller units due to increase in marine operational costs.

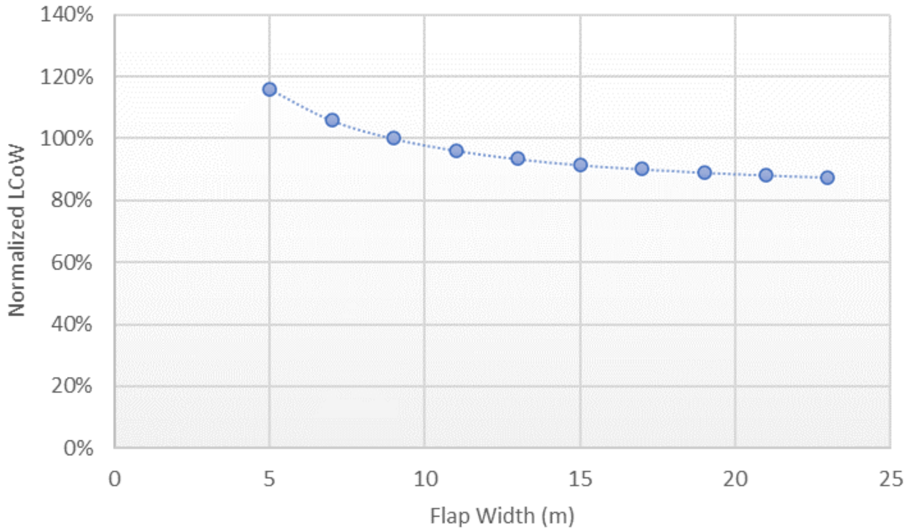

Figure 9 – Flap Width vs. Normalized LCOW

Tradeoff 5 – Flap Height

Flap height is driven by similar considerations as flap width, although the function is slightly less steep. This is due to the increase in the moment arm in the flap structure.

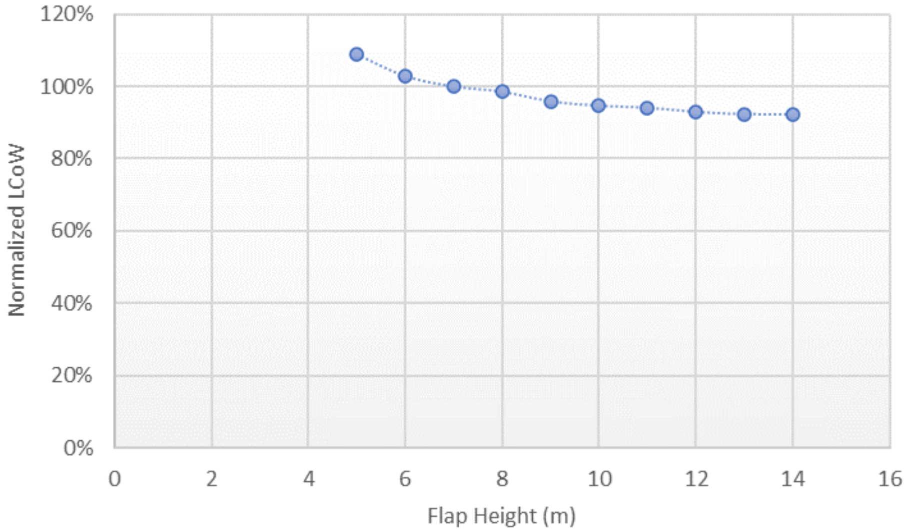

Figure 10 – Flap Height vs. Normalized LCOW

Tradeoff 6 – RO Plant Efficiency

RO plant efficiency is a function of scale, topology and technology choice. To understand the impact of the conversion efficiency, we swept values for RO plant efficiency over a sensible range of values. This includes all the pumping, water pretreatment and other hotel loads of the system. An increase in RO plant efficiency could significantly affect the water production cost.

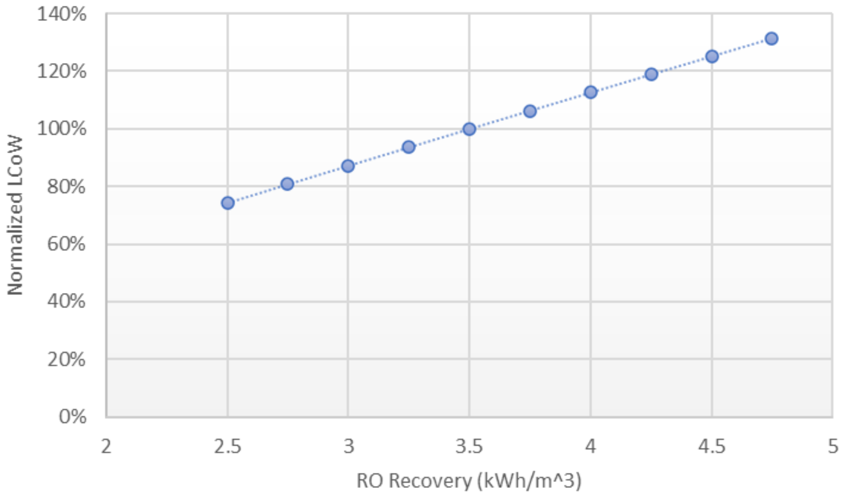

Figure 11 -RO Plant Recovery Efficiency vs. Normalized LCOW

Tradeoff 7 – Fixed Charge Rate

The fixed charge rate largely represents the cost of capital to finance the plant. The DoE stated a default assumption of 7% for most of it’s projects, but early adopter projects will see significantly higher FCR’s due to the increased risks of build a project with unproven technology. We would expect an FCR of > 12% for early adopter projects, which would reduce as experience is gained.

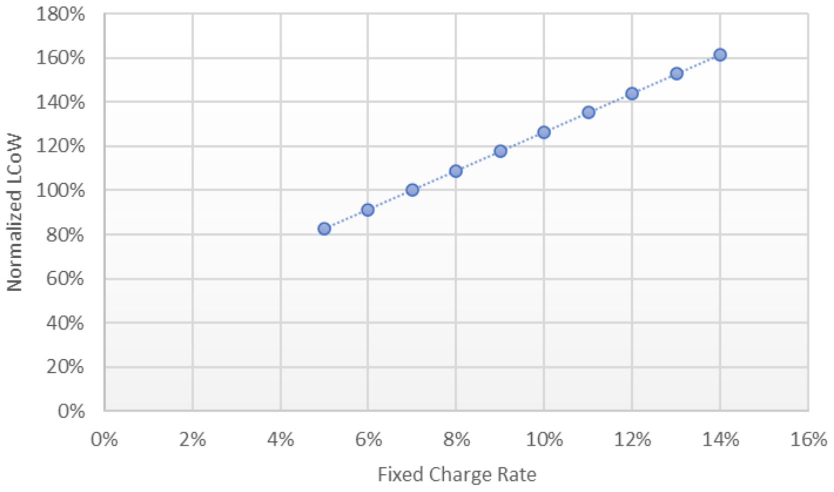

Figure 12 – Fixed Charge Rate vs. Normalized LCOW

Tradeoff 8 – Plant Size

Economies of scale play a major role in making these systems affordable. The following plot shows that the default plant size of 4000m^3/day will place us into a design regime that is relatively attractive. Smaller sizes, especially at < 2000m^3/day would require a significant premium to be paid for the water produced.

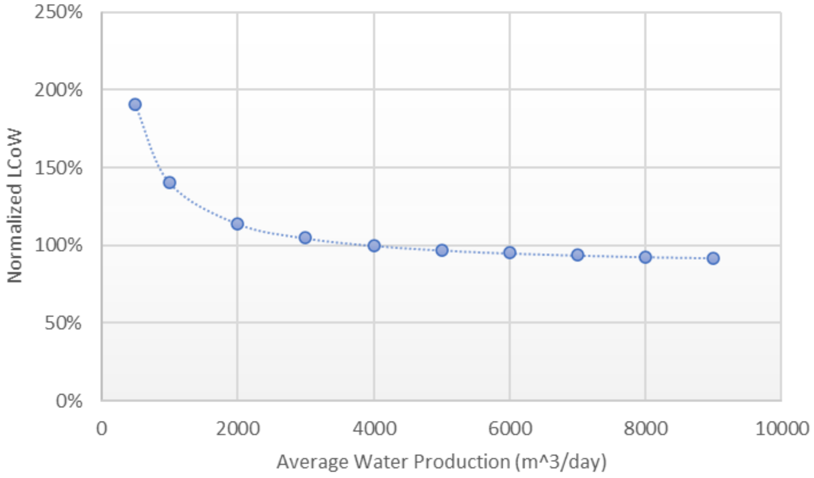

Figure 13 – Plant Size vs. Normalized LCOW

Tradeoff 9 – Foundation Type

Cost for three different foundation types were studied. Baseline costs were established based on a piled foundation installed in a rocky seabed. The foundation is drilled and grouted from a lift-barge to place the piles. The second foundation type assumed a sand/mud seabed into which piles are installed using a vibratory hammer. While the installation cost for the second method is quicker, the piles are heavier due to the need for longer piles. The third foundation assumes the utilization of many smaller micro-piles.

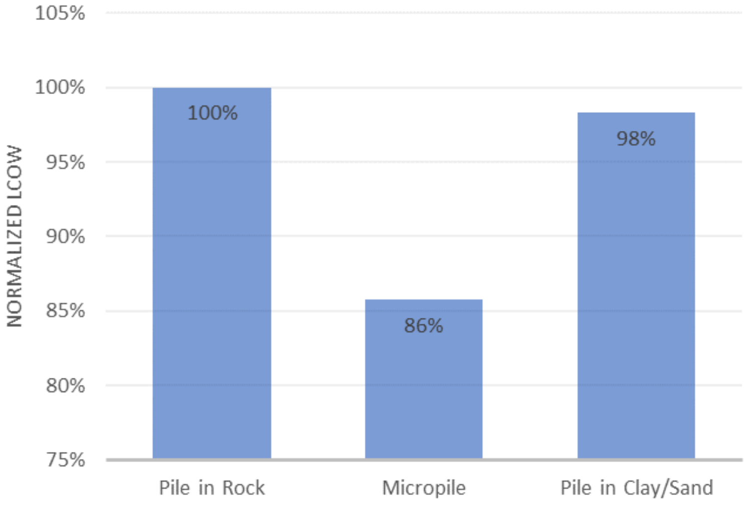

Figure 14 – Foundation Type vs. Normalized LCOW

Tradeoff 10 – Flap Scaling Law

There was some uncertainty in how the flap structural content would scale with changing dimensions. To study the sensitivity of having limited structural design data available for the scaled versions, we carried out this sensitivity study to different approaches.

Area-based: This is probably the simplest approach and simply scaled the structural steel-weight and related cost of the design to the cross-sectional area of the flap.

Moment-Arm Based: In this model, the system was scaled more accurately by utilizing an adapted tapered beam model to scale the steel weight to flap height. This formed our baseline model.

Scaled from Oyster 800: Steel weight estimates from the Oyster 800 device were obtained and scaled to the cross-sectional area of the device. This is by far the most conservative case and we are uncertain to what extent the Oyster 800 design was an overly conservative design. We were surprised that this did not affect our LCoW more.

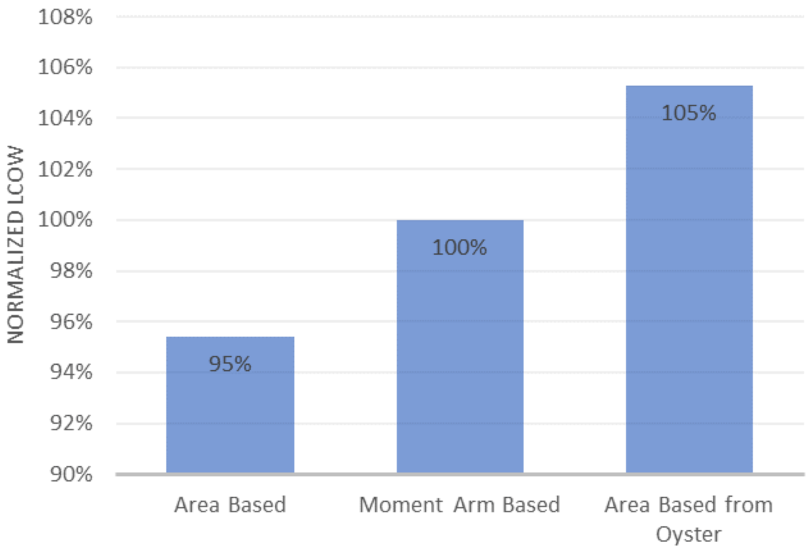

Figure 15 – Flap Scaling Law vs. Normalized LCOW

Trade-off 11 – Deployment site wave conditions

This trade-off studies the impact on the design of 5 different wave conditions to establish uncertainty in respect to wave conditions specifically. Because the plant was re-optimized for each site, it affected the LCoW by only about 25% across the different sites.

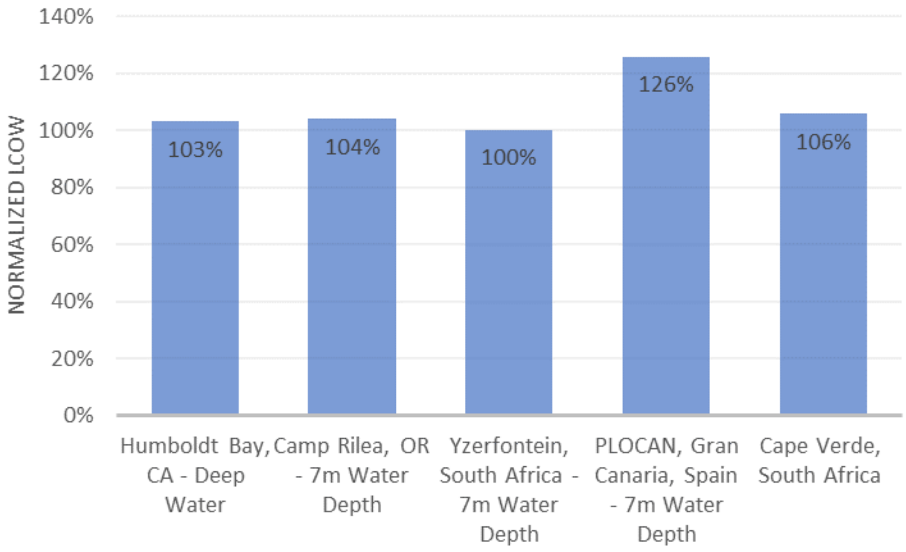

Figure 16 Deployment Site vs. Normalized LCOW

7.2 LESSON LEARNED AND TEST PLAN DEVIATION

Overall, the approach actually worked quite nicely with minimal deviation from the original plan submitted. The project overall required a somewhat iterative approach. The cost-modeling approach is largely driven by the type of engineering and costing data available. For many areas, we were able to complement existing RME data-sets with our own in-house data from similar projects.

8 CONCLUSIONS AND RECOMMENDATIONS

Resolute Marine Energy (RME) has developed a unique technology that harnesses ocean wave energy to produce fresh water. Commercially this technology is called Wave2OTM. A typical commercial application for a Wave2OTM Plant may comprise a plurality of Wave2OTM Trains, each rated for nominal permeate production of 500 m3/day at the rated sea conditions. The current body of work was carried out on their GEN 1.5 product generation.

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- Site Development cost – Because these systems are not utility scale, site development costs play an important role. These costs could be lowered through rapid site-assessment tools including: (1) wave resource assessment, (2) automated environmental assessments and characterizations.

Our objectives were fully met during this initial cost and economic characterization and will allow RME to focus resources on technological pathways that can significantly reduce the cost of water from these wave powered desalination systems. The high-level nature and budget constraints of this study did not allow us to deep-dive into specific engineering aspects of this system and further work is required to refine many aspects of this assessment.

9 REFERENCES

NA

10 ACKNOWLEDGEMENTS

We acknowledge the RME team and their dedicated support and involvement in this project. This project would not have been possible without them.

11 APPENDIX

All the data is contained in the report itself and no further details are required.