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Technological Cost-Reduction Pathways for Oscillating Water Column 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 oscillating water columns in both terminator and point absorber configurations 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 oscillating water columns, a reference device that was developed through the Reference Model project and was augmented with data compiled from literature sources, and a webinar with each of three 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, improved power conversion, an optimized structural design, and array optimization.

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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 oscillating water column wave energy converters in order to accelerate development of the renewable marine hydrokinetic (MHK) energy resource in the United States. For some well-defined issues, recommendations for specific research programs can be made. In the case where an issue lacks definition, the given recommendations outline the problem as clearly as possible and the authors suggest promising avenues for investigation. No single entity, including DOE, is likely or is expected to address all of these paths. However, particular paths are likely to align with the diverse strategic goals of individual companies, institutions, and government agencies. It is hoped that these recommendations can be productively pursued by employing the strategic goals of the community at large.

Issue

The principles of wave energy conversion have been explored since the early 1970s. Innovation in this area has resulted in many prospective device designs. These designs are classified and modeled by considering their method of conversion, their directional dependence, and their deployment depth.[1] There are three main methods of conversion: overtopping devices, oscillating water columns (OWC), and wave activated bodies (WAB). 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 oscillating water column devices oriented as both terminators and point absorbers.

In recent years, the nascent MHK industry has seen tremendous interest and progress in device development and deployments of many device types including oscillating water columns; however, there are still significant improvements needed to make OWCs 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 OWCs before this technology can effectively compete in the marketplace.

Approach

This paper includes information from three main sources:

- Research literature regarding OWC technologies
- Reference Device comprised from the DOE Reference Model Project and augmented with data from literature sources
- Webinars held with companies (Embley Energy Ltd., Ocean Energy Ltd., and Oceanlinx Ltd.) involved in the development and deployment of oscillating water column devices

Cost-reduction pathway 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 incorporates each of the following: 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 most important 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 the Levelized Cost Of Energy (LCOE) as they cross cut all other pathways.
- **Improved Power Conversion** – the method to convert mechanical energy into electrical energy. The power conversion chain has the second highest CapEx, and also has the second highest efficiency losses. Improvements would benefit both the cost (CapEx) and the amount of energy produced.
- **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.
- **Array Optimization** – the placement and spacing of a field of offshore OWCs which can reduce the capital costs of environmental permitting, infrastructure, installation, and mooring costs as well as reduce the operating costs of maintenance. An optimized array will also minimize the negative impact to annual energy production (AEP) of each individual device in the array. As the impacts of an optimized array touch on so many cost components, improvements are likely to greatly reduce LCOE.

Second-Tier Cost-Reduction Pathways

- **Improved Mooring Design** – impacts the capital costs of the mooring system itself and the device structure, deployment costs for the mooring, the maintenance schedule for the mooring system, and maintenance costs for the device. Improved mooring designs also could expand the acceptable deployment locations of a device.
- **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.
- **Increased System Reliability** – addresses failure frequency and duration for a device. System reliability touches upon many cost categories including infrastructure, planned and unplanned maintenance, power conversion chain, and subsystem integration.
- **Planned Maintenance** – a scheduled service event for a device that is driven by the predicted failure rates of components within the device. Execution of planned maintenance is dependent upon weather windows, distance from port, vessel requirements, availability of replacement parts, and predicted failure rates. Maintenance often requires downtime for the device thus negatively affecting availability.

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 benefit the entire industry. Tools that address increased AEP with advanced controls, survivability modeling, new generator designs, failure monitoring, and testing facilities to determine mean time between failures (MTBF) can all be developed generically. Additionally, these research programs could provide publicly accessible data to the community at large. One significant barrier to the nascent MHK industry is the lack of publicly available information about the processes, techniques, and failures that are occurring within the industry.

This young industry has access to 30800 TWhr/yr (3,500 GW)[2] of potential wave resource globally and 2640 TWhr/yr (300 GW)[3] within the U.S. that offset some of the electricity currently provided by fossil-fuel fired generating plants. In 2010, the global electric energy consumption reached 21,431 TWhr/yr and the U.S. alone consumed 4,354 TWhr/yr.[4] The prioritized research paths presented here should aid in harnessing this resource.

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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 oscillating water column wave energy converters. The purpose of this report is to utilize existing information regarding the Marine Hydrokinetic (MHK) industry and for oscillating water column wave energy converters in particular to identify the largest cost drivers and the most promising technological cost-reduction pathways for achieving a lower LCOE. Identifying these cost-reduction pathways for oscillating water columns will help focus research efforts in the areas of greatest potential LCOE reduction and making greater and more economical opportunities for converting ocean energy into a renewable source of electricity. These cost-reduction pathways will help move ocean energy conversion from an immature renewable energy source to a more developed and complete form such as wind and solar.[5] Industry, academia, and government institutions may find the recommendations useful. It is hoped that by acting separately and in concert on these issues, these groups will be able to advance the current state of oscillating water column wave energy converters

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 for the Techno-Economic Assessment Report to be delivered to Congress.

For the purposes of this analysis, relatively large deployments (approximately 100 devices or more) with 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 array, including CapEx and Operational Expenditures, 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 on reducing the LCOE of a technology.

Factor of Safety (FoS)

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

This 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

MHK technology utilizes the body motion in a marine, oceanic environment to generate electricity. It includes the study of how ocean waves and currents affect that body motion and the methods of transforming that body motion (kinetic energy) into electricity.

Ocean Energy Conversion Process

Converting ocean wave energy into usable electricity (could) involve five distinct steps:

1. Primary Energy Capture Device: Hydrokinetic to mechanical power conversion (the "intercepted power")[6]
2. Drivetrain: Conversion of device motions into the final form of mechanical power needed to drive the generator (the "captured power") [6]
3. Generator: Mechanical to electrical power conversion
4. On device Energy Storage: Mechanical or electrical power storage for power quality
5. On device Power Electronics: Electrical power conversion for power quality

Steps 2-5 can be grouped into one category called the power conversion chain, or 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." Taken from Sullivan et al.[7]

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 report prepared by the Hydraulics and Maritime Research Center (HMRC) University College Cork (UCC) for the Ocean Energy Systems International Energy Agency to broaden the definition's applicability to other renewable technology definitions that the DOE uses when assessing cost.[8] 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 that 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 both in one component. Note, off device power electronics and longer term energy storage are not included in the PCC.

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.[5] General definitions of the measure of maturity of technologies are found in the following TRL definitions: [9]

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.[10] 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 TRL3: Concept design evaluation with experiments and elementary models
WEC TRL4: Advanced concept design modeled and validated in laboratory environment
WEC TRL5: Advanced component designs modeled and validated with laboratory environment
WEC TRL6: System and subsystem integration in relevant environment
WEC TRL7: Full-scale prototype deployment in open ocean
WEC TRL8: Full-scale deployment with application in open ocean
WEC TRL9: Utility-scale deployment in open ocean

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 huge energy potential is to convert it to usable electricity through wave energy converters (WECs).

The 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 1 hour. A particular sea state is defined by a wave height, period, directional spreading function, and spectral shape which together 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 spectral shapes define the distribution of energy within a sea state. 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. 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.[11]

Sea states allow the wave climate to be characterized for short durations of time; however, in order to fully 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. [12] JPDs are created through statistical analysis and require many years of data. A recommended timespan of 10 years is often cited 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

Industry exploration of the principles of wave energy conversion carried out since the early 1970s has resulted in many prospective device designs. These designs are classified and modeled by considering their method of conversion, their directional dependence, and their deployment depth.[1] There are three main methods of conversion: overtopping devices, OWCs, and WABs. The methods can then be embodied as point absorbers, terminators, or attenuators, depending on their directional dependence as shown in Figure 1.[13] 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.

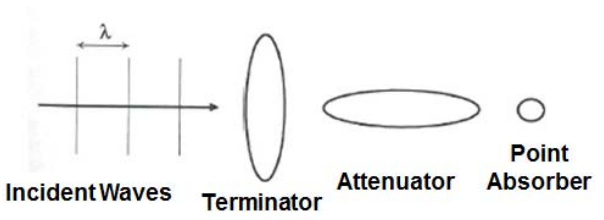

Figure 1: Schematic presented in (Cruz, 2008) highlighting the relative scale and orientation of the distinct directional dependencies.

This report is focused on OWC devices that are deployed in offshore water depths. In this context, offshore is defined by water depths between 50 m and 150 m and implies that the devices will be floating. The definition of an OWC given by the European Marine Energy Centre (EMEC) is the one adopted in this research.

> "An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine is used to generate electricity." [14]

The offshore OWCs can either absorb energy as point absorbers or terminators. This whitepaper will cover both varieties. The OWC point absorbers will have a small characteristic dimension with respect to the incoming waves and will not have directionally dependent absorption characteristics.[15] The OWC terminators will have characteristic lengths that are larger, they will not be fully axisymmetric, and their absorption characteristics will be directionally dependent.[13] The OWC terminators absorb energy perpendicular to the oncoming waves.

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. Hence it is often said that 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 wave cancellation and a reduction in wave 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 in Renzi and Dias[16], 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.

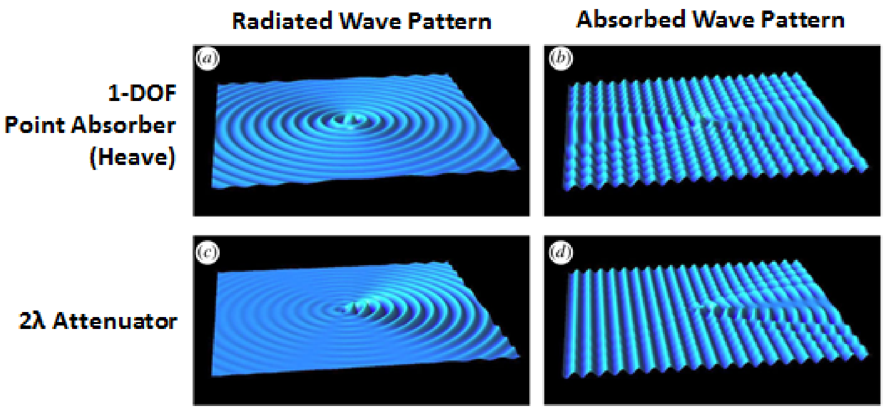

Figure 2: The radiated wave pattern and the absorbed wave pattern for two WABs

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 that absorbed by the device, or equivalently the power absorbed by the device in kW divided by the incident wave power flux in kW/m. 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 that allows for wave cancellation over a much larger width than that which created the radiated waves.

Table 1 summarizes 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.

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.[15]

Directional Dependence	Mode of absorption	Theoretical Capture Width
Point Absorber	1-DOF: Heave Eq. 6.77[15]	$\lambda/_{2\pi} \approx 0.16\lambda$
	1-DOF: Surge or Pitch [16]	$\lambda/_{\pi} \approx 0.32\lambda$
	2-DOF or 3-DOF: Heave+Surge, Heave+Pitch, Heave+Surge+Pitch, or Surge+Sway+Pitch Eq. 6.86 [15]	$3\lambda/_{2\pi} \approx 0.48\lambda$
Attenuator	$\text{Length} = \lambda$ [16]	0.50λ
	$\text{Length} = 2\lambda$ [16]	0.73λ
Terminator*	$\text{Width} = \lambda$ Eq. 6.108 [15]	λ

*It is expected that the theoretical capture width will be dependent upon the width of the 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.,[16] however there is work that clearly shows the dependence between actual capture width and width of device. [17,18]

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) 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 OWC point absorber, can be designed in various ways (e.g., devices from Oceanlinx and Embley Energy) 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 & Anchoring Type
- Symmetry
- Number of bodies and oscillating water columns
- 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: As stated in the definition, currently pursued OWCs are only partially submerged and hence have surface expression. It is possible, however, to have a submerged OWC located below the free surface entrapping a body of air.[15] 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 type 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: These devices are often developed as either point absorbers or terminators. Point absorbers have no directional dependence, whereas terminators have an elongated y-axis perpendicular to oncoming waves. If terminator devices are not aligned to the oncoming waves, their performance will be diminished. The effects of the directional dependence can be ameliorated through the use of mooring systems that allow weathervaning. Additionally, these devices could be deployed only in locations with prominent incoming directions so that their equilibrium orientation is optimized for the majority of incoming waves.

Number of bodies and oscillating water columns: A device may be a single body and a single oscillating water column or a single body with multiple oscillating water columns. 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 oscillating body and the oscillating water column move with respect to one another.

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 oscillating water column, however, only produces power when the motions are vertical with respect to the body. Both the body's oscillation direction and the oscillating water columns direction will be reported.

Drivetrain type: The drivetrain converts the device motions into the final form of mechanical energy, or "captured power"[6] that drives the generator.[8] There are many drivetrain options including: Wells Turbine, variable pitch Wells Turbine, Variable Pitch Turbine, Impulse Turbine, and Deniss-Auld Turbine. The drivetrain will affect the survivability of the device and the power performance.

PCC reference: The PCC must have a reference through which energy is extracted. Broadly categorized, the PCC reference can be fixed or relative.[19] Fixed reference PCCs are connected to the seabed and are often utilized by shore-mounted or near-shore devices. Floating devices deployed offshore must use relative reference PCCs. The relative reference between multiple bodies, or a body and an OWC, 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.[19] 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. For offshore OWC devices the design may has restrictions on the relative motion between body and the OWC since water flowing through the drivetrain would be detrimental.

Survival strategy: Finally, 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.

- Research and academic literature regarding oscillating water column technologies and their energy resources.
- The U.S. Department of Energy (DOE) Reference Model effort [20] and a Reference Device compiled from Literature sources.[17]
- One on one webinars held with companies involved in the development and deployment of oscillating water column devices.

The three sources are described below.

Literature Survey

A literature survey was performed to investigate current research efforts being performed both nationally and internationally on oscillating water column 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 this whitepaper, citations from the literature survey are placed in support of industry and SNL expert assertions.

Reference Model 6

The DOE's Reference Model effort is finalizing its initial investigation of an offshore oscillating water column device oriented as a terminator, labeled Reference Model 6 (RM6).[21] RM6 was designed to be a conservative representation of the technology being pursued by industry developers, such as the ones presented below. It is a generic backward bent duck buoy (BBDB) device most similar to the Ocean Energy Ltd. OE Buoy presented below.[22] It was designed to be deployed in a Northern California wave climate off the coast from Eureka. RM6 is at WEC TRL4; initial designs for the major subcomponents were completed (structural, mooring, and PCC) and scaled testing to confirm performance will be completed by the end of 2013. The principal characteristics of this device 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 anchor
- Symmetry: Symmetric across the x-z plane absorbing energy in a terminator orientation
- Number of bodies and OWCs: 1 oscillating body and 1 oscillating water column
- Primary oscillation direction: The oscillating body primarily heaves and pitches and the oscillating water column primarily heaves
- Drivetrain type: Wells Turbine
- PCC reference: Relative, mutual reaction between oscillating body and oscillating water column
- Oscillation constraint: Height of the air chamber
- Survival strategy: Control pressure inside the air chamber via vents

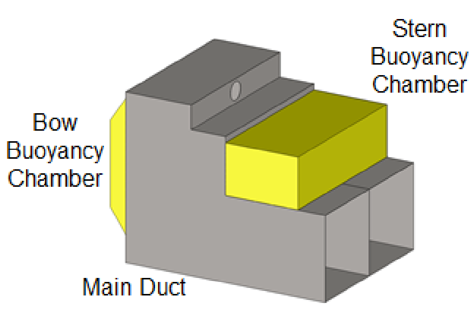

Figure 3: Graphic representation of RM6 indicating the three main components of the structural design.

Cost analysis for the RM6 device is not yet complete and hence this information cannot be used to frame expectations from the industry developers. Although the RM6 was unable to supply the cost breakdown for an oscillating water column, research was far enough advanced to identify key cost-reduction pathways. The major identified cost-reduction pathways identified through RM6 are:

1) Device Profile – Device performance could be increased significantly by choosing the optimal device profile to match the deployment characteristics by altering the surface area of the air chamber as well as the length of the device. Additionally expect that the shape of the air chamber and the device itself should be optimized to reduce viscous effects.
2) Advanced Controls – Device performance could be increased significantly by using a more advanced control strategy. Currently resistive damping is applied to the PCC.
3) PCC Efficiency – A Wells Turbine, either standard or variable pitch, is the drivetrain in this system due to the fact that we are limited to linear relationships. The low efficiency and, for the standard Wells Turbine, narrow banded response of these turbines makes them less than ideal. Further work to investigate alternative PCCs that can provide higher efficiency would be worthwhile.
4) Device Structure – The weight of the device is expected to be a substantial component of the cost. Thus, expect this will be identified as a cost-reduction pathway.

The information outlined above was used in part to frame the conversations with Embley Energy Ltd., Ocean Energy Ltd., and Oceanlinx Ltd.

The next section describes a reference device compiled from literature sources that serves to analyze the cost and performance of this device type.

Reference Device Compiled from Literature

An estimate of the major components in the cost breakdown structure (CBS) were obtained from a 2002 feasibility study performed by the UK Department of Trade and Industry (DTI) (DTI is now BIS).[17] DTI evaluated OWC devices in a specified deployment climate using experimental model testing and frequency domain numerical modeling. The economics of an offshore OWC in a point absorber configuration with an 11.0 m diameter as shown in Figure 4 was evaluated.

Figure 4: Generic offshore OWC oriented as a point absorber evaluated by DTI

The principal characteristics of the generic offshore OWC oriented as a point absorber are as follows:

- Primary maintenance location: At port
- Placement in the water column: Surface expression

- Buoyancy type: Neutrally buoyant
- Mooring and anchoring type: Four point catenary mooring, no weathervaning. If adequate sediment exists, the anchor can be drag-in or suction-can anchor systems. If there is no sediment then gravity anchors, drilled and grouted piles or rock anchors can be used.
- Symmetry: Fully symmetric around the z-axis operating as a point absorber
- Number of bodies: 1 oscillating body and 1 oscillating water column
- Primary oscillation direction: The oscillating body primarily heaves and the oscillating water column primarily heaves
- Drivetrain type: Fixed pitch Wells turbine
- PCC reference: Relative, mutual reaction between oscillating body and water column
- Oscillation constraint: Height of air chamber.
- Survival strategy: Because of its symmetry and design, extreme waves may submerge the device without disabling or affecting it.

In this study, the offshore OWC point absorber is operated in 45kW/m environment over a lifetime of 25 yrs. The pneumatic average annual power produced by this device is 160kW. The installed capacity of 100 devices is 14 MW. Figure 5 below shows the CBS derived from this work.

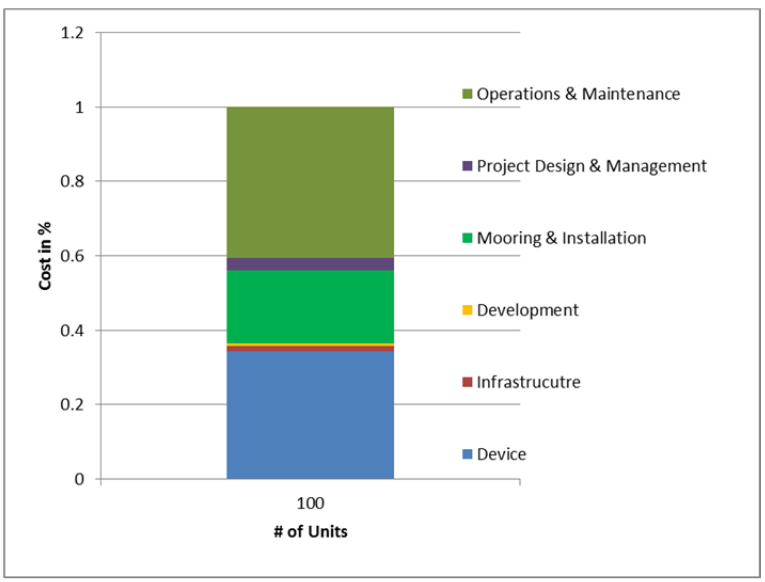

Figure 5: Percentage cost breakdown of a 100 device array of offshore OWC point absorbers over a project lifetime of 25 years.[17]

The project cost includes O&M and capital costs, where capital costs assume an 8% return on investment over the project life of 25 years. The device costs assume steel prices from 2002. It is not clear to the authors that the mooring & installation cost estimates presented by DTI are representative of the industry. Additionally, the OpEx was estimated from a ~10,000MWhr per annum wind farm; the applicability of this estimate is not clear.

DTI emphasized three areas to reduce LCOE:

1) Advanced Controls – Research in wave prediction to account for differing capture factors owing to wave height would increase the device efficiency.

2) Improved Power Chain Conversion – More efficient turbines such as the optimized fixed pitch turbine as presented in DTI could further increase the AEP of an offshore OWC oriented as a point absorber by an estimated 10%.
3) Structural Costs – Improved design of the buoy and chamber itself could reduce costs and increase the rate of capture of the pneumatic energy. This would affect both the numerator and the denominator of the cost of energy equation, making it a high priority.

The key risk areas identified in the study that would require validation before full scale prototype testing were mooring and riser integrity, and buoy accessibility for maintenance. Additionally, the high cost of deployment, mooring and cabling were seen as prohibitive. These could be considered UK DTI's secondary areas for research that would reduce LCOE.

Since this study was completed in 2002 advances have been made in the industry. This report is summarized here not as the optimal or even average representation of the industry today, it is summarized to orient the reader to the relative magnitudes of the CBS.

Aggregated Information from Industry

Over the course of a few weeks in January of 2013, three webinars were held separately with three companies whose primary mission is the development of oscillating water column wave energy converters for the production of electricity. During the webinars, each company was asked several questions relating to their cost-reduction pathways. The companies were:

- Embley Energy Ltd.
- Ocean Energy Ltd.
- Oceanlinx Ltd.

Industry Descriptions

Embley Energy Ltd.

Embley Energy Ltd. is a UK company that has been pursuing the development of offshore OWCs since 1994. The development of the SPERBOY™ has transitioned from a multi-chamber OWC design to a single chamber OWC design. The multi-chamber design has been deployed at 1/5th scale in the Plymouth Sound off the coast of southern England. Research on the current single chamber design has been ongoing for the past decade. The new SPERBOY design is unique in that it is pursuing composite concrete for the structure fabrication. Embley Energy has deployed a 1/5th scale device and has performed some advanced modeling on this new generation SPERBOY as well. The principal characteristics of SPERBOY 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 with subsurface floats, gravity anchor
- Symmetry: Fully symmetric around the z-axis operating as a point absorber
- Number of bodies and OWCs: 1 oscillating body and 1 oscillating water column
- Primary oscillation direction: The oscillating body primarily heaves and the oscillating water column primarily heaves
- Drivetrain type: Off-the shelf turbine (single rotation direction for bi-directional air flow); use multiple turbines and generators on one device
- PCC reference: Relative, reaction between oscillating body and mass dominated water column
- Oscillation constraint: Height of the air chamber
- Survival strategy: Embley Energy has found no need for a survival strategy.

Figure 6: Artist's rendition of the SPERBOY; the length of the column is dependent upon the deployment location. This picture is courtesy of Embley Energy Ltd.

More information regarding Embley Energy Ltd. and the SPERBOY OWC can be found on their website: http://www.sperboy.com/.

Ocean Energy Ltd.

Ocean Energy (OE) Ltd. is an Irish company that has been developing their OE buoy during the past ten years. The OE buoy is an offshore oscillating water column device oriented as a terminator. It is an "L" shaped OWC of the general backward bent duct buoy (BBDB) variety,[22] that capitalizes on the relative motion of the oscillating body and the oscillating water column. The development process of the OE buoy has moved it through three phases of testing: 1:50 in a controlled wave tank environment (HMRC), 1:15 in a controlled wave tank environment (Ecole Centrale de Nantes), and 1:4 in the protected Galway Bay off the coast of Ireland. The testing in Galway Bay lasted for over three years. Currently the deployment of a pre-commercial full-scale device is planned at a grid connected testing facility. The principal characteristics of this device 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 with surface floats, drag embedment anchor
- Symmetry: Symmetric across the x-z plane absorbing energy in a terminator orientation
- Number of bodies and OWCs: 1 oscillating body and 1 oscillating water column
- Primary oscillation direction: The oscillating body primarily heaves and pitches and the oscillating water column primarily heaves
- Drivetrain type: Fixed-pitch self-rectifying impulse turbine (HydroAir from Dresser Rand; single rotation direction for bi-directional air flow)
- PCC reference: Relative, mutual reaction between oscillating body and oscillating water column
- Oscillation constraint: Height of the air chamber
- Survival strategy: Control pressure inside the air chamber via vents.

More information regarding Ocean Energy Ltd. can be found on their website: http://www.oceanenergy.ie/.

Figure 7: The 1:4 scale OE buoy deployed off the coast of Ireland in the protected Galway Bay. This picture is courtesy of Ocean Energy Ltd. and the European CORES project.

Oceanlinx Ltd.

Oceanlinx Ltd. is an Australian company that has been pursuing the development of nearshore and offshore OWCs since 1997. The blueWAVE device, an offshore cluster of six OWCs, has been under development since 2004 and is the subject of this research. The development process of blueWave has moved it through two large scale testing campaigns. In the first, a single floating 1/3rd scale device was tested in 2007 in protected waters off of Port Kembla. This deployment was followed in 2010 with a grid connected deployment, achieving DNV verification of electricity yield, of the blueWAVE grid with the cluster of devices off of Port Kembla Harbour. Furthermore, Oceanlinx has achieved DNV certification for their prototype blueWAVE structural design. Currently the deployment of a full-scale nearshore device is planned for the southeast coast of Australia. The principal characteristics of blueWAVE shown in Figure 8 are:

- Primary maintenance location: *In situ*
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally buoyant
- Mooring and anchoring type: 6-point slack moored, drag embedment anchor
- Symmetry: Cluster arrangement is symmetric across the x-z plane & y-z plane predominantly absorbing energy in a terminator orientation; individual OWC also symmetric across the x-z plane & y-z plane
- Number of bodies and OWCs: 1 oscillating body and 6 oscillating water columns in a single frame (all bodies have the same length)
- Primary oscillation direction: The single oscillating body primarily heave (bodies cannot oscillate independently of one another) and the six oscillating water columns primarily heave
- Drivetrain type: airWAVE (a 3rd generation Denniss-Auld; dual rotation direction for bi-directional air flow)
- PCC reference: Relative, reaction between oscillating water columns and mass dominated body
- Oscillation constraint: Height of the air chamber
- Survival strategy: Control pressure inside the air chamber via vents.

More information regarding Oceanlinx Ltd. can be found on their website: http://www.oceanlinx.com/.

Figure 8: Deployed prototype and artist's rendition of the blueWave offshore OWC technology from Oceanlinx Ltd. This picture is courtesy of Oceanlinx Ltd.

Webinar Process

Details of the process by which Sandia National Laboratories (SNL) conducted the webinars with the above companies are contained below. Blank worksheets and sample questions are given in order to protect proprietary information.

Cost Breakdown Structure Worksheet

Sandia National Laboratories (SNL) provided a cost breakdown structure (CBS) table to each of the three companies to be filled out in advance of the webinar. 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 the following component and O&M costs:

CapEx

- Device/Structural components
- PCC
- Subsystem integration
- Infrastructure
- Mooring
- Installation
- Decommissioning
- Development

OpEx

- Planned maintenance
- Unplanned maintenance
- Replacement parts
- Insurance
- Environmental monitoring
- Consumables
- Other – grid transmission charging

Further, major categories affecting the power performance were identified and the companies were asked to rank their potential for effect on the LCOE. These major categories are:

AEP

- Advanced Controls altering energy production/performance

- PCC Choice/Design altering energy production/performance
- Device Profile altering energy production/performance
- Array Layout altering energy production/performance
- Other

The companies were given the following guidance. Cost percentages were to be calculated for a single device in a full scale array 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.

Webinar Structure

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. The timeframe for evaluation of the potential of identified cost-reduction pathways is 2030.

Each webinar interview of industry personnel had SNL and DOE representatives in attendance; these representatives compiled notes from the conversation. Webinars typically lasted over an hour and began with a brief overview of general and company specific oscillating water column device technology. Questions were phrased in an open-ended format to minimize the influence on the answer. Time was allotted for the developer to cover any topic that was not included in the CBS.

Questions were targeted for each developer based on their responses to the CBS. For example, the grid connection of Oceanlinx' s blueWave device conveys more insight into infrastructure costs, while Embley Energy's research into the use of composite concrete in the structure gives more weight to their insights into structure and design.

Questions focused on:

- What component or operation has highest cost?
- What is the associated potential for cost reduction?
- What is the potential for improvement in the component or operation?
- What are the paths for improvement?
    a. How likely is each path to be successful?
- What barriers have you overcome or improvements have you made already?

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. Once consolidated and refined, the comments were incorporated back into the company specific CBS and that was returned to that company for verification and elaboration if necessary. The final comments from the three companies were then collected and combined with the data from the literature sources.

Analysis Process

The CBS from each developer and the reference device contained breakdowns of the cost and potential for cost reduction for CapEx and OpEx. Further, the CBS contained breakdowns of the potential for cost reduction in areas that affect the AEP only. These breakdowns 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. For instance, the mooring from a company may be 10% of its cost, but the potential room for improvement is at 4 out of 4. This is compared to the structure cost which may be 35% of the cost, and the potential for improvement is described as a 2 out of 4. The final ranking combined both the cost and the potential rating into one number which would rank the structure higher than the mooring. Within each of the CapEx, OpEx, and AEP categories the line items were then ranked as to their importance.

Additionally, specific technology developments mentioned during the webinar 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.

Finally the three CapEx, OpEx, and AEP categories 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 of other renewable technology developments. A sum of these ratings was used to prioritize the technology developments.

Prioritization and Paramount Cost-Reduction Pathways

The following prioritization is based on the quantitative information provided in the CBSs, information obtained during 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. In some cases, the path to cost reduction is well defined and concrete actions can be recommended. In others, the issue may be coming into focus, in which case the recommendations outline the problem as clearly as possible, and suggest promising avenues for investigation. However, it is likely that particular paths do align with diverse strategic goals identified by companies, institutions, and government agencies. No single entity, including DOE, is likely or is expected to address all of these paths. Hence, it is hoped that these recommendations can be pursued by collectively employing the strategic goals of the community at large.

Most Promising Cost-Reduction Pathways

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

- Advanced Controls
- Improved Power Conversion
- Optimized Structural Design
- Array Optimization

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 or through control of the device's geometry/mass characteristics. Regardless of the control type, execution of the control is predicated upon knowledge of the oncoming waves. In the case of PCC control, the oncoming wave knowledge is required on a wave-by-wave basis. In the case of device geometry/mass control, the oncoming wave knowledge is required on a sea-state by sea-state basis.

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 power produced can be increased anywhere from 5% to 275%, this is a top cost-reduction pathway.[23] [24]

This cost-reduction pathway is considered to be the most promising of all pathways evaluated. Both the Reference Model effort and the industry webinars indicated advanced controls as a top cost-reduction pathway. The Sandia whitepaper authors also rated advanced PCC controls highly and note that there is opportunity for significant increased energy capture with existing devices as well as new devices. The literature review indicates that advanced controls of the PCC coupled with wave prediction would result in a significant reduction in LCOE.

Research Paths

The goal of an advanced controls research effort would be to expand the range of resonant-power-absorption in order to increase the primary energy capture of the device. This goal can be achieved either through changing the structure or through control of the PCC.[24]

To achieve enhanced primary energy capture through structural controls would require one research path. The effectiveness of structural controls will be limited by the extent to which the device's mass and waterplane area can be altered and the speed with which these alterations can take place. Hence, the execution of this control strategy will be limited with expected increases in the annual energy production to be less than the PCC control strategies.

- Structural Control: This control strategy would utilize electro-mechanical controls to physically alter the waterplane area or mass of the device. The degree to which these alterations could be achieved would be closely tied to the original structural specifications. [25] To fully realize the benefits of structural control, the equilibrium structural design would have to be the mid-point design allowing for both smaller and larger waterplane areas to be achieved or more or less mass to be attributed to the device. These electro-mechanical controls would need to be tested. Special attention should be given to the speed with which the controls could be executed, the additionally complexity added to the system, and the efficiency improvement that could be attained.

To achieve enhanced primary energy capture through PCC controls would require one research path with two primary thrusts. Control of the PCC will be limited by the PCC s capabilities (maximum and minimum power values), however the response is effectively instantaneous and the range of frequencies that can be improved is much larger than the structural controls. Hence, PCC control coupled with wave prediction is expected to yield higher increases in the annual energy production of the device.[26]

- 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 would develop algorithms capable of generating a real-time incoming wave field for the WEC array based on the wave measurement system.[27][28] Non-linear and stochastic-capable algorithms will be needed to generate the incoming wave fields. Both scaled device tank testing and full-scale ocean deployment will be needed to demonstrate this technology.
- PCC Control: Both active and passive control strategies can be pursued for the offshore OWC devices. [24] Active control strategies require putting energy back into the device in order to achieve instantaneous and consistent phase matching.[29] 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. Given the nonlinear and stochastic input from the wave prediction portion of the research and the fact that the devices operate in an ocean environment that 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 will be needed to demonstrate this technology.

Improved Power Conversion

Definition

Improving the PCC requires each sub-component to be addressed. Each distinct component operates collectively with the others to achieve a single goal and hence there are many opportunities to affect the final design. For the purposes of the research, the PCC grouping was used to obtain the overall cost of realizable mechanical 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 hold the most promise for cost reduction of this subsystem of ocean wave energy conversion.

Justification

The power conversion chain is the second highest capital expenditure for the offshore oscillating water column designs according to the industry interviews. Additionally, the second highest level of efficiency losses in the device is due to the power conversion chain. Hence, the power conversion chain has the ability to affect both 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 power conversion chain. A nonexclusive and un-prioritized list of promising pathways is presented below.

- Drivetrain Design: The air turbine is subject to bi-directional air flow as the water level rises and drops within the enclosed chamber. This aspect places a unique boundary condition on the drivetrain for the OWCs that is not usually placed on air-turbines—either efficiently changing the rotation direction of the turbine, or efficiently rotating in a single direction while subject to bi-directional air flow. Thus, the drivetrain design for OWCs is a custom developed design that has only been used for a short duration of history.[30] Hence efficiency improvements to the designs should be pursued and are expected. [29,31] These efficiency improvements will increase the amount of grid delivered power. Additionally, designing the drivetrain for manufacture will decrease the capital expenditure on this item.
- Generator Design: The frequency with which the water level rises and drops is highly variable, which causes the air-turbine to spin 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.[32,33,34]
- Short Term Storage: 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, so the ability to reduce the amount of required storage while optimizing its benefits would be important. Developing a program that focuses on understanding storage requirements and the system effects these have would help to direct the industry towards optimal on-board storage requirements. [35,3637]
- Sizing Power Electronics: Sizing components in the power electronic chain is a balancing act weighing system efficiencies, converted power, and storage requirements. [38] A research program designed to optimize grid delivered power as a function of these influences could help direct the industry towards more optimal designs.
- Incremental Efficiency Improvements: The power conversion chain 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 generator is sized to only handle a maximum peak power flow, which is dependent upon the flow rate and pressure within the air chamber. Often times, offshore OWCs will vent the air chamber to reduce the pressure in order to decrease the power flow to the generator to prevent over-power events. Venting effectively throws away mechanical power that could be transformed into grid-delivered power. If the number of venting events could be reduced then the grid-delivered power could be increased.

Optimized Structural Design

Definition

The physical structure or the structural design refers to the necessary components that resist the loads imparted to the conversion device through waves and mooring connection points. The profile of the device, its general size and shape are determined by power conversion requirements; the physical structure is determined by the loads that must be mitigated. Optimizing the structural design incorporates concepts 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 to reduce the capital cost, the maintenance costs, and to lengthen the design life. Optimized structural design seeks to minimize the safety factors used at the component and system levels while maintaining device performance and integrity.[39]

Justification

The physical structure is the highest capital expenditure for the offshore oscillating water column designs according to the industry interviews. Additionally, the physical structure tends to drive the design life of the WEC. Clearly, the physical structure has a high impact on the LCOE for the offshore OWCs and there are many examples both in wind and aerospace which indicate this area has a high potential for improvement. As demonstrated in the aerospace industry, a more complete knowledge of the system (loads, fatigue, vibration, etc.) allows significant reductions in material weight and safety factors, while also improving performance and reliability.

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. Each offshore OWC designer will likely determine a unique solution for their design, thus the thrust of this research is to develop the universal 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 research paths is presented below. These paths 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.

- 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 an offshore OWC, much greater understanding is needed regarding the loads which occur during extreme events.[40][41] The loads originate from the mooring system and from dynamic nonlinear loading on the structure. The dynamic nonlinear loading on the structure includes pressures on the submerged structure, inundation, slap (i.e., water striking an un-submerged section) events, and slam (i.e., the structure striking the surface of the water) events. Detailed device structural analysis (likely via finite element analysis (FEA)) must be coupled with more accurate load estimates. The numerical technique identified to determine these loads [42] would be beneficially complemented with experimental determination via sub-scale physical models.

- Fatigue Modeling: These devices are placed in an environment where they will be continuously subjected to cyclic pressure loading from the waves and cyclic tension loading from the mooring lines and umbilical cables.[43][44] Additionally, certain designs could result in cyclic slap and slam events. Developing modeling tools that can begin to address the fatigue of the structure could be very important to ensuring the longevity of the design.
- Material Case Studies: The specific materials chosen for a design will vary across the industry. Regardless, the need for a process to qualify a particular material for a design application is more generic. Publicly accessible case studies performed on likely material candidates would provide guidance on the best qualification practices. The new structural design could 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 newly required design to withstand the loads using alternative materials as well as 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 overtime, and this has been seen in offshore wind gearboxes.[45] Data from these case studies would be used to seed a larger database that contains material response with 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 a set of procedures developed from case studies focused on fabrication of modular designs in order to achieve better manufacturing and transportation costs. Case 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 case studies would act as publicly accessible procedures for determining how a new design could be similarly fabricated. These procedures studies 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.
- Structural Component Testing Facility: Every mature industry utilizing composites (wind, automotive, aerospace, etc.) has recognized the need for testing of new materials in structural components. When utilizing a new material system in a design profile, the structural integrity of an entire component is often verified using substructural testing methodologies. Coupon testing identifies the material response and failure mechanisms required to begin structural design. However, expanding this knowledge to include structural details and manufacturing processes cannot ensure the integrity of the entire component. Therefore, the industry would benefit from a facility able to test structural components under complete loading conditions to ensure the new materials application to the WEC device will withstand the survival and fatigue loads and can deliver on the expected life.

Array Optimization

Definition

Array Optimization refers to the spacing and orientation of offshore OWCs 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 both capital costs in many categories and 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 poor layout choices. Hence with so many factors influenced through the array layout, this area has been identified as one of the most promising pathways to minimizing the LCOE value for offshore OWC 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 producing in 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 research paths is presented below. These paths include both model tool development as well as the use of 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. [10]

- 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 OWCs 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 OWCs 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 OWC 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,[46] cannot account for the hydrodynamics of interacting bodies and thus may only offer direction for

preliminary studies.[i] The modeling tool that can accurately derive the dynamics of the shared anchoring and mooring solution should be able to account for interacting bodies.

- Performance Optimization through Controls: Optimization of the power from the array, as opposed to a single device, will be an important driver of the infrastructure required to deliver power to the grid. There are many valid optimization goals including: storage optimization, maximizing power delivered, producing a continual and target power output, producing power with few fluctuations, minimizing structure fatigue, or minimizing PCC fatigue. This control strategy will require an accurate array performance model. A modeling tool capable of implementing these various optimization algorithms needs to be developed.
- 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.[47] This is also an important step for obtaining the appropriate licenses and permits for an array and will facilitate discussions with regulators and stakeholders.
- Infrastructure Design Optimization Procedures and Case Studies: 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 should be used to direct the optimal layout and then procedures for systematically studying the effect on sub-sea cable lengths, substations, and communications with the array should be developed. Case studies could be generated to offer initial starting points for companies to use when beginning 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,[48] location and number of substations necessary, length of sub-sea cables, translatability to distinct deployment locations, number of connection points, and redundancy.
- Installation & Maintenance Procedures: In a similar manner to the Infrastructure Procedures, Installation & Maintenance Procedures should be developed from publicly accessible case studies. These case studies should use advanced failure rate models that account for the deployment environment as well as the array layout. These case studies will determine the procedures for systematically studying the effects of the array layout on distinct installation schemes and on expected maintenance patterns. Various aspects that should be included in this case study are: very large WEC arrays vs. clusters of smaller arrays,[48] size of maintenance vessels, size of installation vessels, expected duration of installation, number of devices that should be serviced at the same time, and finally rates and expected duration of maintenance on the devices, the mooring system, and the electrical interconnection system (sub-sea cables, substations, umbilical cables, etc.).
- Grid Integration Case Studies: The needs of the national grid with a high penetration of renewables which supply power from variable generation sources (i.e.: solar, wind, waves) will be significantly different than the needs of a micro-grid such as one for a remote village with critical infrastructure requiring constant power. Case studies could be developed to focus on weighing supply from the array against the demand of the grid in order to minimize the generation that utilities must hold in reserve to meet the needs of the end user.[49] Various

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

solutions that could be studied include power electronics, energy storage, and varying generation sources (diesel, renewables, natural gas, etc.).

Second-Tier Cost-Reduction Pathways

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

- Mooring Design
- Optimized Device Profile
- Increased System Reliability
- Planned Maintenance

Improved Mooring Design

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 is being used as a guide for 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 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 in which 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 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 developing creative ways to absorb the design loads at distinct locations that are separate 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.[50–52] Areas of concern include: rope construction, creep failure, fatigue, abrasion damage, wear resistance, and chemical diffusion, along with the issues stemming from the interfacial contact between any steel component and the mooring line. One notable interest 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.[50] 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 are both of interest. These new lines must be suited to the marine environment and capable of withstanding large loads. The testing will ensure the 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 guideline for WEC mooring systems[ii]. 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 they will not result in large environmental catastrophes if the system fails. These new standards should address both the design environment and the required FoS.
- Active Mooring Design: Currently mooring systems are designed as independent systems from the WEC. However, the opportunity exists 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 reduce the loads on the structure and thus protect the structure during severe storms.

Optimized Device Profile

Definition

The profile of the device, its general size as well as shape, is determined by power conversion requirements. Optimizing the device design through physical changes to the device profile can increase the energy capture. Changes to the device profile can include volume changes (scale-up), drag reduction changes, optimized cross-sectional shapes, or optimized

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[ii] 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.

natural resonances. The types of optimization that are pursued are strongly tied to the type of WEC that is being considered.

Justification

Offshore OWCs are both WABs and OWCs in one; hence careful selection of the natural resonances associated with the structure and the water column will influence the AEP of the device. Additionally, all devices can benefit from drag reduction as well as optimized cross-sectional shapes. Hence, optimizing the device profile is important to reducing the LCOE for the offshore OWC.

Research Paths

The research paths below focus on determining the most optimal profile for the offshore OWC in either a terminator or point absorber configuration.

- Optimize Natural Resonances for Deployment: Since offshore OWCs are resonant absorbers, the location of their natural resonances is extremely important to their primary energy capture. For floating OWCs both the resonance(s) of the oscillating body and the resonance(s) of the OWCs must be considered. Models will be necessary to provide developers engineering-level tools capable of narrowing the design space and yielding solutions in a time-efficient manner. The rapid turnaround enables designers to investigate performance and cost trends prior to moving to an advanced prototype design.
- Optimize scale of OWC Terminator Device: As described in Table 1, the width of the terminator device is expected to influence the theoretical capture limit of the device. Hence, the optimal width of the device should be heavily considered when determining the final profile. The theoretical capture limit cannot be the sole factor; considering the directional spectra of the deployment climate, the structural stability, as well as the additional cost to increase the width should all be factors in the final width decision. To date, the author knows of no theoretical work similar to the work of Yemm et al.[16] describing the dependence of the theoretical capture width on the device width. However, there is work on oscillating wave surge converters that show the dependence of attained capture width on device width.[18,17]
- Optimize Air Chamber Design: Losses in the air chamber of the OWC can be minimized through high-fidelity modeling techniques that can account for viscosity. Typical RANS solvers, such as Star CCM+ or OpenFoam, should be utilized to obtain a fully optimized air chamber shape that will help to ensure efficient flow of the air through the turbine. Additionally, the optimal air chamber height should be investigated with engineering – level design tools.
- 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, should be utilized to ensure efficient flow around and within the structure.

Increased System Reliability

Definition

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.

Justification

System reliability is viewed as a promising pathway because it affects both the availability and the OpEx costs. Experience in other renewable energy technologies also indicates that increased reliability can substantially reduce the cost of energy. [53] 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.

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.

A nonexclusive and un-prioritized list of promising research paths is presented below. These paths 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.

- 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.
- Reducing system complexity: By reducing the complexity of the WEC there will be fewer failure points and a more reliable device will naturally result. 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: Failures on the structure and mooring system will arise from selected materials or coatings. Testing these materials in the marine environment under equivalent 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 a WEC will subject them to.
- Subsea Electrical Infrastructure Testing Facilities: The sub-sea cable and substations within an array offer points of failure that are catastrophic to an arrays performance. Thus, increasing the reliability of the sub-sea electrical infrastructure required to transport electricity back to shore is of high priority. The testing facility should utilize power sources that mimic the power produced from an array and should 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 should be developed.

Planned Maintenance

Definition

Planned maintenance is a scheduled service event for a WEC. Planned 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. In general the planned maintenance schedule is driven by the predicted failure rates of components within the device. Additionally, a half-life refurbishment of the device in which it is towed back to shore is a portion of the planned maintenance. Execution of planned maintenance is dependent upon: weather windows, distance from port, vessel requirements, availability of replacement parts, and predicted failure rates. Maintenance often requires downtime for the device thus negatively affecting availability. In general, the incurred costs for planned maintenance are less than for unplanned maintenance. However, the nascent WEC industry needs more experience with deployed devices to quantify costs for unplanned events. Instead, a shortened planned maintenance interval deals with failures and wear which increases the cost associated with this category. We note that unplanned maintenance is closely related to the Increased System Reliability pathway and the relevant research paths can be found under that section.

Justification

There is significant potential to reduce the costs associated with maintenance activities.[41] Recent work by Dalton has shown that the cutoff for the weather window, often dictated by vessel size, can strongly affect the LCOE of a device. [54] Since maintenance affects the availability and the operational expenditures, this result is not surprising. Hence, optimizing planned maintenance an important cost-reduction pathway to pursue.

Research Paths

The goal of this research path is to increase the accuracy of failure models and the estimated downtime between possible maintenance windows. Additionally this research path is targeted at decreasing the amount of time that must be spent maintaining the device.

- 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 this program would develop a failure models for key components. It is expected that these models would need to consider component failure/fatigue specifications, resource characteristics, number of cycles, and range of operation.
- Resource Classification: This classification scheme should not only identify a site based on the incident power and survival conditions, but should also be targeted towards identifying opportunities for maintenance. Maintenance is dependent upon weather windows, distance to port, and availability of vessels and thus all of these aspects need to be included in the resource classification. 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. Failures that occur during certain seasons may cause longer down times due to the statistical lack of a weather window. Tools to predict weather windows for any location as well as analysis to classify the deployment resource will assist the industry both in failure modeling as well as investor expectations. [55,56] As mentioned above, the work by Dalton [54]has shown how important it is to understand the resource that a developer will have to work within, hence resource classification is a way to standardize the expected O&M costs associated with particular deployment locations.

- Designing for Maintenance: It is inevitable that failures will occur. Incorporating design practices that promote this philosophy will reduce the time and costs associated with maintenance and repairs. This can include use of common components, accessibility to high-priority sections, and “plug-and-play” components which do not require servicing.
- Design for Deployment/Recovery: Design practices that promote ease of deployment and recovery of the device will be important to increasing the reliability of the device when failures occur. This can include improved locking/unlocking mechanisms, standardized methods of attachment for custom vessels, and lighter weight devices.

Less Promising Cost-Reduction Pathways

Pathways that also lead to lower LCOE but were considered less effective than those in the previous lists include:

- Infrastructure Improvements
- Installation Procedures
- Unplanned Maintenance
- Subsystem Integration

Although these pathways were not prioritized heavily, important strides can be made in these areas 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 are pushing towards more customized solutions.

Installation procedures strongly affect O&M as well. Since the majority of these devices will be maintained *in situ* they are not expected to be recovered very often. Hence, the installation and recovery of these devices is not a top priority for reducing the LCOE of the device. Regardless, the design of the interconnections between the mooring, umbilical cable, and device could be improved to decrease the time needed to connect the device. Also consideration of the size and shape (device profile) in terms of installation and recovery is important.

Unplanned maintenance is required when an unexpected failure occurs. The early stage of this industry has not allowed for proper scoping of this particular aspect. The steps identified in planned maintenance as well as system reliability begin to address the concept of unplanned maintenance, but without first addressing the topics raised in these areas it is impossible for the industry, at a planning stage, to really identify a difference between planned and unplanned maintenance. As more applicable knowledge of component MTBF is understood through modeling and aggressive testing campaigns and as more components are customized to their particular application, it is expected that unplanned maintenance will transform into planned maintenance, thus reducing the cost.

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. 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.

Conclusions

The WEC industry has yet to penetrate the U.S. electricity market despite the large potential resource available. Work by Weber [57] has effectively explained 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 an oscillating water column. 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. These 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 government agencies. Hence it is hoped that these recommendations can be pursued by collectively employing the strategic goals of the community at large.

In general, conversations with the industry leaders of offshore OWCs in either terminator or point absorber configurations have highlighted both consensus and division. There appeared to be a split between the use of COTS and the relevance of the oil and gas industry within this group. Both COTS and oil and gas procedures and standards allow for the WEC industry to vet their designs quickly and effectively without having to generate infrastructure and custom designs for a particular device type that may not succeed. Hence, low efficiency high complexity solutions may be acceptable in the beginning. Thus, it is reasonable that both COTS and oil and gas procedures and standards have played a prominent role in the development of devices to date. Some of the developers, however, recognized that the needs of offshore OWCs are unique and that custom solutions, standards, and infrastructure are needed to economically develop these devices. This split highlights the tensions that the industry as a whole is encountering.

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. Interestingly, there is also consensus that tools currently available to industry are not sufficient to optimize their designs and as a result the devices being deployed have low conversion efficiencies and exaggerated FoS resulting in LCOE values that are far from optimized. These developers highlighted that they do not feel they have the opportunity to pursue high risk R&D; instead, their current priority is to compete on the market today which requires responding to present funding calls.

Research programs need to focus on device-independent tools that will enable the entire industry. Tools that address increased AEP with advanced controls, survivability modeling, new generator designs, failure monitoring, and testing facilities to determine MTBF can all be developed generically. Additionally, these research programs need to provide publicly accessible data to the community at large. A significant barrier to the nascent WEC industry is the lack of publicly available information about the processes, techniques, and failures that are occurring within the industry.

Though young, this industry has access 30,660 TWhr/yr (3,500 GW)[2] of potential wave resource globally and 2640 TWhr/yr (300 GW)[3] within the United States. This resource provides the potential for a highly predictable renewable energy source. The information presented in this whitepaper can be used to direct the WEC community towards high-impact research paths that are needed to improve the techno-economic performance of WEC devices and make this a reliable and cost competitive source of renewable energy.

Appendix A – Blank CBS Worksheet

Please visit the "Instructions" tab before completing the table

Levelized Cost of Energy = (CAPEX + OPEX) / ADE where:
CAPEX is capital expenditures
OPEX is operational expenditure
ADE is annual delivered energy

[crossed cell] Do not fill cell

[grey cell] Outisde the scope of technology development R&D

Assumption: ___ devices in an array, array rating ___ MW, ___ year deployment lifetime.

	Cost Component	Percent of Total Project Cost (Totaling 100%)	Potential for Cost Reduction (Rate between 0-4; 0 = no potential, 4 = high potential)	Comments (if applicable)
CAPEX	**Development** (e.g., permitting, environmental compliance, site assessment, system design & engineering, etc.)		[Outside scope; do not fill]	
	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 (e.g., drive train components, generator, 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**		[Outside scope; do not fill]	
	Environmental Monitoring and Regulatory Compliance		[Outside scope; do not fill]	
	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			
CAPEX + OPEX Total	[Do not fill]		[Do not fill]	
ADE	**Advanced Controls Altering Energy Production/Performance** (e.g., energy capture means)	[Do not fill]		
	PTO Choice/Design Altering Energy Production/Performance (e.g., energy capture means)	[Do not fill]		
	Device Profile Altering Energy Production/Performance (e.g., energy capture means)	[Do not fill]		
	Array Layout Altering Energy Production/Performance (e.g., energy capture means)	[Do not fill]		
	Add Other Areas of Delivered Energy not Captured Above if Needed	[Do not fill]		

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