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Technological Cost-Reduction Pathways for Point Absorber Wave Energy Converters in the Marine Hydrokinetic Environment

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Abstract

This report considers and prioritizes the potential technical cost-reduction pathways for offshore point absorber wave energy converters designed for ocean resources. This report focuses on cost-reduction pathways related to the device technology rather than environmental monitoring or permitting opportunities. Three sources of information were used to understand current cost drivers and develop a prioritized list of potential cost-reduction pathways: a literature review of technical work related to offshore wave activated body point absorbers, a reference device that was developed through the DOE Reference Model project, and a webinar with each of four industry device developers. Data from these information sources were aggregated and prioritized with respect to the potential impact on the lifetime levelized cost of energy, the potential for progress, the potential for success, and the confidence in success. Results indicated the four most promising cost-reduction pathways include advanced controls, optimized structural design, improved power conversion, and optimized device profile.

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Executive Summary

Purpose

Under the direction of the U.S. Department of Energy (DOE), Sandia National Laboratories has compiled this whitepaper to identify paramount technical research and development cost-reduction pathways for wave activated body (WAB) point absorber wave energy converters in order to accelerate development of the renewable marine hydrokinetic (MHK) energy resource in the United States.

Issue

The principles of wave energy conversion have been explored since the early 1970s. Many prospective device designs have been created during this period of innovation. These designs are classified and modeled by considering their method of conversion, their directional dependence, as well as their deployment depth.[1] There are three main methods of conversion: overtopping devices, oscillating water columns, and wave activated bodies. The methods of conversion can then be realized as attenuators, point absorbers, or terminators which relate to their directional dependence. This whitepaper focuses on offshore WABs oriented primarily as point absorbers.

In recent years, the nascent MHK industry has seen tremendous interest and progress in device development and deployments including point absorbers; however, significant improvements are still needed to make wave activated body point absorber wave energy converters cost-competitive with other forms of power generation. Technological advancements are needed to lower the lifetime levelized cost of energy (LCOE) for large-scale deployments of point absorbers so that this technology can effectively compete in the marketplace.

Approach

This paper includes information from three main sources:

- Research literature regarding point absorber technologies
- The DOE Reference Model Project
- Webinars held with companies (Columbia Power Technologies, LLC., Northwest Energy Innovations, Ocean Power Technologies, Inc., and Oscilla Power Inc.) involved in the development and deployment of point absorber wave energy converters

Cost-reduction prioritization is based on the quantitative information provided by the literature review, the industry webinars, and the experience and engineering judgment of the whitepaper authors. It is important to note that these cost-reduction pathways were evaluated through a long-term lens (year 2030+) in which large deployment numbers (approximately 100 devices or more) are assumed. The prioritization factors in the impact on LCOE, the potential for progress, the potential for success given a 2030 timeframe, and the level of confidence in success.

Results

The cost-reduction pathways were separated into three tiers, with the first two tiers listed below.

Most Promising Cost-Reduction Pathways

- **Advanced Controls** – measures that increase the availability and/or increase the primary capture efficiency of the device. These measures are likely to have the largest effect on LCOE as they cross cut all other aspects.
- **Optimized Structural Design** – a design that manages loads on the structure and maintains device performance while minimizing the manufacturing cost and the factors of safety. As this pathway affects both Capital Expenditures (CapEx) and Operational Expenditures (OpEx) it will have a high level of impact on LCOE.
- **Improved Power Conversion** – method to convert mechanical energy into electrical energy. The power conversion chain is a multiple component system with a single purpose, which provides many avenues for improvements in both the cost and the amount of energy produced.
- **Optimized Device Profile** –physical changes to the device profile that can increase the energy capture. Changes to the device profile can include volume changes (scale-up), drag reduction changes, or optimized cross-sectional shapes.

Second-Tier Cost-Reduction Pathways

- **Array Optimization** – impacts CapEx in permitting, infrastructure, installation, maintenance, and mooring. A poorly designed layout may have a negative impact on the energy capture performance of the devices.
- **Improved Mooring** – impacts the capital costs of the mooring system itself and the WEC structure, deployment costs for the mooring, the maintenance schedule for the mooring system, maintenance costs for the device.
- **System Reliability, Maintenance and Availability** – addresses scheduling and frequency of maintenance, failure frequency, and availability of a device.

While the diversity of designs in the industry adds complexity, large research programs can be developed to focus on device type independent tools that will enable the entire industry. Tools that address increased Annual Energy Production (AEP) with advanced controls, survivability modeling, new generator designs, failure monitoring, and testing facilities to determine the mean time between failures (MTBF) can all be developed generically. Additionally, these research programs need to provide publicly accessible data to the community at large. The nascent wave energy converter (WEC) industry would benefit greatly by access to publicly available information about the processes, techniques, and failures that are occurring within the industry.

This young industry has access to 30,800 TWhr/yr (3,500 GW)[2] of potential wave resource globally and 2,640 TWh/yr (300 GW)[3] within the U.S. that can impact favorably the local and global electric energy markets. In 2010, the global electric energy consumption reached 21,431 TWhr/yr and the US alone consumed 4,354 TWhr/yr.[4] The prioritized research paths presented here should aid in harnessing this resource and in offsetting a portion of the electric energy supplied by non-renewable sources.

Motivation and Background

Purpose of the Whitepaper

Under the direction of the DOE, Sandia National Laboratories has compiled this whitepaper to identify predominant cost-reduction pathways for wave activated body (WAB) point absorber wave energy converters. The purpose of this report is to utilize existing information regarding the Marine Hydrokinetic industry and for point absorber wave energy converters in particular to identify the largest cost drivers and the most promising technological cost-reduction pathways leading to a lower LCOE. By identifying these cost-reduction pathways for wave activated body (WAB) point absorbers, greater and more economical opportunities could be made available for converting ocean energy into a renewable source of electricity. These cost-reduction pathways will help move ocean energy conversion from a nascent renewable energy source to a more developed and complete source such as wind and solar.

The cost-reduction pathways are based in MHK technologies and as such the whitepaper facilitates the DOE's endeavor to provide public documentation and information as detailed supporting information for a Techno-Economic Assessment Report to be delivered to Congress.

For the purposes of this analysis, relatively large deployments (approximately 100 devices or more) and a target timeframe of the year 2030 are assumed. These assumptions tend to diminish the importance of product development costs and siting issues in favor of technological improvements that scale with the size of an array deployment.

Terms and Definitions

Annual Energy Production (AEP)

Describes the average annual energy generated (after accounting for device or array availability) and delivered to the point of grid interconnection.

Capital Expenditures (CapEx)

Those investments in physical property, plant, and equipment—all fixed assets.

Commercial Off the Shelf (COTS) components

Commercially available components are frequently used by the MHK industry. These components were designed for another industry but meet or exceed an immediate MHK design specification.

Cost Drivers

The elements of the commercial array, including CapEx and Operational Expenditures (OpEx), that comprise a large percentage of the total system cost.

Cost-Reduction Pathways

These are proposed directions for research and development that will have an impact toward reducing the LCOE of a technology.

Factor of Safety (FoS)

The Factor of Safety is a term that describes the structural capability to carry a load beyond the expected or actual loads. It is the ratio of the allowable working unit stress to the expected stress. The factor of safety is a standardized way to compare strength or reliability between systems.

Levelized Cost of Energy (LCOE)

It is the level sales revenue per megawatt-hour (MWh) of grid-tied electricity production needed for an electricity generating venture to "break-even" in the sense that the project covers all capital and operating expenses and satisfies a minimum rate of return for investors. In general this is the lifetime CapEx and OpEx costs divided by the Annual Energy Produced including device availability.

Marine Hydrokinetic (MHK) Technologies

The study of body motion in a marine, oceanic environment—describing how ocean waves and currents affect those bodies within said environment. In particular, MHK is often the study of energy converting devices used to transform the motions (kinetic energy) of the marine environment into electricity.

Ocean Energy Conversion Process

The process of converting ocean wave energy into usable electricity involves five distinct steps:

- Primary Energy Capture Device: Hydrokinetic to mechanical power conversion (the "intercepted power" [5]
- Drivetrain: Conversion of device motions into the final form of mechanical power needed to drive the generator (the "captured power" [5]
- Generator: Mechanical to electrical power conversion
- On device Energy Storage: Mechanical or electrical power storage for power quality
- On device Power Electronics: Electrical power conversion for power quality

Steps 2-5 can be grouped into one category called the power conversion chain, PCC (definition given below). Although the primary energy captured is part of the full conversion process, optimization of this portion of the ocean energy conversion process is addressed independently of the PCC in this whitepaper.

Operations and Maintenance (O&M)

"The decisions and actions regarding the control and upkeep of property and equipment. These are inclusive, but not limited to, the following: 1) actions focused on scheduling, procedures, and work/systems control and optimization; and 2) performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability, and safety." Excerpted from Sullivan, G.[6]

Operational and Maintenance Expenditures (OpEx)

Those investments involved in the operation and maintenance of an electricity generating venture—the ongoing costs for running an electricity generating venture.

Power Conversion Chain (PCC)

The power conversion chain definitions have been adapted from the Hydraulics and Maritime Research Center (HMRC) to broaden the definition's applicability to other renewable technology definitions that the DOE uses when assessing cost. The PCC is composed of the following components:

- a drivetrain that converts the device motions into the final form of mechanical power needed to drive the generator (e.g. hydraulics, shafts, bearings, gearboxes)
- a generator that converts mechanical power into electrical power
- short term storage may be used to either affect power quality or other aspects of power conversion chain
- power electronics that enable power quality requirements to be met (the SCADA is part of the power electronics)

In general, the drivetrain – generator pair is often referred to as the Power Take-Off (PTO) in the WEC industry. This general term will be avoided and particular subcomponents will be identified specifically. In the case that a linear generator is used, the drivetrain and generator are indistinguishable since this power conversion mechanism accomplishes the goals of each in one component. Note, off device power electronics and longer term energy storage is not included.

Technology Readiness Level (TRL)

Technology Readiness Levels are used to classify new or unproven technologies by identifying elements and processes of technology development required to reach proven maturity levels and ensure project success.[7] General definitions of the measure of maturity of technologies are found in the following TRL definitions: [8]

TRL 1 – 3: Innovation and Basic Technology Research
TRL 4 – 6: Emergence of Technology - Proving Feasibility of Technology through Testing and Validation
TRL 7 – 8: Integration of Technology into Commercial Type System
TRL 9: Technology and System Ready for Full Commercial Deployment

To more fully capture the WEC technology development process, the TRL guidelines have been further refined into WEC TRLs. [9] These WEC TRLs identify the numerical modeling and experimental expectations that correspond to each readiness level. The WEC TRLs provide a guide for the industry to pursue successful design optimizations, prototype deployments, and utility scale commercialization. The WEC TRLs are identified below.

WEC TRL 1-2: Device type exploration and selection
WEC TRL 3: Concept design evaluation with experiments and elementary models
WEC TRL 4: Advanced concept design modeled and validated in laboratory environment
WEC TRL 5: Advanced component designs modeled and validated with laboratory environment
WEC TRL 6: System and subsystem integration in relevant environment
WEC TRL 7: Full-scale prototype deployment in open ocean
WEC TRL 8: Full-scale deployment with application in open ocean
WEC TRL 9: Utility-scale deployment in open ocean

Wave Activated Body (WAB)

A wave activated body is a device with components that oscillate in response to wave motion and thus capture wave energy.

Wave Energy Converter (WEC)

A wave energy converter is a device that generates electrical energy from ocean wave motions.

Overview of the Resource and Device Type Technology

Resource Overview

The potential application of WECs in the ocean resource is clearly enticing based on the power available in the waves, however an advanced understanding of the resource is required in order to predict how the device will behave in that resource. This procedure for understanding the resource requires more statistical treatments than other renewable technologies including solar, wind, and tidal turbine devices.

Long period ocean waves are generated by temperature differences from solar radiation causing wind to blow across the oceans. The mixture of well-developed waves arriving from some distant storm and newly formed wind waves can produce a large number of wave components with distinct incident directions and with varying amplitudes, phases, and periods. The wave energy resource, as defined by the component definitions, is not only spatially but also temporally variable on the scale of seasons, days, and hours. The wave resource may be variable, but it is immense, continual, and has high energy density (higher than either solar or wind). One method to harness some of this energy potential is to convert it to usable electricity through wave energy converters (WECs).

Electric Power Research Institute (EPRI) produced a technical report in 2011 evaluating the potential wave resource on the outer shelf of the United States.[3] This report found that there is 2,640 TWh/yr (300GW) of potential wave resource along the United States coastal territory. This resource is not distributed evenly around the United States; below is a sampling of the distribution of the more energetic resource sites which would make good candidates for wave energy development:

- West Coast (WA, OR, CA): 590 TWh/yr (67 GW)
- Hawaii: 130 TWh/yr (15 GW)
- East Coast (NC through ME): 200 TWh/yr (23 GW)
- Alaska (Pacific Ocean): 1,360 TWh/yr (155 GW)

The spatial and temporal variability of ocean waves requires statistical treatment. Ocean waves are categorized by sea states which are valid for a short duration of time, typically 30 minutes to one hour. A particular sea state is defined by a wave height, a period, a directional spreading function, and a spectral shape which all determine the directional power in the sea state. WEC devices that are not directionally dependent may ignore the directional spreading function to obtain omni-directional power calculations. Often times, deployment locations are first categorized by assuming omni-directional waves. The selection of the most representative spectral shape for the wave climate is dependent upon the particular deployment location, although a standard wave spectral formulation will often be used. The spectral shapes define the distribution of energy within a sea state. Since most WECs have frequency-dependent performance characteristics it is important to accurately determine the spectral shape at the deployment location. Most commonly the significant wave-height (Hs), and peak period (Tp), are used by the oceanographic community as inputs to define standard spectral shapes like JONSWAP, Bretschneider, or TMA. [10]

Sea states allow the wave climate to be characterized for short durations of time, however in order to describe the deployment conditions that should be expected on an annual basis additional descriptions are required. A joint-probability distribution (JPD) is used to characterize the likelihood of a particular significant wave-height occurring with a particular peak period.[11] JPDs are created through statistical analysis and require many years of data; 10 years of data is recommended to produce an accurate representation of the proposed deployment site. Since wave-height, period, and direction are not statistically independent, JPDs can be created for wave-height and period, wave-height and direction, and period and direction. The JPD characterization can then be used with the chosen spectral shape to determine the average annual power, or energy, present in the waves at a particular location. This treatment is also used to provide inputs for modeling WEC devices and allows for predictions of the average annual power produced by a device at that location.

Device Type Technology Overview

Introduction

The exploration and study of the principles of wave energy conversion blossomed in the early 1970s. Since that time, many prospective device designs have been created and prototyped. These designs are classified and modeled by considering their method of conversion, their directional dependence, as well as their deployment depth.[1] There are three main methods of conversion: overtopping devices, oscillating water columns, and WABs. The methods can then be embodied as point absorbers, terminators, or attenuators which relate to their directional dependence as shown in Figure 1. [12] Point absorbers are able to convert incident wave energy from any direction with equal efficiency and are thus normally fully axisymmetric while terminators and attenuators are orientation-dependent and are not fully symmetric. Terminators are oriented perpendicular to the incoming wave fronts while attenuators are oriented parallel to the incoming wave fronts. Each device can be deployed offshore, near-shore, or it can be shore-mounted. These distinctions in depth often influence the type of mooring pursued and can be integral to the method of power conversion.

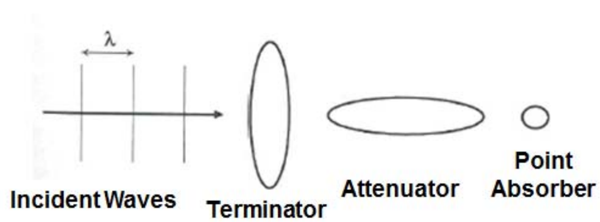

Figure 1: Schematic presented in Cruz, 2008 highlighting the relative scale and orientation of the distinct directional dependencies.

This report is focused on WAB point absorbers that are deployed in offshore water depths. In this context, offshore is defined by water-depths between 50 meters and 150 meters that often imply that the devices will be floating and hence require a self-reacting mechanism to produce electricity. WAB point absorbers convert the incident power into electricity through a structure oscillating in response to the incident resource. Another important aspect of a point absorber besides its directional independence is its size. As implied by the term “point absorber” these devices convert a portion of ocean energy from the wave at a single point and thus have a small characteristic dimension with respect to the incoming wavelength.

Theoretical Operation

Absorbing wave energy with WEC devices requires that energy is removed from the waves thus resulting in a reduction of wave height of both the incident and reflected waves. WABs and oscillating water column devices are good wavemakers because they are able to produce waves that are out of phase with the incoming waves thus allowing cancellation and a reduction in height.

The directional dependence and the primary oscillation directions place theoretical limits, much like the Betz limit in wind, on the absorption capabilities of a WEC device. These absorption capabilities are dependent upon the waves that the device can produce (i.e. the profile of the radiated wave) when oscillated in the primary oscillation direction(s). For maximum energy to be absorbed by the device, it must oscillate with an optimal phase and amplitude. Figure 2, first presented by Cruz[13] shows the radiated wave pattern and the absorbed wave pattern for two WABs: a heaving point absorber and an attenuator of length 2λ, where λ is the wavelength of the incident wave.

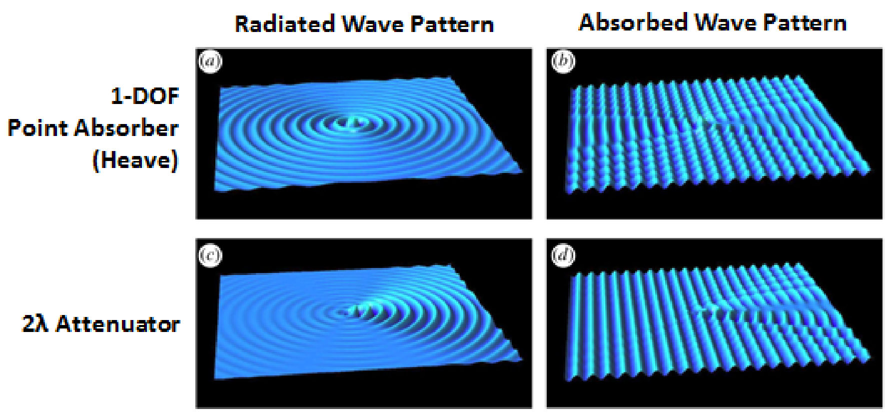

Figure 2: The radiated wave pattern and the absorbed wave pattern for two WABs. Reproduced from Cruz 2008.

From these plots it is clear that the radiated patterns (Figure 2 a & c) are quite different between the two devices, and hence it is reasonable to expect that their absorption capabilities are also different as shown in Figure 2 b & d. In Figure 2 b & d, the wave is incident from the left and the calm portion shown to the right of the absorber indicates absorption. Absorption is measured by the capture width which specifies the width of the incoming wave that contains the same amount of power as absorbed by the device. The capture width is calculated by dividing the absorbed power in kW by the incident wave power flux in kW/m and hence the capture width has units of length. The absorbed wave patterns in Figure 2 also shows that each device is absorbing more energy than contained in its frontal width, a surprising aspect of WEC devices. Thus a capture width ratio, the ratio of the capture width to the frontal width of the device, can be larger than one. However, this is clearly the result of the dispersive nature of radiated waves hence allowing for cancellation over a much larger width than what created the radiated waves.

Table 1 summarizes the theoretical capture widths for a single body operating with the specified directional dependence and primary oscillation direction or length/width characteristics.

Table 1: The theoretical capture widths for a single body (or oscillating water column) operating with the specified directional dependence and primary oscillation direction or length/width characteristics. Equations reference Falnes, 2002

Directional Dependence	Mode of absorption	Theoretical Capture Width
Point Absorber	1-DOF: Heave Eq. 6.77[14]	$\lambda/_{2\pi} \approx 0.16\lambda$
	1-DOF: Surge or Pitch[13]	$\lambda/_{\pi} \approx 0.32\lambda$
	2-DOF or 3-DOF: Heave+Surge, Heave+Pitch, Heave+Surge+Pitch, or Surge+Sway+Pitch Eq. 6.86 [14]	$3\lambda/_{2\pi} \approx 0.48\lambda$
Attenuator	$\text{Length} = \lambda$ [13]	0.50λ
	$\text{Length} = 2\lambda$ [13]	0.73λ
Terminator*	$\text{Width} = \lambda$ Eq. 6.108 [14]	λ

*It is expected that the theoretical capture width will be dependent upon width of device (similar to length dependence of attenuator). At this time the authors know of no work resulting in a similar formulation to Yemm et al.;[13] however there is work that clearly shows the dependence between actual capture width and width of device.[15,16]

These theoretical capture widths were derived using linear analyses (linear potential flow theory) which cannot be achieved in reality. Thus, there are many factors that reduce the actual output of a device from the theoretical limit including: viscous and friction losses, motion limitations, and nonlinearities that move beyond the applicability of linear potential flow theory. These factors combine to thwart achievement of the theoretical limit; however, for the devices where the limit is a function of the asymmetry (width and length) then there is an inherent advantage to scaling the device in that direction. Hence, comparing the theoretical capture widths can be instructive when considering the specific technology developments that can influence the LCOE of the device type.

Design Characteristics

A particular device type, such as the offshore WAB point absorber, can be designed in various ways (e.g., devices from OPT and Oscilla) thus further diversifying the industry. Within each device type, there are other design characteristics that will influence the power performance as well as the CapEx and OpEx costs. These characteristics can be divided into the following categories:

- Primary Maintenance Location
- Placement in the Water Column
- Buoyancy
- Mooring and Anchoring Type
- Symmetry
- Number of Bodies
- Primary Oscillation Direction
- Drivetrain Type
- PCC Reference
- Oscillation Constraint
- Survival Strategy

Primary Maintenance Location: Maintenance can either be performed *in situ* or the device can be disconnected from electrical and mooring infrastructure, towed back to a sheltered site, and serviced there. A device may be designed to be serviced *in situ* however there could be failures that require servicing on shore. Execution of maintenance is dependent upon: weather windows, distance from port, vessel requirements, availability of replacement parts, and predicted failure rates. Hence the location of planned maintenance will affect the availability of the device, the optimal profile of the device, and the operational expenditures.

Placement in the Water Column: A device may either be situated in the water column such that it has surface expression or it may be submerged below the surface. When combined with the buoyancy category, it is clear which of these devices are freely floating. These configurations will affect the survivability and power performance of the device.

Buoyancy: A device may be either neutrally buoyant or have positive or negative buoyancy. This characteristic will affect the type of mooring that can be used on the device as well as the power performance of the device.

Mooring and Anchoring Type: Selection of a mooring design is dependent upon many factors: shallow or deep water deployment, primary motion of the WEC (i.e., heave, pitch, etc.), seabed type, and desired watch circle.[1] Typically, the extreme wave environment will drive the size of the system components, and hence it is used to design the mooring system. Additional factors to consider in the mooring system design are cost, ease of installation, translation to different deployment sites, and scalability for WEC farm integration.

The oil and gas industry has offered guidance on configuration, materials, and Factors of Safety (FoS). The mooring configuration can affect the PCC selection as well as the power performance, or it can be selected to interact minimally with the device performance. Mooring systems that are designed to influence the power performance are either tension based systems or systems that allow weathervaning. Mooring systems that are designed to only influence the device motion during storms are slack catenary based systems that may or may not have auxiliary floats. The mooring systems can be spread or single point; full weathervaning is possible with single point mooring systems whereas it is limited for spread systems. The anchor choice is tied to the mooring design; possible anchor options include gravity, drag-embedment, pile-driven/suction, vertical load anchors, and drilled and grouted anchors.[1] Only the pile-driven, vertical load, and grouted anchors can withstand vertical forces. The mooring system will always affect the survivability of the device.

Symmetry: Point-absorbers may be fully axisymmetric making them completely directionally-independent, or they can have asymmetries and prominent lengths in particular directions. The directional dependence, if present, can influence the mooring selection as well as the power performance. These hybrid devices, although directionally dependent, may operate more like a point absorber due to the small characteristic dimensions of the device with respect to the incoming wavelength.

Number of Bodies: A device may be a single body or multiple bodies. A single body is defined by the response to the incident waves; if multiple bodies are rigidly connected to one another such that the response to the waves is the same for all bodies, then this is considered a single body. When each body responds independently to the incoming waves, they are considered multiple bodies. The buoyancy and mooring configuration can influence the number of bodies required to produce electricity.

Primary Oscillation Direction: The water particle motion in a wave is circular and hence the direction that the body oscillates in is not limited to up and down motions (heave or vertical). The primary oscillation direction results in a primary mode of energy extraction from the waves. Clearly, this characteristic will affect the theoretical device performance, as shown in Table 1, as well as the most suited drivetrain type.

Drivetrain Type: The drivetrain converts the device motions into the final form of mechanical energy, or "captured power" [5], that drives the generator.[17] There are many drivetrain options including rack and pinion, ball-screw, and hydraulic systems. Many of these drivetrain systems can be designed to be linear or rotary in operation. If a direct drive permanent magnet system is used, then the drivetrain and generator are condensed into one part. Additionally, if piezoelectric or magnetostrictive materials are used then the conversion from mechanical to electrical energy is completed without relative motion and without the addition of a generator.

PCC Reference: The PCC must have a reference through which energy is extracted. Broadly categorized, the PCC reference can be fixed or relative.[18] Fixed reference PCCs are connected to the seabed and are often utilized by shore-mounted or near-shore devices. Devices deployed offshore must use relative reference PCCs. The relative reference between multiple bodies can be either mutual reaction (bodies responding with similar orders of magnitude) or one body can be inertially dominated (mimicking a "fixed reaction") while the other is dynamically responding to the waves.[18] The PCC reference, mooring design, and number of bodies are all interdependent.

Oscillation Constraint: A device's response to large events is a fundamental characteristic of the device. The constraints placed on the system during these large events influence the peak power production and hence the sizing of the power conversion system. The constraints can also influence the survivability of both the device and the power conversion chain. Typically devices that oscillate in the vertical direction require limitations on the motion between the bodies, whereas devices that oscillate in pitch may be able to eliminate the need for motion restrictions.

Survival Strategy: A device's strategy to survive the 100-yr storm is a vital design consideration and can heavily influence the economics of the device. Developers have many options available to them, a few of these include: submerging the devices below the significant wave action, restricting the relative motion between bodies using a "lock" (either the generator or a mechanical latch), or designing the system to have minimal reaction to large waves. A basic knowledge of this strategy must be known in order to have a comprehensive understanding of a device's characteristics.

In the next subsections, the devices investigated in this report will be introduced and defined with respect to the characteristics and maturity, TRL, levels defined above.

Sources of Information

Three main sources of information were used for the determination of cost-reduction pathways and are described below.

- Research and academic literature regarding WAB point absorber technologies and their energy resources.
- The U.S. DOE Reference Model effort [19]
- Webinars held with companies involved in the development and deployment of WAB point absorber devices.

Literature Survey

A literature survey was performed to investigate current research efforts being performed both nationally and internationally on WAB point absorber devices. The results point both to current issues and solutions as well as current gaps in research that are not addressing present, or future, needs of the MHK industry. While industry hurdles may be alluded to in individual papers, the literature survey was used to set the stage for investigation of those issues to be discussed during the industry webinars and spreadsheets and to then aid in determining those cost-reduction pathways that would have the most significant impact on reducing the LCOE and the most success if pursued.

Throughout the whitepaper citations from the literature survey were placed in support of industry and SNL expert assertions.

Reference Model 3

The United States' DOE Reference Model effort is finalizing its initial investigation of an offshore WAB point absorber, labeled Reference Model 3. RM3 was designed to be a conservative representation of the technology being pursued by industry developers, such as the industry examples profiled below. It was designed to be deployed in a Northern California wave climate off the coast from Eureka. RM3 is at WEC TRL4; it has been tested in the laboratory and initial designs for the major subcomponents were completed (structural, mooring, and PCC). The principal characteristics of this offshore WAB point absorber are:

- Primary maintenance location: *In situ*
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally Buoyant
- Mooring and anchoring type: 3-point slack moored, drag embedment anchors
- Symmetry: Fully z-axisymmetric
- Number of bodies: 2 bodies
- Primary oscillation direction: Heave motion between bodies
- Drivetrain type: Linear Hydraulic
- PCC reference: Relative, reaction between bodies with a mass-dominated spar
- Oscillation constraint: Yes, requires end-stops
- Survival strategy: Not considered

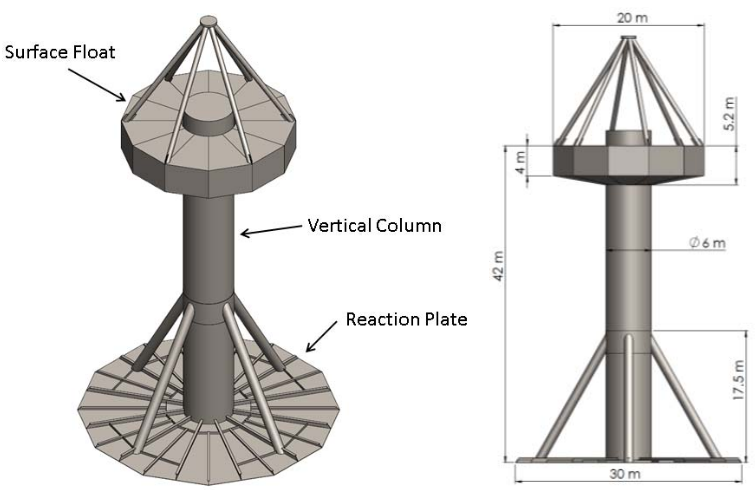

Figure 3: Representation of the RM3 device. (*Reference Models for MHK Technology Design, Analysis, and Levelized Cost of Energy (LCOE) Estimates*, 2013)

As seen in Figure 3, the wave power buoy design has a surface float which translates with wave motion relative to a vertical column spar buoy which connects to a subsurface reaction plate. This design was analyzed for power performance and cost in a generic wave resource based on data from a location near Eureka, California. Figure 4 shows the relative cost of identified categories as a function of installed capacity and cost components over a lifetime of 25 years.

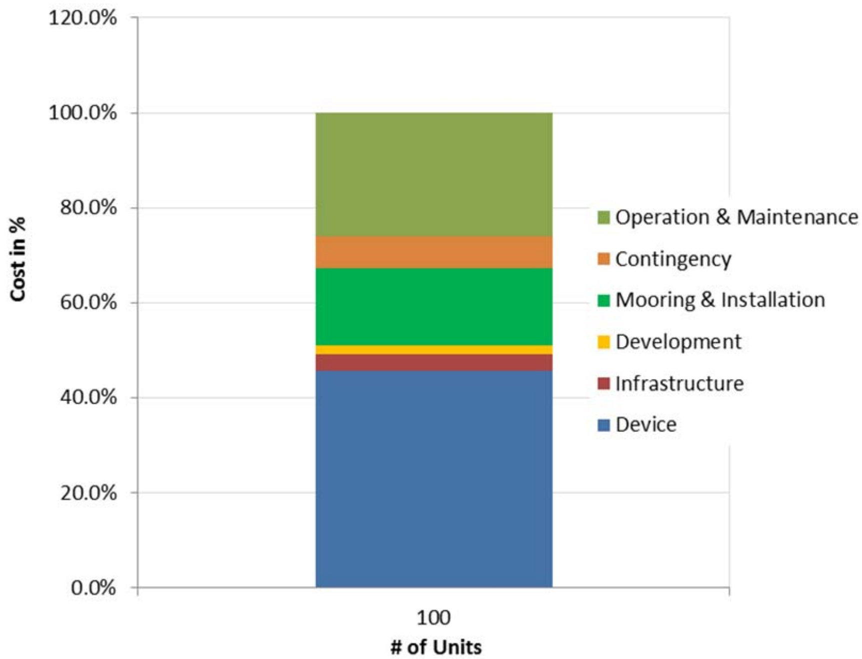

Figure 4: High-Level Cost Breakdown — Point Absorber Technology over a 25 year lifetime.

Evaluation of Figure 4 shows the RM3 technical cost drivers for a 100 unit deployment scale include:

- Device Structural Components, including the PCC
- Mooring & Installation
- Operation & Maintenance

Cost-reduction pathways have emerged from the initial Reference Model 3 effort. These preliminary cost-reduction pathways possibilities include:

- Optimize Structural Design – The structure represents a large portion of the CapEx, which includes costs arising from manufacturing, transportation, and material usage. Reducing the power to weight ratio is an effective method to reduce LCOE. [20,21]
- Advanced Controls – Device performance could be increased significantly by using a more advanced control strategy. Prediction of wave behavior coupled to the control and adaption of the action of the PCC is an active area of academic and commercial research. [22,23–26]
- Improved Power Conversion – Further work to investigate alternative components in the PCC that can provide higher efficiency would be worthwhile. Drivetrain and generator designs that are customized to the application increase both reliability and efficiency. [27,28]
- Array Optimization – An optimized array would minimize CapEx and OpEx associated with installation, mooring materials, maintenance and infrastructure costs. [18]

- Improved Mooring Design – An improved mooring design would consider new materials and be designed for loads appropriate to WEC devices. Benefits of this design would decrease mooring materials costs, installation costs, and maintenance costs. In addition, resilient mooring structures would lengthen the period between scheduled maintenance operations and could expand acceptable deployment locations for a WEC array.[1]

Aggregated Information from Industry

Over the course of a few weeks in August 2012, four webinars were held separately with four companies whose primary mission is the development of point absorbing type wave energy converters for converting wave oscillations into electricity. During the webinars, each company was asked several questions relating to their cost-reduction pathways. The companies were:

- Columbia Power Technologies, LLC.
- Northwest Energy Innovations
- Ocean Power Technologies, Inc.
- Oscilla Power Inc.

Industry Descriptions

Columbia Power Technologies, LLC

Columbia Power Technologies is a U.S. company headquartered in Virginia that has been pursuing the development of a WEC device since 2005. The SeaRay, a hybrid point absorber – attenuator device, was studied in this report. The SeaRay started its development in 2009 and in 2011 it was tested in a scaled environment in Puget Sound. The SeaRay has progressed from v0 to v3 with the newest design iteration completing scaled testing in 2012; the design progression has resulted in significant changes to the device and its projected cost. The cost estimates are for the v3 design which has only undergone scaled testing, but the company has had experience with an ocean deployment of the v2 device in Puget Sound. The principal characteristics of this offshore WAB point absorber shown in Figure 5 are:

- Primary maintenance location: *In situ*
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally buoyant
- Mooring and anchoring Type: 1-point slack moored with weathervaning, drag embedment anchor
- Symmetry: Symmetric across the y-z plane with an elongated x-axis parallel to the waves in an attenuator configuration
- Number of bodies: 3 bodies
- Primary oscillation direction: Pitch motion between forward float and central spar and between aft float and central spar
- Drivetrain type: Rotational direct drive
- PCC reference: Relative, reaction between 'wings' with a mass-dominated spar
- Oscillation constraint: None
- Survival strategy: There is a geometry reconfiguration that avoids relative motion between the bodies.

Figure 5: Representation of a prior generation of the Columbia Power Technologies Manta device. [http://www.columbiapwr.com/rayseries.asp]

More information regarding Columbia Power Technologies, LLC and the SeaRay can be found on their website: http://columbiapwr.com/ray-series/.

Northwest Energy Innovations.

Northwest Energy Innovations is a Portland Oregon based firm pursuing the development of the Wave Energy Technology – New Zealand (WET-NZ) device within the United States. The WET-NZ design, a hybrid point-absorber – terminator device, is the result of a research consortium between Industrial Research Limited (IRL) and Power Project Limited (PPL). The WET-NZ design started its development in 2006 and has been tested three distinct times (at different scales) in the open ocean. In 2012 it was tested at half scale at the Northwest National Marine Renewable Energy Center's (NNMREC) ocean test site. The principal characteristics of this offshore WAB point absorber shown in Figure 6 are:

- Primary maintenance location: *In situ*
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally buoyant
- Mooring and anchoring type: 3-point slack moored, drag embedment anchors
- Symmetry: Symmetric across the x-z plane with an elongated y-axis perpendicular to the waves in a terminator configuration
- Number of bodies: 2 bodies
- Primary oscillation direction: Pitch and heave motion between bodies
- Drivetrain type: Rotational hydraulic
- PCC reference: Relative, reaction between bodies with a mass-dominated spar
- Oscillation constraint: No
- Survival strategy: The float is allowed to rotate 360°.

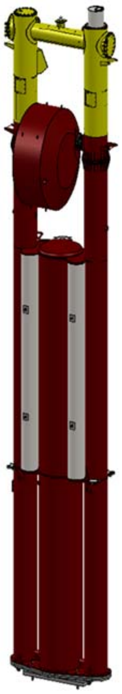

Figure 6: Representation of the Northwest Energy Innovations WET-NZ device. [http://www.nwenergyinnovations.com/technology/how-it-works/]

More information regarding Northwest Energy Innovations and the WET-NZ device can be found on their website: http://www.nwenergyinnovations.com/rd/.

Ocean Power Technologies Inc.

Ocean Power Technologies (OPT) is a U.S. company, headquartered in New Jersey that has been pursuing the development of a WEC since 1994. The PowerBuoy 150 (PB150) is studied in this report and development work began in 2002. OPT has achieved Lloyd's Register certification for the PB150. OPT has been awarded the first FERC license issued for a wave power station in the US. Additionally OPT has grid connected a PB40 at the US Marine Corps Base Hawaii (MCBH) at Kaneohe Bay meeting IEEE and UL standards (as certified by Intertek). They have completed three projects in which PB40's or PB150's have been deployed in the open ocean and they have two current projects with devices either deployed or scheduled to be deployed within a year. The principal characteristics of this offshore WAB point absorber shown in Figure 7 are:

- Primary maintenance location: *In situ*
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally buoyant
- Mooring and anchoring Type: 3-point slack moored, gravity anchors
- Symmetry: Fully z-axisymmetric
- Number of bodies: 2 bodies
- Primary oscillation direction: Heave motion between bodies
- Drivetrain type: Linear direct drive
- PCC reference: Relative, reaction between bodies with a mass-dominated spar

- Oscillation constraint: Yes, requires end-stops
- Survival strategy: The spar is locked to the float.

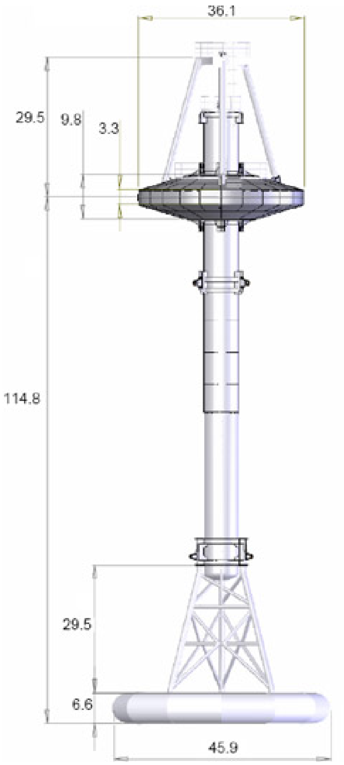

Figure 7: Representation of the Ocean Power Technologies PowerBuoy 150 device (dimensions shown in feet). [http://www.oceanpowertechnologies.com/pb150.html

More information regarding Ocean Power Technologies, Inc. and the PowerBuoy device can be found on their website: http://www.oceanpowertechnologies.com/technology.htm.

Oscilla Power Inc.

Oscilla Power Inc was founded in Salt Lake City UT in 2009 and has been steadily pursuing the development of the iMEC technology. This device does not require relative motion since mechanical strain energy is converted directly into electrical energy through reverse magnetostriction. Reverse magnetostriction results when changes in the strain of ferromagnetic materials results in changes to the magnetic field. This device is unique from the other devices studies since it does not involve relative motion and instead requires reaction of the oscillating structure against ground. iMEC has been tested in the laboratory and initial designs for the major subcomponents have been completed (structural, mooring, and power conversion chain). The principal characteristics of this offshore WAB point absorber shown in Figure 8 are:

- Primary maintenance location: *In situ*
- Placement in the water column: Surface expression
- Buoyancy type: Positively Buoyant
- Mooring and anchoring Type: 3-point tension-legged, gravity anchors
- Symmetry: Fully z-axisymmetric

- Number of bodies: 1 body
- Primary oscillation direction: Heave motion between body and anchor
- Drivetrain type: Reverse Magnetostrictive
- PCC reference: Fixed, reaction against seabed
- Oscillation constraint: No, there is no relative motion in this device
- Survival strategy: Not known.

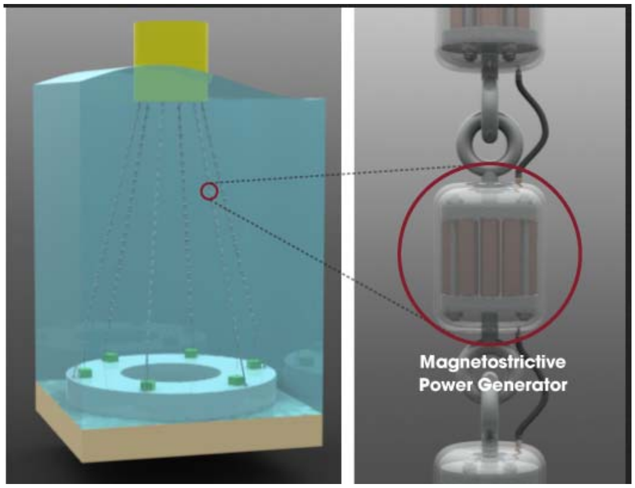

Figure 8: Representation of a prior version of the Oscilla Power iMEC device. [http://oscillapower.com/wp-content/uploads/2012/02/wavearraythreepanel11.png].

More information regarding Oscilla Power Inc. and the iMEC device can be found on their website: http://oscillapower.com/imec-technology/.

Webinar information Gathering Methods

Details of the process by which Sandia National Laboratories (SNL) conducted the webinars are contained below. Sample questions and blank worksheets are given in order to protect proprietary information. The four companies interviewed were DOE funding awardees.

Webinar Process

The stated goal of the webinar was to assess the viability of various cost-reduction pathways as well as the largest unknowns in projected costs. Each webinar interview of industry personnel had in attendance SNL and DOE representatives; these representatives compiled notes from the conversation. The timeframe for evaluation of the potential of identified cost-reduction pathways is 2030.

To ensure consistency regarding interaction with industry participants, all webinars used the same question set (below).

1. What are your assumptions when determining the LCOE of your utility-scale project?
2. What are the most promising cost-reduction pathways for your company to pursue?

3. What are potential areas for improvement that would require an incremental improvement or smaller investment (i.e., the low hanging fruit)?
4. What are potential game changing improvements that could significantly reduce the LCOE but would require significant resources to achieve?
5. Have you generated economic or performance data that can inform and that can help DOE meet its data and analysis requirements (e.g. identification of components with significant technical headroom for targeted R&D and LCOE reduction; techno-economic assessment) that you are able to provide?
6. What areas have the most uncertainty in your cost predictions?

Some questions addressed the various assumptions made during the process of determining levelized cost of electricity. Other questions probed which specific cost-reduction pathways are easily investigated owing to little effort or resource input. Likewise, questions regarding some of the more substantial cost-reduction pathways, yet more difficult in terms of dedication and resource allocation, were also discussed. Some of the concluding remarks during the webinars involved discussions relating to cost-reduction uncertainties and how those uncertainties might affect levelized cost of electricity.

After each webinar, the multiple transcripts from SNL and DOE were collated by topic. This ensured that all information was complete and correct as captured. This report gives emphasis to the information acquired from the industry webinars.

Cost Breakdown Structure Worksheet

After the webinar was conducted, Sandia National Laboratories (SNL) provided a cost breakdown structure (CBS) table to each of the four companies to be filled out to detail quantitative data about the cost-reduction pathways. A blank CBS is included in Appendix A. The industry participants were asked to estimate the percentage of their costs that were devoted to CapEx and OpEx. Those percentages were broken down further into component and O&M costs.

CapEx:

- Device/Structural Components
- PCC and Capture Means
- Subsystem Integration
- Infrastructure
- Mooring
- Installation
- Decommissioning
- Development

OpEx

- Planned Maintenance
- Unplanned Maintenance
- Replacement Parts
- Insurance
- Environmental Monitoring
- Consumables
- Other – grid transmission charging

For each cost component, the companies were asked to identify one or more cost-reduction pathways. They were asked to estimate the cost effect of each proposed pathway and the timeline to achieve it. Additionally they were asked to score the potential for cost-reduction and the potential for improved power generation of the proposed pathway on a scale of 0 to 4 (0 being no potential, and 4 being high potential).

The companies were given the following guidance. Cost percentages were to be calculated for a single device in a full scale array (approximately 100 devices or more) and for mature technology (TRL=9) deployed for the expected lifetime of the device. The focus of this effort was stated to be decreasing technology development costs only, and would not include cost-reduction pathways on environmental permitting, and insurance, etc.

Analysis Process

The CBS from Columbia Power Technologies LLC, Ocean Power Technologies Inc., and Oscilla Power Inc. and the reference device contained breakdowns of the cost, the potential for cost-reduction, and the potential for energy generation improvement in the CapEx. There was incomplete information on the operational expenditures. The CapEx values were first averaged into single values for each line item in the CBS worksheet. A weighting system was applied to adjust for the TRL of the company's technology; for instance, a company that had a full scale deployed system was given more weight than a company whose technology was still in testing at a wave tank facility. This weighting was applied to both the expenditures as well as the potential for cost-reduction. The final ranking for each line item in the CBS resulted from a weighted average of the cost and the potential for cost-reduction.

Additionally, specific technology developments that were mentioned during the webinar, offered in the completed CBS worksheet, or found in the literature search that addressed areas in the line items of the CBS were generalized, compiled, and counted. These developments, along with the judgment of the whitepaper authors, offered the basis for the presented research paths. Thus, the number of times a research path was mentioned served to corroborate the ranking of the potential for progress given by each developer.

Since no data was explicitly collected on increased AEP separate from decreased CapEx, the whitepaper authors determined the most logical divides within categories to begin to differentiate the two. This separation was not re-communicated to the developers, and hence the third category of AEP reflects the views of the whitepaper authors. The AEP categories were determined to be Advanced Controls, 'Captured' Power Conversion, Array Layout, and Device Profile.

Finally the three categories (CapEx, OpEx, and AEP) were compared to one another to obtain the overall prioritized ranking. In order to compare the three areas against one another, they were ranked (on the scale identified) based on the following considerations:

- impact on LCOE (scale: 1-10),
- potential for progress in the area (scale: 1-4),
- potential for success in the timeframe (2030) considered (scale: 1-4)
- confidence in success (scale: 1-4)

The first two considerations were populated directly from the ranked CBS analysis well as identified improvements from the webinars and literature survey. The last two rankings were based on the judgment of the whitepaper authors drawing on experiences with other renewable technology developments. A sum of these ratings was used to prioritize the technology developments.

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Prioritization and Paramount Cost-Reduction Pathways

Prioritization is based on the quantitative information provided by the industry webinars, the experience and engineering judgment of the whitepaper authors, the results of the DOE Reference Model effort, and the literature review. It is important to note that these cost-reduction pathways were evaluated through a long-term lens (year 2030+) in which large deployment numbers (approximately 100 devices or more) are assumed. This approach reduces the impact of product development costs because these costs are amortized over a large number of production units.

Most Promising Cost-Reduction Pathways

These pathways are judged to be the most promising for an oscillating water column device and are discussed below.

- Advanced Controls
- Optimized Structural Design
- Improved Power Conversion
- Optimized Device Profile

Advanced Controls

Definition

Advanced controls refer to the procedures capable of increasing the capture efficiency of the device. These procedures can be implemented through control of the PCC. Regardless of the control type, execution of the control is predicated upon knowledge of the oncoming waves.

Justification

The lowest efficiency in the ocean energy conversion process is the primary capture efficiency (or conversion efficiency) of the energy capture device, i.e. the 'intercepted' power. Currently only a small percentage of the incident energy in a climate, over a narrow range of frequencies, is actually converted into grid-delivered power. The low conversion efficiency is rooted in the basic operation of the devices as resonant-power-absorbers. The advanced controls proposed above effectively expand range of resonant-power-absorption. Since the power produced by a device affects all aspects of the levelized cost of energy and since the absorbed power can be increased anywhere from 5% to 330% this is a top cost-reduction pathway. [22,23–26]

This cost-reduction pathway is considered to be the most promising of all pathways evaluated. The Reference Model effort determined that rapid tuning control strategies were the best path to significant reduction in LCOE. The industry webinars and spreadsheets also indicated "advanced controls with foreknowledge" as a top cost-reduction pathway. The Sandia whitepaper authors also rated advanced nonlinear controls highly and noted that there is opportunity for significant increased energy capture with existing devices as well as new devices. The literature review indicates that advanced nonlinear control coupled with wave prediction could result in a 50% reduction in LCOE.

Research Paths

The goal of an advanced nonlinear controls research effort would be to fundamentally change the current point absorber structurally-defined phase matched absorption to an intelligent controls-based phase matched absorption.

This nonlinear controls-based approach could capture more than twice as much energy as current systems and result in a 50% reduction in LCOE.

To achieve this goal would require one research path with two primary thrusts.

- Wave Prediction: This effort would be comprised of two components: wave measurement and wave prediction algorithms. The wave measurement effort would focus on the sensors, hardware, and systems needed to adequately feed-in to the wave prediction effort. The wave prediction task could develop algorithms capable of generating a real-time incoming wave field for the WEC array based on the wave measurement system. Non-linear and stochastic-capable algorithms would be needed to generate the incoming wave fields. Both scaled device tank testing and full-scale ocean deployment would be needed to demonstrate this technology.[29]
- PCC control: This effort would focus on optimizing device control to minimize LCOE. Both active and passive control strategies can be pursued for the offshore point absorber devices.[24,30] Active control strategies require putting energy back into the device in order to achieve instantaneous and consistent phase matching. Alternatively passive control strategies implement phase matching through latching or clutching techniques where the phase match is only achieved for a portion of the wave cycle.[22,31] Given the nonlinear and stochastic input from the wave prediction portion of the research and the fact that the devices operation in an ocean environment is fundamentally nonlinear, the PCC control algorithm will need to be nonlinear and capable of mitigating the effects of stochastic input. This device control effort is very closely tied to the performance and specifications of the PCC. To fully realize the potential of advanced nonlinear controls, more capable PCC s may need to be utilized. Both scaled device tank testing and full-scale ocean deployment would be needed to demonstrate this technology.

Optimized Structural Design

Definition

The physical structure or the structural design refers to the design that incorporates the necessary components to resist the loads imparted to the device through waves and mooring connection points. The profile of the device, its general size and its shape is determined by power conversion requirements; the physical structure is determined by the loads that must be mitigated. Optimizing the structural design must incorporate the costs of manufacturing, transportation, and material usage. The global economy that we operate within incentivizes production of devices in locations where raw materials, fabrication, and labor are inexpensive. This in turn requires that devices are designed to be transported to their deployment locations. Additionally, the type and amount of materials used to produce a structure should be optimized according to the capital cost, maintenance costs, and design life. Optimized structural design seeks to minimize the safety factors used at the component and system levels while maintaining device performance and integrity.[21,20] Though not dependent on the introduction of new structural materials, optimized structural design compliments material improvements in that it further improves power to weight ratios and can positively impact deployment and maintenance through reduced weight.

Justification

This CRP was identified and highly rated by both the Reference Model project and industry developers as a significant path toward lowering cost of energy and it impacts both capital and operational expenses. Wind energy experience can be leveraged in order to make initial gains in this area, once adapted for the marine environment. As demonstrated in the aerospace industry, a more complete knowledge of the system allowed significant reductions in material weight and safety factors, while also improving performance and reliability. Efforts to reduce the power to weight ratio through structural optimization is a fundamental method for lowering LCOE. Because this CRP topic encompasses both capital and operational expenses, it will have significant impact.

Research Paths

The underlying goal of this research is to better understand the loads acting on the structure. After the loads on the structure are fully understood, the structural designer can utilize the information to reduce excess margin in structural safety factors, investigate new materials for the primary structure, and improve manufacturability with modular design and design for fabrication, while maintaining or improving device performance. Optimization of the structural design of point absorber devices will minimize weight and reduce excess margin in safety factors.

Each device designer will likely determine a unique solution for their design, thus the thrust of this research is to develop the tools that allow them to customize that design. The loads acting on the structure drive the physical design, and without accurately and fully understanding those loads, progress in this area will be negligible.

A nonexclusive and un-prioritized list of promising pathways is presented below. These pathways include model tool development, the use of case studies that will further the industry knowledge, as well as testing facilities suited to examining the structural integrity of components.

This goal can be achieved through multiple paths, including:

- Survivability Modeling: Current understanding of requirements for survivability in extreme events is quite limited and thus optimized structural design is not possible. To truly optimize the structure of a point absorber, much greater understanding is needed regarding the loads which occur during extreme events. Detailed device structural analysis (probably Finite Element Analysis) should be coupled with more accurate load estimates. While these load estimates may be obtained from high-fidelity CFD calculations, it is also possible that experimental determination via sub-scale physical models will be more cost-effective and universally applicable.
- Fatigue Modeling: These devices are placed in an environment where they will be continuously subjected to cyclic pressure loading from the waves, cyclic tension loading from the mooring lines and umbilical cables, as well as cyclic bending moments.[1,32] Additionally, certain designs could result in cyclic greenwater, slap, and slam events. Developing modeling tools that can begin to address the fatigue of the structure will be very important to ensure the longevity of the design.
- Material Case Studies: The specific materials chosen for a design will not be unanimous across the industry. Regardless, the process to qualify a particular material for a design is more generic. Publically accessible case studies performed on likely material candidates would offer guidance on the best qualification process. The new structural design should be generated from the survivability and fatigue loads found through the above proposed modeling tools. The development of case studies would focus on maintaining the power performance of a particular device and investigate the ability of the newly required design to withstand the loads using alternative materials. These case studies would also engage the manufacturing industry to ensure that the fabrication methodologies are conducive to volume production. Unique influences from the marine environment would need to be incorporated including saltwater uptake and biofouling as these two processes can affect the integrity of the material over time, and this has been seen in offshore wind gearboxes.[33] Data from these case studies would seed a larger database that contains material response in consideration of environmental influences to WEC-specific loading, and would engage the manufacturing industry early to ensure volume production is possible with the desired materials.

- Manufacturing Procedures: Since each device is unique, what is proposed here is an investigation of how particular designs could be fabricated modularly in order to achieve better manufacturing and transportation costs. These studies would identify the raw materials, labor, tooling, factory capital costs, and transportation costs associated with a particular design, and identify areas where better manufacturing and transportation costs could be achieved. These studies would act as publicly accessible procedures for determining how a new design could be similarly fabricated. These procedures would engage the manufacturing industry to determine how the survival and fatigue loading data (generated from models above) could be used to generate more simplified designs applicable to volume production and they may also identify the infrastructure development required to see volume production become a reality.
- WEC Design Standards: Offshore oil and gas standards are currently being applied to WEC designs in order to obtain the necessary insurance prior to deployments[i]. These standards often employ high FoS due to the catastrophic nature of their failures considering that they are manned stations. The survivability modeling and fatigue modeling research paths should be employed to inform new standards customized to WEC deployments. Additionally, instrumented WEC deployments should be supported to determine the correlation of the modeling results with reality.

Improved Power Conversion

Definition

Each distinct PCC component operates collectively with the others to achieve a single goal. Improving the PCC requires each component to be addressed, and hence there are many opportunities to affect the final design. For the purposes of this research the grouping PCC was used to obtain the collected cost of captured mechanical power to electrical power. However, during the webinar individual questions were targeted to each component of the PCC in order to identify the research paths that held the most promise for this subsystem of ocean wave energy conversion.

Justification

The power conversion mechanism has a high number of distinct components operating collectively for a single goal; therefore, there are many opportunities to affect the final design. The PCC is a major capital expenditure for the offshore WAB point absorber designs according to the industry interviews and the reference model project. Additionally, there are efficiency losses in the device owing to the PCC. Hence, the PCC has the ability to affect the numerator and the denominator in the cost of energy equation thus making it a top cost-reduction pathway.

Research Paths

There are multiple ways to improve the PCC. A nonexclusive and un-prioritized list of promising pathways is presented below.

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[i] Note: Standards specific to WEC designs are in initial stages through efforts in the IEC. However, current standards relate to nomenclature, resource, and power production. Standards specific to the structural design and anchor and mooring are not as developed and are not based on large bodies of reliable data.

- Systems-Level Performance Model: Determining the requirements for each component of the PCC necessitates a systems-level performance model. This model can assist the developer in understanding where COTS (Commercial Off The Shelf components) are appropriate and where custom solutions may be necessary. This model will also assist in specifying the requirements for the custom solutions. Without this model, it is difficult to determine if the components selected are the best match for a particular designs operation.
- Drivetrain Design & Manufacture: There are a limited number of ways in which mechanical power can be produced from the wave activated body, however optimizations to these designs are needed. Incremental optimizations relating to efficiency losses and manufacturability of the drivetrain can be realized.
- Generator Design: Developing generators/a generator industry for low speed high torque applications would be beneficial. In addition, the wave oscillation frequency is highly variable. Thus the drivetrain is oscillating at a variable rate. However, most generators are designed to operate efficiently around a single rotation rate. This aspect of the generator requires either short term storage or inefficient operation. Hence, designing custom generator solutions catered to this variably-cyclic environment could result in higher levels of grid-delivered power.[27][28]
- Incremental Efficiency Improvements: The PCC can be viewed as a series of efficiency losses. At each step in the power conversion chain there is an opportunity to look for higher efficiency components.
- Survivability: The role of the entire PCC in survival conditions will drive the size of each of the components and hence the cost. If a method can be found to remove the PCC from the load pathway or to ameliorate the effects of large loads on the PCC, then the sizes of each of the components could be reduced. It is possible that an additional component may have to be added to the WEC in order to completely remove the PCC from the load pathway thus mitigating the savings in reduced component size.
- Storage Minimization: On-board storage requirements in a system are driven by peak to average power ratios, sizing of power electronics, and power delivery requirements. On-board storage methodologies are extremely expensive and heavy, thus reducing the amount of required storage is important. Developing a program that focuses on understanding storage requirements and the system effects these have will help to direct the industry towards decreased on-board storage requirements.
- Sizing Power Electronics: Sizing components in the power electronic chain is a balancing act weighing system efficiencies, converted power, and storage requirements. A research program designed to optimize grid delivered power as a function of these influences could help direct the industry towards more optimal designs.

Optimized Device Profile

Definition

The profile of the device, its general size and its shape determines the initial energy capture of the device or the primary conversion efficiency. Optimizing the device design through physical changes to the device profile can increase the initial energy capture. Changes to the device profile can include volume changes (scale-up), drag reduction changes, or optimized cross-sectional shapes. The types of optimization that are pursued are strongly tied to the type of WEC that is being considered.

Justification

The offshore WAB in a point absorber configuration has a theoretical absorption limits set by the primary oscillation direction(s). All devices can benefit from drag reduction as well as optimized cross-sectional shapes. Hence, optimizing the device profile is one of the most important changes that can be made to significantly reduce the LCOE for the offshore point absorber device.

Research Path(s)

The research paths below focus on the more practical aspects of determining the most optimal profile for the point absorber device.

- Drag Reduction: Viscous drag results in lower AEP for all WEC devices. Drag influences the amplitude of oscillation as well as the phase relationship between the oscillation and the incident wave. Hence, research to optimize designs to reduce viscous losses will result in increased AEP. High-fidelity modeling techniques that can account for viscosity, such as Star CCM+ or OpenFoam, could be utilized to ensure efficient flow around and the structure.
- Optimal Cross-Sectional Design: The cross-sectional profile of the device will influence the hydrostatic restoring force upon variable submergence, the total volume and hence AEP, and the drag characteristics of the device. Hence determining the optimal width/diameter and the shape of the cross-section will influence multiple aspects relating to the AEP of the device.
- Optimized Size of the Device: As implied by the term "point-absorber" these devices convert a portion of ocean energy from a wave at a single point. Therefore, the device has a small characteristic dimension with respect to the incoming wavelength. Hence, the optimal scale of the device should be heavily considered when determining the final design. The theoretical capture limit cannot be the sole factor; the structural stability, as well as the additional cost of manufacture and transport of a larger device should be factors in the final decision.
- Low-Order Performance Models: These models would provide developers engineering-level tools capable of narrowing the design space and yielding solutions in a time-efficient manner. While not as accurate as their high-fidelity counterparts, the rapid turnaround enables designers to investigate performance and cost trends prior to moving to an advanced prototype design. The high-fidelity tools are necessary for developing the most-optimal design and validating lower-order models.

Second-Tier Cost-Reduction Pathways

These pathways also lead to lower LCOE but were not considered as effective as those in the previous list.

- Array Optimization
- Improved Mooring
- System Reliability, Maintenance, and Availability

Array Optimization

Definition

Array Optimization refers to the spacing of offshore WAB point absorbers within a large deployment of devices. In general, this optimization requires placing devices as close together as possible in order to reduce infrastructure costs, installation costs, maintenance costs, and mooring costs. The array layout will affect the power performance of each device individually as well as the power output from the array and the environmental effects of the array.

Justification

The array layout impacts capital costs in many categories as well as the performance of the devices. The affected capital costs include environmental permitting, infrastructure, installation, maintenance, and mooring. It is unlikely that the annual energy production of an individual device can be significantly increased through layout choices, however, it is highly plausible that the annual energy production of an individual device can be decreased dramatically through layout choices. With so many factors influenced through the array layout, this area has been identified as one of the most promising pathways to minimizing the levelized cost of energy value for offshore WAB point absorber devices.

Research Paths

The goal of this research is to minimize the foot-print of the array required to produce a target amount of energy with the fewest devices and anchors possible. Minimization of the footprint (to reasonable limits) will ensure minimized infrastructure, installation, and maintenance costs. Minimization of the footprint should also facilitate the prospect of shared mooring which could dramatically reduce the cost of the mooring and anchoring system required. The difficulty in achieving the above minimization is rooted in producing the target energy with the fewest devices possible. Thus the main goal of this research lies in developing the tools required to understand the performance implications of WEC-WEC interactions. Without this tool, it will not be possible to minimize the foot-print of the array while achieving the target energy with the fewest devices possible.

A nonexclusive and un-prioritized list of promising pathways is presented below. These pathways include both model tool development and case studies that will further the industry knowledge. The wave energy development roadmap that outlines distinct WEC TRLs addresses array development as its own research and development process; most of the research paths identified below are introduced there.[9]

- Performance Modeling: The purpose of a wave energy converter is to absorb energy from the ocean waves. The implication of this when placing devices within an array is that there could be less energy available to devices downstream. Thus an array performance model, based on hydrodynamic interactions, must be developed so that the effect of wave interactions between the offshore WAB point absorbers can be understood. This model will facilitate the optimal array layout such that the target energy production from the array can be achieved with the fewest number of devices possible.
- Shared Mooring Modeling: Placing offshore WAB point absorbers close to one another will facilitate and possibly necessitate the use of shared mooring and anchoring solutions for the array. Pursuit of these shared solutions is highly attractive since the cost of anchoring and mooring for offshore structures is typically one of the top three capital expenditures for the offshore WAB point absorber devices. Models capable of capturing the full dynamical system need to be developed in order to pursue high accuracy solutions. Current industry standard mooring models, like OrcaFlex,[34] cannot account for the hydrodynamics of interacting bodies and thus may only

offer direction for preliminary studies.[ii] A modeling tool that can accurately derive the dynamics of the shared anchoring and mooring solution would be able to account for interacting bodies.

- Environmental Modeling: This requires assessment of the environmental impacts of the array on a large scale. Potential environmental impacts include sediment transport locally and at the shoreline, changes in the wave height and period, and bottom scour. The representation of the array inside this model should attempt to depict the core capture characteristics of the device.[35] This is also an important step for obtaining the appropriate licenses and permits for an array and would facilitate discussions with regulators and stakeholders.
- Infrastructure Procedures: The energy extraction by devices will be dependent upon both the device's performance and the array control strategy thus resulting in developer dependent optimal designs. However, regardless of the design, the process that should be followed in order to investigate an array's impact on infrastructure will be similar. The modeling tools developed above could be used to direct the optimal layout. Then, procedures for systematically studying the effect on sub-sea cable lengths, substations, and communications with the array could be developed. The case studies would offer an initial starting point for companies to use to assess array development and to determine the procedures to follow to minimize the infrastructure requirements. Various aspects that should be included in these case studies are very large WEC arrays vs. clusters of smaller arrays,[36] location and number of substations necessary, length of sub-sea cables, translatability to distinct deployment locations, number of connection points, and redundancy.

Improved Mooring

Definition

Improved mooring designs for individual devices will address the conceptual mooring design solution, materials utilized in the design, and the appropriate design environment and Factors of Safety (FoS). Currently, the offshore oil and gas industry practices are being used as a guide to WEC mooring designs, similar materials are being used, and the same design environment and FoS are being applied. However, WECs operation and the deployment locations are fundamentally different from the structures being moored in the oil and gas industry; WECs are moored in much shallower water than oil and gas structures and WECs are designed to have large oscillation amplitudes in predominant frequency ranges whereas offshore platforms are designed to stay motionless.

Justification

The capital and the operational costs associated with the mooring and anchoring system combine to identify this subsystem as an important area to focus research. Extreme wave environments typically drive the mooring and anchoring design. Hence, improved designs could also result in decreased structural loads on the WEC (lowering CapEx investment in the structure) as well as more favorable environment interactions with the sea-floor thus increasing the possible deployment locations of a design. Thus alterations to the mooring design for an individual device have the ability to impact: the capital costs of the mooring system itself and the WEC structure, deployment costs for the

[ii] The capability to account for the hydrodynamics of interacting bodies is currently being studied by OrcaFlex.

mooring, the maintenance schedule for the mooring system, maintenance costs for the device (as discussed above in the installation section), as well as expanding the acceptable deployment locations of a device.

Research Paths

The goal of the mooring design research effort is to develop new WEC-specific mooring solutions that consider both the operational and survival requirements as well as the unique deployment depths.

This goal can be achieved through multiple paths including:

- Mooring Design: The designs should maintain the WEC within a certain area (footprint) and must withstand the required design loads. Design development can be assisted with established numerical models that are capable of predicting the dynamics of mooring lines within the water column when subjected to waves and current. However, any new design must be thoroughly investigated utilizing already developed numerical models that also acknowledge the unique deployment depth, material limitations, and large responses of these devices. Novel designs should focus on reducing the mooring system footprint and develop creative ways to absorb the design loads at distinct locations from the WEC attachment points. For each design, identifying statistical metrics relating to the loading (subject to both operational and extreme conditions) and device watch-circle should be developed. These metrics will assist in determining the applicability of particular materials to the mooring design.
- Materials Research: Implementing successful mooring designs will need judicious materials selection, operation and environment testing (reliability), and materials development. These variables should be included in both numerical models and WEC deployments. Although the marine and oil industries have adopted several new polymer and carbon fiber technologies that might be applicable to WEC mooring designs, investigations into materials reliability testing are critically needed to determine if they meet mooring requirements. [37,38,39] Areas of concern include: rope construction, creep failure, fatigue, abrasion damage, wear resistance, chemical diffusion, along with the issues stemming from the interfacial contact between any steel component and the line mooring line. One notable concern for the WEC devices using steel construction is the effect of rust on mooring since decreases on fiber strength have already been reported for lines coated with rust particles.[38] This is one of many examples of materials issues that can influence performance, lifetime, and maintenance schedules. Thus identifying new synthetic fibers, exploring weaves, construction, and new protection materials for mooring lines along with accelerated testing of these materials is of interest. These new lines must be suited to the marine environment and capable of withstanding large loads. The operation and environmental testing will ensure appropriate fatigue properties to establish operation and maintenance routines.
- Mooring Design Standards: This path would involve determining the guidelines and regulations that currently exist for mooring systems, critically assessing WECs similarities and dissimilarities to other moored marine structures, modeling WEC devices, and developing recommended guidelines for WEC mooring systems. It is expected that the most suited guidelines will result in lower FoS than those applied to oil and gas since WECs are unmanned and system failures are not likely to result in large environmental catastrophes. These new standards should address both the design environment as well as the required FoS.
- Active Mooring Design: Current mooring systems are designed as independent systems from the WEC. However, there is the opportunity to develop mooring systems that are integral to a WECs power performance in operational waves and survivability in severe waves. Operationally an active mooring system could be part of

the WEC control system for power extraction. Additionally, an active mooring design could be used to protect the structure during severe storms thus reducing the loads on the structure.

System Reliability, Maintenance, and Availability

Definition

Research paths presented here are subcategorized by system reliability, maintenance, and availability. System reliability addresses failure frequency and duration for a device. It touches upon many of the categories in the cost breakdown structure including: infrastructure, planned and unplanned maintenance, power conversion chain, and subsystem integration. There are many ways to tackle reliability concerns since they exist in each of the following subsystems of a WEC device: structure, power conversion, mooring, and grid connection components. System reliability directly effects the performance of planned and unplanned maintenance, and the availability of the device to make power. This cost-reduction pathway will focus on each of these aspects.

Justification

This pathway is viewed as promising because it affects both the availability and the OpEx costs. The costs for unplanned maintenance are greater than for planned maintenance and can strongly effect availability and therefore the LCOE of the device.[40,41] Experience in other renewable energy technologies also indicates that increased reliability can substantially reduce the cost of energy.[42] Since WECs are located in marine environments their reliability is even more critical as access is typically more difficult than terrestrial systems. Additionally, WECs are constantly subject to cyclic oscillations of varying magnitude and frequency—an operational aspect uncommon to other electro machinery devices.

The webinars and data in the CBS were unable to effectively elucidate the differences between reliability, maintenance, and availability. Each of these aspects is strongly tied to the others and hence, the information here is presented in one category that covers all three aspects with equal weighting. The research paths presented below are identified with their main driver.

Research Paths

The main pathway to increasing system reliability is to characterize the mean time between failures (MTBF), both numerically and experimentally, for components and subsystems in load specific simulated environments. It could be that the outcome of this analysis is that more customized designs are needed to meet the specific performance goals, or that a redesign of a particular group of components can ameliorate the failures from COTS.

- Reducing system complexity: By reducing the complexity of the WEC there will be less failure points and hence a more reliable device will naturally be developed. Reduction of system complexity can be achieved through higher accuracy models that point towards simpler solutions and a "systems design" approach to the WEC. Additionally, reductions in system complexity may require the use of more customized components.
- Materials Testing and Failure Model Development: Failures on the structure and mooring system will arise from selected materials or coatings. Testing these materials in the marine environment under mimicked conditions (be it load or marine growth) will help to classify the failure modes of the materials. This research program is

required to accurately develop failure models because often times these materials do not come with failure or fatigue specifications when subject to the unique conditions particular to WEC devices.

- Full-Scale Power Conversion Chain Testing Facilities: Since the power conversion mechanism has the highest number of components operating collectively for a single goal, it is likely that most failures will occur here. Hence a program focused on system integration and system testing at full scale (or close to full scale) would help to identify failure modes in individual components as well as subsystems and find solutions on-shore where the cost is lower. This program should focus on developing the facilities and capabilities required to address reliability in the power conversion chain.
- Sub-sea Electrical Infrastructure Testing Facilities: The sub-sea cable and substations within an array contain potential points of failure that are catastrophic to an array's performance. Thus, increasing the reliability of the sub-sea electrical infrastructure required to transport electricity back to shore is a high priority. The testing facility could utilize power sources that mimic the power produced from an array and could subject the sub-sea infrastructure to accelerated life testing. New techniques to identify defects in the sub-sea cable and associated fiber optics for communications could be developed.

Addressing maintenance requires predicting failure rates of components within the device. The information obtained from the system reliability CRP can be used to inform the predictive models resulting in greater accuracy. However, maintenance challenges require a broader lens to understand all of the aspects that must be considered. Maintenance can either be performed *in situ* or the device can be disconnected from electrical and mooring infrastructure, towed back to a sheltered site, and serviced there. Execution of maintenance is dependent upon weather windows, distance from port, vessel requirements, availability of replacement parts, and predicted failure rates. Recent work by Dalton has shown that the cutoff for the weather window, often dictated by vessel size, can strongly affect the LCOE of the device.[41]

- Resource Classification: This classification scheme should not only identify a site based on the incident power and survival conditions to inform design conditions, but should also be targeted towards identifying opportunities for maintenance. In addition this classification scheme should be used as inputs to the developed failure models since it is expected that components that repeatedly operate at the extremes would be more likely to fail.
- Failure Modeling: Currently there are no failure models for WECs and there is no recommended architecture for what that failure model would look like. This research project would outline the necessary information required to construct a failure model. Additionally failure models for key components could be developed. These models should consider component failure/fatigue specifications, resource characteristics, number of cycles, and range of operation.
- Designing for Maintenance: It is inevitable that failures will occur. Use of design practices that mitigates this reality would reduce the time and costs associated with maintenance and repairs. This could include use of common components, accessibility to high-priority sections, and "plug-and-play" components which do not require servicing.
- Design for Deployment and Recovery: The incorporation of design practices that promote ease of deployment and recovery of the device will be important to increasing the reliability of the device when servicing must occur. This can include improved locking/unlocking mechanisms, standardized methods of attachment for custom vessels, and lighter weight devices.

Specifically addressing the availability of a device is predicated upon accurate MTBF estimates and predictive models, however it is also strongly dependent upon dedicated monitoring and controls. Controls targeted to increasing the availability of the device tend to focus on health-monitoring to minimize both the necessary human interaction and downtime for each device.

- Health and Diagnostic Monitoring and Controls: Component and subsystem failure can occur based on multiple causes from fatigue, extreme events, or random events. Health and diagnostic monitoring and controls should be able to address the first two causes. Once the life of a component or sub-system has been established, monitoring can occur to determine when a likely fatigue failure will happen. Furthermore, the maximum loads, voltages, etc. for each component and subsystem establish the extreme event threshold. Controls that can be used to manage the dynamic loads on the system and decrease both fatigue and extreme event failure rates could dramatically alter the LCOE of a device through decreased downtime (i.e., directly affecting AEP and OpEx) and increased lifetime (i.e., directly affecting levelization of CapEx). Clearly, control strategies of this sophistication require system-level performance models that are able to continuously update with the number and magnitude of cycles to predict when a fatigue event will occur. Additionally, the system-level performance model would need to feed into a cost model in order to optimize LCOE based on performance or on OpEx costs.

Less Promising Cost-Reduction Pathways

These pathways also lead to lower LCOE but were not considered as effective as those in the previous list.

- Infrastructure
- Installation
- Subsystem Integration

Although these pathways were not prioritized heavily, important strides can be made and do interact with other high priority items particularly through O&M.

Infrastructure relates not only to the ports and manufacturing facilities needed to fabricate, deploy, and service these devices, but also to the electrical supply chain, local grid capacity, custom O&M vessels, and device communication techniques/materials required to realize cost competitive technologies. Much of the infrastructure currently available to the WEC industry is from the oil and gas industry. These solutions offer an entry point for the WEC market, however the unique operating constraints of WECs is pushing towards more customized solutions.

Installation of WEC devices includes the deployment of the device itself as well as the required infrastructure to support the device. Hence vessel time and man-hours required to set up the electrical cable, mooring and anchoring configuration, the device itself, and interconnection of all of these components are included in the installation process. Additionally, the installation procedure strongly affects the maintenance costs since recovery and redeployment of the WEC will have to follow the same installation and interconnection procedure laid out for the initial installation. Focus on the design of the device, mooring connection points, and electrical cable connection points through the lens of installation can drive the design of each of the subsystems mentioned. Close and early collaboration with vessel operators, remotely operated vehicle operators, and the research and design team within the company may be necessary to find optimal solutions for each device.

Subsystem integration is an important aspect of producing a reliable product. There are advancements to be made in this area, however the most important influence this has is on the O&M costs that result from a poor subsystem integration procedure. Hence, the core aspects of this area are already addressed in the System Reliability section with the Power Conversion Chain Test Facility. Another large aspect of subsystem integration are the interconnections between the mooring, umbilical cable, and device; again this has already been addressed in the Installation section. As more experience is gained in designing, fabricating, assembling, deploying and recovering these devices great gains are expected in the quality assurance procedures relating to subsystem integration.

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Conclusions

The WEC industry has yet to penetrate the U.S. electricity market despite the large potential resource available. Work by Weber[44] has effectively attributed this low penetration through the lens of low techno-economic performance; however few concrete paths have been offered to alter the current state of the industry in order to bolster the techno-economic performance. This paper systematically prioritizes the technology developments that can alter this paradigm for a WAB point absorber. Prioritization occurs through critical assessment of three data sources: impartial modeling data (cost and performance), industry supplied data (cost and cost-reduction pathways), and literature searches. This analysis considers each aspect of the cost of energy: capital expenditures, operational expenditures, and the amount of energy produced. The impartial modeling data and industry supplied data are used to rank the key cost drivers, capital and operational, in a design. All three data sources are used to determine the potential for cost-reduction of identified cost drivers as well as the opportunity for power improvement. Prioritization is based on evaluation of this data as well as the confidence in success within a given timeframe. For the purposes of this analysis, arrayed utility-scale deployments (approximately 100 devices or more) and a target timeframe of the year 2030 are assumed.

The prioritized cost-reduction pathways are presented with specific research paths that could be pursued in order to achieve the cost-reductions. In some cases in this nascent industry, all aspects of an issue could not be clearly delineated; the recommended research paths concerning these issues include likely areas for productive study. All of the research paths were identified by the whitepaper authors, industry supplied data, literature searches, and experiences with other technologies such as wind and aerospace. It is unlikely that every research path could be pursued by one company, institution, or government agency. However, it is likely that particular paths do align with diverse strategic goals identified by companies, institutions, and/or government agencies. Hence it is hoped that these recommendations can be pursued by collectively employing the strategic goals of the community at large.

The experience of this first whitepaper led to changes in the interview process with the industry partners in subsequent whitepapers. In order to ensure complete data sets in the subsequent whitepapers and to target questions to areas of high cost and high levels of potential improvement, the CBS will be sent to the industry partners to be filled out before the webinar. Then the webinars will use this information to obtain answers to more targeted questions. Unfortunately the data set for this whitepaper on point absorber WEC devices did not have information on the OpEx costs as the developers did not fill these sections out. Hence the whitepaper authors did not have sufficient information to weigh the relative cost of OpEx against CapEx. Filling out the CBS ahead of time will ensure that each company provides the necessary cost data and that the data is complete thus ensuring a thoughtful and comprehensive conversation.

Additionally the CBS will be altered in order to more explicitly identify influences on the AEP. AEP information was included in the CBS presented in Appendix A – Blank CBS Worksheet, however by including it with the cost data it was often difficult to separate the effects of improving the AEP vs. decreasing the capital expenditure. Hence the format will be changed in order to more fully differentiate decreased capital expenditure from increased AEP. Effects of arrays will be directly taken into account in future iterations. During these webinars the developers were not specifically queried regarding the effects of arrays. Some developers mentioned technological developments regarding arrays, however it was not mentioned at the rate that the whitepaper authors believe is would have been if questions were targeted to this area.

In future iterations, the webinar will be used to determine the cost-reduction pathways and their potential impact thus reducing the burden on the developer to fill this information in. It is hoped that the changes listed above will allow for a deeper understanding of the opportunities available to reduce the cost of energy of MHK devices.

All of these developers highlighted the importance for increased deployments. They believe that deployments will continue to shed light on the relative importance of the identified research paths and identify new research paths. Though young, this industry has access to 30,800 TWhr/yr (3,500 GW)[2] of potential wave resource globally and 2640 TWhr/yr (300 GW)[3] within the United States. This resource offers a local and global market for a highly predictable renewable energy source. The information presented in this whitepaper can be used to help direct the WEC community towards high-impact research paths that could greatly improve the techno-economic performance of these devices.

Appendix A – Blank CBS Worksheet

	Cost Component	Percent of Total Project Cost (Totaling 100%)	Cost Reduction Pathway (Proposed Modification)	Predicted Cost Effect (¢/kWhr saved)	Projected Schedule to Achieve Cost Reduction (e.g., 1y, 3y, 5y, 10y, 15+y)	Potential for Cost Reduction (Rate between 0-4; 0 = no potential, 4 = high potential)	Potential for Generation Improvement (Rate between 0-4; 0 = no potential, 4 = high potential)	Comments
CAPEX	**Development** (e.g., permitting, environmental compliance, site assessment, system design & engineering, etc.)							
	Infrastructure (e.g., subsea cables, cable landing, dockside improvement, dedicated O&M vessel, etc.)							
	Mooring/Foundation (e.g., mooring line, anchors, buoyancy tanks, connecting hardware, etc.)							
	Device Structural Components							
	Power Take Off and Capture Means (e.g., drive train components, generator, control system, etc.)							
	Subsystem Integration (e.g., assembly, testing & QA)							
	Installation (e.g., transport to site, cables, morring/foundation, etc.)							
	Decommissioning (e.g., gains from recycling, losses from remediation, etc.)							
	Add Other CAPEX Cost Components not Captured Above if Needed							
	Subtotal							
OPEX	**Insurance**							
	Environmental Monitoring and Regulatory Compliance							
	Planned Maintenance (e.g., marine operations, shoreside operations, etc.)							
	Unplanned Maintenance (e.g., generator, gearbox and driveshaft, hydraulic system, etc.)							
	Replacement Parts							
	Consumables							
	Add Other OPEX Cost Components not Captured Above if Needed							
	Subtotal							
Total								

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