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

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Abstract

This report considers and prioritizes the primary potential technical cost-reduction pathways for offshore wave activated body attenuators designed for ocean resources. This report focuses on technical research and development 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 attenuators, a reference device 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 indicate the five most promising cost-reduction pathways include advanced controls, an optimized structural design, improved power conversion, planned maintenance scheduling, and an optimized device profile.

Acknowledgements

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The authors would like to thank Daniel Laird for his original guidance on the prioritization method as well as his continued programmatic support throughout this work. The authors would also like to thank contributions from the larger SNL team with expertise in specific research paths including: Bernadette Hernandez-Sanchez, Brian Naughton, Todd Griffiths, and Kelley Ruehl. The contribution of additional review by Sandia staff is also appreciated.

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Contents

Executive Summary

Purpose

Under the direction of the U.S. Department of Energy, Sandia National Laboratories has compiled this whitepaper to identify paramount technical research and development cost-reduction pathways for attenuator 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 is not well defined, 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. During this time, industry innovation has produced many prospective device designs. These designs are classified and modeled by considering their method of energy conversion, their directional dependence, and their deployment depth.[1] There are three main methods of conversion: overtopping devices, oscillating water columns, and wave activated bodies (WAB). The methods of conversion can then be further realized as attenuators, point absorbers, or terminators depending on their directional dependence. This whitepaper focuses on offshore WABs with an attenuator directional dependence.

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

Approach

This paper includes information from three main sources:

- Research literature regarding offshore WAB attenuator technologies
- A reference cost breakdown for the attenuator device compiled from literature sources
- Webinars held with companies (Oceantec Energías Marinas, Pelamis Wave Power, and Waveenergyfyn) involved in the development and deployment of ocean wave attenuator devices

Cost-reduction pathway prioritization is based on the quantitative information provided by the industry webinars, the literature review, 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. In addition, no quantitative monetary values for the presented cost-reduction pathways are calculated as only a few prototype devices have been deployed. The prioritization considers 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 LCOE as they cross cut all other aspects.
- **Optimized Structural Design** – a design that manages loads on the structure and maintains device performance while minimizing the cost and the factors of safety. The structure is the highest capital expenditure (CapEx) and, therefore, there is much room for improvement.
- **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.
- **Planned Maintenance Scheduling** – a scheduled service event performed *in situ* or at a port. Maintenance costs relate directly to the service vessel size and failure rates. Additionally, maintenance affects device availability.
- **Optimized Device Profile** – device size and shape that minimizes the device cost of energy. Longer attenuators theoretically absorb more energy, so by optimizing the length and the profile (to reduce drag), significant reductions to LCOE can be realized.

Second-Tier Cost-Reduction Pathways

- **Array Optimization** – impacts CapEx in permitting, infrastructure, installation, maintenance, and mooring. A poorly designed layout may have a negative impact on the energy capture performance of the devices.
- **Installation** – includes the deployment and setup of the device itself, as well as the required support infrastructure. The installation procedure includes labor costs associated with device deployment, the required physical and electrical connections and grid interconnections. The design of the installation procedure also strongly affects the future maintenance costs of recovery and redeployment.
- **Mooring Design** – impacts the capital costs of the mooring system itself and the WEC structure, deployment costs for the mooring, the maintenance schedule for the mooring system, and maintenance costs for the device.
- **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.

In general, conversations with the industry leaders in offshore WAB attenuator devices have highlighted the need to develop the modeling tools, infrastructure, and standards that will allow this industry to move away from oil and gas and grow into an independent industry. While the diversity of designs in the industry adds complexity, research programs can be developed to focus on device type independent tools that will advance the entire industry. Tools that address increased annual energy production (AEP) with advanced controls, survivability modeling, new generator designs, failure monitoring, and testing facilities to measure the mean time between failures (MTBF) can all be developed generically. Additionally, these research programs need to provide publicly accessible data to the community at large. One significant barrier to the nascent wave energy converter (WEC) 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 30,660 TWhr/yr (3,500 GW)[2] of potential wave resource globally and 2640 TWhr/yr (300 GW) [3] within the U.S. that can 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 US 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 offshore WAB attenuators. The purpose of this report is to utilize existing information regarding the Marine Hydrokinetic industry, and offshore WAB attenuators 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 offshore WAB attenuators will help focus research efforts in the areas of greatest potential LCOE reduction and result in 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 a nascent renewable energy source to a more developed and complete source such as wind and solar. [5,6]

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

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

Terms and Definitions

Annual Energy Production (AEP)

Describes the average annual energy generated and delivered to the point of grid interconnection.

Capital Expenditures (CapEx)

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

Cost Drivers

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

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)

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

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 involves five distinct steps:

1. Primary Energy Capture Device: Hydrokinetic to mechanical power conversion (the "intercepted power") [7]
2. Drivetrain: Conversion of device motions into the final form of mechanical power needed to drive the generator (the "captured power") [7]
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, to improve power quality for example.

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. [8]

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 Hydraulics and Maritime Research Center (HMRC) University College of Cork (UCC) in which the definitions' applicability has been broadened to other renewable technology definitions that the DOE uses when assessing cost. [9] 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 Supervisory Control and Data Acquisition, or 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.[6] General definitions of the measure of maturity of technologies are found in the following TRL definitions: [10]

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. [11] These WEC TRLs identify the numerical modeling and experimental expectations that correspond to each readiness level. The WEC TRLs provide a guide for the industry to pursue successful design optimizations, prototype deployments, and utility scale commercialization. The WEC TRLs are identified below.

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

Wave Activated Body (WAB)

A wave energy converter device type that employs moving parts that when shifted by the oscillatory wave motion can generate energy. These devices are in contrast to oscillating water columns or overtopping devices.

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 to accommodate a larger number of parameters 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).

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 (300 GW) of potential wave resource along the United States coastal territory. This resource is not distributed evenly around the United States; below is a sampling of the distribution of the more energetic resource sites which would make good candidates for wave energy development:

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

The spatial and temporal variability of ocean waves requires statistical treatment. Ocean waves are categorized by sea states which are valid for a short duration of time, typically 30 minutes to one hour. A particular sea state is defined by a wave height, 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 appropriate spectral shape for representing 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.[12]

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.[13] JPDs are created through statistical analysis and require many years of data; 10 years of data is recommended to produce an accurate representation of the proposed deployment site. Since wave-height, period, and direction are not statistically independent, JPDs can be created for wave-height and period, wave-height and direction, and period and direction. The JPD characterization can then be used with the chosen spectral shape to determine the average annual power, or energy, present in the waves at a particular location. This treatment is also used to provide inputs for modeling WEC devices and thus also allow for predictions of the average annual power produced by a device at that location.

Device Type Technology Overview

Introduction

The exploration of the principles of wave energy conversion since their discovery in 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, and oscillating water columns, and WABs. The methods can then be embodied as point absorbers, terminators, or attenuators, depending on their directional dependence as shown in Figure 1.[14] 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

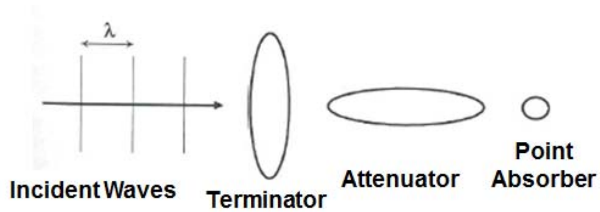

Figure 1: Schematic presented in (Cruz, 2008) highlighting the relative scale and orientation of the distinct directional dependencies.

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.

This report is focused on WABs oriented as attenuators and deployed offshore. In this context, offshore is defined by water-depths between 50 m and 150 m and often implies that the devices will be floating. The definition of an attenuator given in the Annex III report sponsored by the International Energy Agencies implementing agreement on Ocean Energy Systems (IEA-OES) is the one adopted in this research.[9]

> "Attenuators are floating devices aligned to the incident wave direction. Passing waves cause movements along the length of the device. Energy is extracted from this motion. These types of devices are typically long multi-segment structures. The device motion follows the motion of the waves. Each segment, or pontoon, follows oncoming waves from crest to trough. The floating pontoons are usually located either side of some form of power converting module. Passing waves create a relative motion between the pontoons. This relative motion can then be converted to mechanical power in the power module, through either a hydraulic circuit (most common) or some form of mechanical gear train." [9]

The above definition of attenuator is relatively strict in that energy must not only be extracted along the length of the device but that the pontoons are also connected to one another. There are devices that absorb energy in an attenuator configuration but the individual bodies are not connected to one another; a device like Wavestar is an example. [15] When the bodies are not connected to one another they are able to operate as point absorbers (i.e. independently of one another). These devices are effectively tightly packed directional arrays of point absorbers. Hence, devices of this type are not considered in this report; the strict definition of attenuators given above is used as the selection criteria for these devices.

A benefit of attenuators is that they generally have lower anchor and mooring loads when compared with WABs in either point absorber or terminator configurations. They have a relatively small cross-sectional area perpendicular to the on-coming waves which reduces the surge pressure exerted on the devices. Additionally, these devices tend to have shallow draft and, hence, drag is diminished.

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 OWC 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.

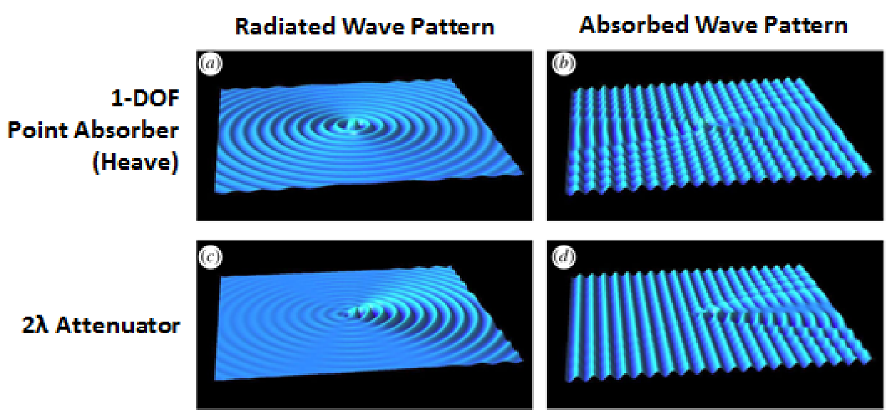

Figure 2: The radiated wave pattern and the absorbed wave pattern for two WABs (Yemm et al., 2012)

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. The capture width is calculated by dividing the absorbed power in kW by the incident wave power flux in kW/m and, hence, the capture width has units of length. The absorbed wave patterns in Figure 2 also show 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)

Directional Dependence	Mode of absorption	Theoretical Capture Width
Point Absorber	1-DOF: Heave Eq. 6.77 [17]	$\lambda/_{2\pi} \approx 0.16\lambda$
	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 [17]	$3\lambda/_{2\pi} \approx 0.48\lambda$
Attenuator	$\text{Length} = \lambda$ [16]	0.50λ
	$\text{Length} = 2\lambda$ [16]	0.73λ
Terminator*	$\text{Width} = \lambda$ Eq. 6.108 [17]	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 that in Yemm et al.;[16] however, there is work that clearly shows the dependence between actual capture width and width of device. [18,19]

These theoretical capture widths were derived using linear analyses (linear potential flow theory) that are not 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 such as attenuators 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 WAB attenuator, can be designed in various ways (e.g., devices from Pelamis and Oceantec), 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, predicted failure rates, among other things. Hence the location of planned maintenance will affect the availability of the device, the optimal profile of the device, and the operational expenditures.

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

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

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

The oil and gas industry has offered guidance on configuration, materials, and Factors of Safety (FoS). The mooring configuration can affect the PCC selection as well as the power performance, or it can be selected to interact minimally with the device performance. Mooring systems that are designed to influence the power performance are either tension based systems or systems that allow weathervaning. Mooring systems that are designed to only influence the device motion during storms are slack catenary based systems that may or may not have auxiliary floats. The mooring systems can be spread or single point; full weathervaning is possible with a single connection point to the device. 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: Attenuators have an elongated x-axis parallel to oncoming waves. They are often fully symmetric around the x-axis, although this is not mandatory. If these 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: A device may be composed of multiple bodies moving with respect to one another. It may also be composed of a single body moving with respect to ground or with a self-reacting on board body. The buoyancy and mooring configuration can influence the number of bodies required to produce electricity.

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

Drivetrain type: The drivetrain converts the device motions into the final form of mechanical energy (or "captured power" [7]) that drives the generator.[9] There are many drivetrain options including rack and pinion, ball-screw, and hydraulic systems. Many of these drivetrain systems can be designed to be linear or rotary in operation. If a direct drive permanent magnet system is used, then the drivetrain and generator are condensed into one part. The drivetrain affects 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.[20] 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 relatively referenced PCCs. Relative reference can be achieved through multiple bodies or through reaction to an onboard body. The relative reference between multiple bodies can be either mutual reaction (bodies responding with similar orders of magnitude) or one body can be inertially dominated (mimicking a "fixed reaction") while the other is dynamically responding to the waves.[20] In the case of an onboard body, there is a mutual reaction based on the onboard body reacting at a distinct frequency due to inertia that is different than the frequency associated with the bodies' reaction to the waves (e.g. a flywheel or gyroscope). 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 WAB attenuators, the angle between pontoons in both the vertical and horizontal axes will have a maximum value.

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 defined above.

Sources of Information

As mentioned above under "Approach", three main sources of information were used for the determination of cost-reduction pathways.

- Research and academic literature regarding ocean wave attenuator technologies and their energy resources.
- A reference cost breakdown for the attenuator device compiled from literature sources.
- Webinars held with companies involved in the development and deployment of ocean wave attenuator 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 attenuator devices. The results point to both to current issues with solutions and to 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 Device: LCOE Estimates from Literature

The reference device was compiled from literature focused on a cost breakdown with relevant CapEx and OpEx categories based on the Pelamis Wave Power P1 Device. The Hydraulics and Maritime Research Centre at University College Cork (HMRC at UCC) offered the majority of the data for the cost break down structure.[21]

The Pelamis 'P1' design is 120m long and 3.5m in diameter. This is shorter in length, narrower and lighter than the design evaluated in the industry webinar with Pelamis (the 'P2' design is detailed in the industry descriptions below). The P1 has four tube sections and three separate power conversion modules. The first prototype was deployed and grid connected in 2004 at the European Marine Energy Centre (EMEC) and underwent testing until 2007. In 2008, an array of three devices was deployed and operated off the coast of Portugal at the Aguçadoura site for the Portuguese electricity utility Energías.

The principal characteristics of the P1 are as follows:

- Primary maintenance location: At port
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally buoyant, equal freeboard and draft
- Mooring and anchoring type: Not directly modeled/specified; taken as 10% of the initial CapEx
- Symmetry: Fully symmetric around the x-axis, absorbing energy in an attenuator orientation
- Number of bodies: 4 oscillating bodies
- Primary oscillation direction: Pitch
- Drivetrain type: Hydraulic rams
- PCC reference: Relative, mutual reaction between two oscillating bodies
- Oscillation constraint: Limit to achievable hinge angles (vertical and horizontal)
- Survival strategy: Hull shape limits maximum range of motion

In this study the P1 is rated at 750kW and is deployed off the coast near Belmullet, Ireland in an array of 160 units resulting in an array rating of 120MW. It was assumed that connections were a daisy chained electrical cable between devices. Further, it was assumed that only 2 km of the cable was trenched for installation with the remainder un-trenched. The performance of this device has never been explicitly stated and, thus, the actual levelized cost of energy has not been deduced. However the formulas and data offered in Dalton et al.[22] have been used to generate an independent cost breakdown structure (CBS) based on a 30 year deployment period. Figure 3 below shows the CBS derived from this Dalton paper. A major thrust in Dalton's paper is to illustrate the importance of weather windows and their effect on maintenance ship capabilities (i.e. maximum service wave-heights). However, without having the benefit of an advanced failure model, the O&M values are derived by simply applying the equation given in the cited paper once per year. In terms of the categories above, this is:

$\text{O\&M} = 30 \text{ years} * (3\% \text{ of Device CapEx} + 3\% \text{ of Mooring } + 3\% \text{ of Infrastructure CapEx})$.

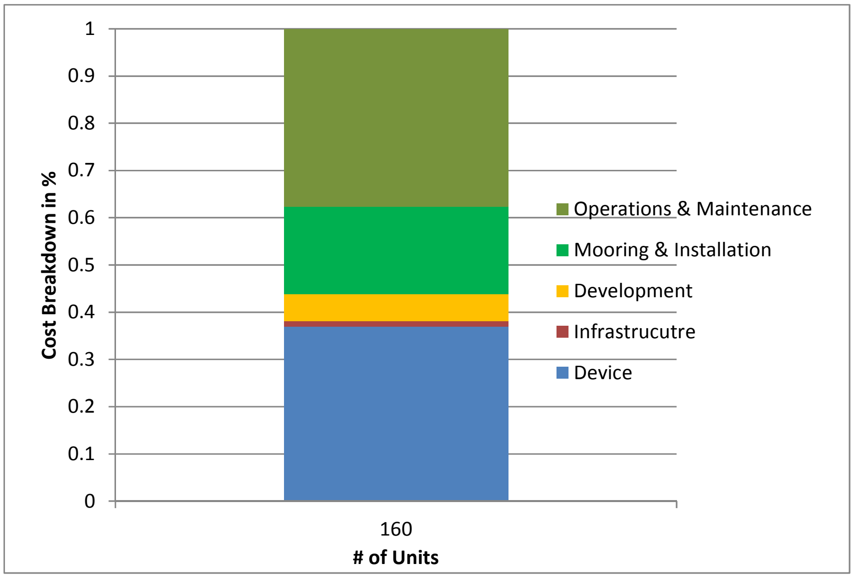

Figure 3: Percentage breakdown of major costs associated with a 160 unit 120MW P1 array deployed for 30 years. Breakdown is derived from data and equations presented in an economic performance study by Dalton.[21]

Together, this independent look at the cost breakdown for an attenuator and the literature review identified key cost-reduction pathways being openly discussed. The major identified cost-reduction pathways in these two sources are:

1. Device Profile – The overall length of the device as well as number of pontoons will be significant drivers in both the amount of power produced and the capital expenditures. [16,20,23]
2. PCC Efficiency – Further work to investigate alternative PCCs that can provide higher efficiency would be worthwhile. PCCs may be gyroscopes, air turbines, hydroelectric turbines, hydraulic rams, and others.[24–27] Additionally, the number of PCCs, driven by the number of pontoons, will be a large CapEx driver.[16,20,23,28]
3. Device Structure – The unballasted weight of the device is a substantial component of the CapEx. Cylinders, ellipsoids and other more unconventional shapes have been modeled to determine the highest power capture for the lowest structural cost.[16,20,21,29]
4. Advanced Controls – Device performance could be increased significantly by using a more advanced control strategy. Prediction of wave behavior coupled to the control and adaption of the action of the PCC to that wave behavior is an active area of academic and commercial research.[16,28]
5. Maintenance – In general, these devices do not lend themselves to *in situ* servicing. Recovering, maintaining, and then redeploying these devices while accounting for weather windows is expected to have a large effect on the plant availability and hence the overall power delivered.[16,21]

The information outlined above was used to frame the conversations with Oceantec Energías, Marinas Pelamis Wave Power, and Waveenergyfyn in the webinars. A description of the webinar process is below.

Aggregated Information from Industry

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

- Oceantec Energías Marinas
- Pelamis Wave Power
- Waveenergyfyn

Industry Descriptions

Oceantec Energías Marinas

Oceantec Energías Marinas is a Spanish company founded by Iberdrola and Tecnalia Research & Innovation in 2008. The development of their single pontoon offshore attenuator began in 2004. In 2006, Oceantec patented their PCC, which allows for the pitch oscillation of the single body to couple to an inertial flywheel that spins in reaction to the pitching body. The development process of their device has included a 1:37.5 scaled wave tank test to evaluate the hydrodynamic behavior, a 1:15 scaled wave tank test to assess the power performance, and a 1:4 prototype deployment off the Spanish coast. The ocean testing in protected waters lasted for 2 months. The principal characteristics of this device shown in Figure 4 are:

- Primary maintenance location: At port
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally buoyant
- Mooring and anchoring type: 4-point slack moored with +/- 22.5deg weathervaning, gravity anchor
- Symmetry: Fully symmetric around the x-axis, absorbing energy in an attenuator orientation
- Number of bodies: 1 oscillating body
- Primary oscillation direction: Pitch
- Drivetrain type: Flywheel (rotating mass) in a gyroscope connected to hydraulic rams
- PCC reference: Relative, inertial reaction between oscillating body and flywheel
- Oscillation constraint: Gyroscope can only precess +/-60°
- Survival strategy: Generator sized to limit maximum precession angle of gyroscope

In addition to their WEC development, Oceantec Energías Marinas has also developed techno-economic models to calculate the LCOE of various devices.[20] This model has lead Oceantec to select a new platform (an offshore oscillating water column in a point absorber configuration) to develop into a product. More information regarding Oceantec Energías Marinas can be found on their website: http://www.oceantecenergy.com/.

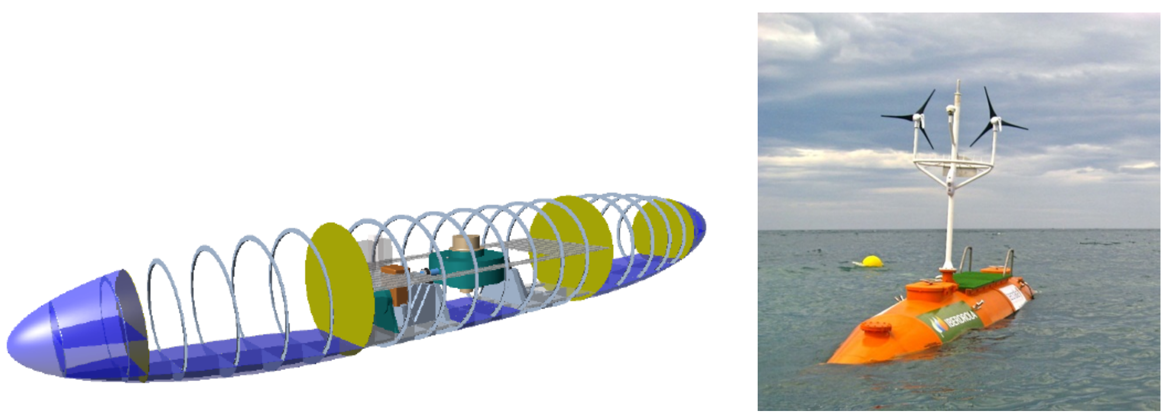

Figure 4: Schematic showing location of power conversion subsystem and picture of deployed quarter-scale prototype from Oceantec Energías Marinas. These pictures are courtesy of Oceantec Energías Marinas.

Pelamis Wave Power P2 Device

Pelamis Wave Power is a Scottish company that has been pursuing the development of the Pelamis device since 1998. Pelamis Wave Power is working in conjunction with major UK utilities, E.ON and ScottishPower Renewables, on the deployment of two, second generation, P2 Pelamis machines at EMEC. The P2 design is longer, wider and heavier, has more pontoons, and has eliminated the separate power conversion modules that the P1 design had. The E. ON P2 device was installed in October 2010 and the ScottishPower machine in May 2012; both are undergoing a progressive testing program. Pelamis has undergone in-depth third party verification of the machine and its moorings. Pelamis Wave Power currently has plans to develop five commercial grade wave arrays. The principal characteristics of the P2 attenuator shown in Figure 5 are:

- Primary maintenance location: At port
- Placement in the water column: Surface expression
- Buoyancy type: Neutrally buoyant
- Mooring and anchoring type: 3-point slack moored attached to a single point on the device allowing for +/- 90deg weathervaning, an additional yaw restraint line, anchor suitable for deployment location
- Symmetry: Fully symmetric around the x-axis, absorbing energy in an attenuator orientation
- Number of bodies: 5 oscillating bodies
- Primary oscillation direction: Pitch and yaw
- Drivetrain type: Hydraulic rams allowing for two degrees of freedom at each joint (relaxes directional dependence)
- Drivetrain reference: Relative, mutual reaction between two oscillating bodies
- Oscillation constraint: Limit to achievable hinge angles (vertical and horizontal)
- Survival strategy: Hull reaction to wave curvature naturally limits the range of required motion as a function of wave steepness with the long streamlined device “diving” below the steepest waves; thus, generator must only be sized to limit the hinge angles

More information regarding Pelamis Wave Power and the P2 device can be found on their website: http://www.pelamiswave.com/.

Figure 5: The E. ON P2 device installed and operating in EMEC. This picture is courtesy of Pelamis Wave Power.

Waveenergyfyn

Waveenergyfyn is a Danish company that has been pursuing the development of their Crestwing device for the past eight years. The Crestwing is an offshore articulated attenuator composed of two bodies. Although the device is an attenuator, it does have an elongated direction that is perpendicular to the waves (similar to a terminator). This large surface area of the device is necessary for its performance; the device is designed to be a light wave-follower with a restoring force supplied through atmospheric pressure as opposed to the weight of the pontoons. [30] The development process of the Crestwing has moved it through 3 phases of testing: 1:30 in a controlled wave tank environment (Aalborg University), 1:20 in a controlled wave tank environment (DHI, Hoersholm Denmark), and 1:5 off the coast of Frederikshavn, Denmark. The ocean testing in protected waters lasted for 4 months. Currently the deployment of a full-scale device is planned at DanWEC off the northwest coast of Hanstholm, Denmark. The principal characteristics of this device 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 attached to a single point on the device allowing for complete weathervaning, drag embedment anchor
- Symmetry: Symmetric across the x-z plane absorbing energy in an attenuator orientation
- Number of bodies: 2 oscillating bodies
- Primary oscillation direction: Pitch
- Drivetrain type: Rack & Pinion
- PCC reference: Relative, mutual reaction between two oscillating bodies; only produces power in one direction
- Oscillation constraint: Cannot produce power in sway (horizontal directions), limit to achievable hinge angle in heave (vertical directions) based on rack & pinion length
- Survival strategy: Disengage PCC through the use of electrical or slide clutches

More information regarding Waveenergyfyn can be found on their website: http://www.waveenergyfyn.dk/.

Figure 6: The 1:5 scale Crestwing device deployed off the coast of Frederikshavn Denmark from September 2011 through December 2012. This picture is courtesy of Waveenergyfyn.

Webinar Process

Details of the process by which Sandia National Laboratories (SNL) conducted the webinars are contained below. Blank worksheets and sample questions are given; however, the worksheets from webinar participants are not disclosed 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. 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 or performance
- PCC choice/design altering energy production or performance
- Device profile altering energy production or performance
- Array layout altering energy production or performance
- Other

The companies were asked to fill out the CBS in advance of the webinar and were given the following guidance. Cost percentages were to be calculated for a single device in a full scale array and for mature technology (i.e., 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 attenuator technology. Questions were phrased in an open-ended format to ensure there was as little influence on the answers as possible. 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, Pelamis currently operates a deployed WAB attenuator device and therefore has more insight into planned and unplanned maintenance procedures and costs than Waveenergyfyn, which is currently moving towards full scale deployment.

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 maturity 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 and 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, which may be 35% of the cost, and the potential for improvement is at 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 three 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), and
- 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, the reference device 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.

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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, 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 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 discussed below are judged to be the most promising for reducing LCOE for the offshore WAB attenuator.

- Advanced Controls
- Optimized Structural Design
- Improved Power Conversion
- Planned Maintenance Scheduling
- Optimized Device Profile

Advanced Controls

Definition

Advanced controls can be used to increase the annual energy production (AEP) of a device through increasing the availability or increasing the primary capture efficiency of the device, or by doing both. Controls targeted to increasing the availability of the device tend to focus on autonomous operation and health monitoring to minimize the human-interaction and downtime for each device. Additionally, controls targeted towards availability may facilitate device operation in a broader range of sea states by incorporating wave forecasting techniques. Advanced controls can also refer to the procedures capable of increasing the capture efficiency of the device. These procedures can be implemented through control of the drivetrain and generator and are often predicated upon knowledge of the oncoming waves, although there are proxy techniques as well.

Justification

In the calculation of LCOE, the AEP is the denominator cutting across all costs; hence, improvements in the AEP are paramount to all others. Additionally, there are a number of attainable advancements that can be made to increase the AEP of offshore WAB attenuators. Pelamis Wave Power has stated that control algorithm development is "considered the most important route for future performance improvements."[16] Although the body of research on controls specific to offshore WAB attenuators is small, there has been considerable research into the use of controls on other WEC types.[31–36] This research has consistently shown the potential for large increases, on the order of hundreds of percent, in absorbed power with the use of advanced controls.

Research Paths

Current device availability is influenced by three main factors: knowledge of incident climate severity, component and subsystem failures combined with maintenance strategies and options, and autonomous operation capabilities. Separate research paths may be used to address each of these factors.

- Autonomous Operation: The ability of a device to operate autonomously without constant interaction is required as a primary step in advanced controls. Communication between the device, resource, and forecasted resource is necessary for autonomous operation. Additionally, the control system must monitor the system state and execute controls based upon a supplied algorithm. Simulation environments could be developed to test the control's response to distinct resources using system-level performance models. This environment can then be expanded to hardware-in-the-loop testing.
- Wave-forecasting: As described in the Resource Overview, information regarding the energy spectrum in the resource is normally delivered in 30 minutes to one hour increments from measurements. Forecasts of likely wave states three hours in advance can be made with programs such as WAVEWATCH III. [37] These predictions are useful for identifying gross changes in the expected energy, but on these time scales this information can result in excessive suspension of operation to protect the system when severe events are forecast. Increasing the predictive capabilities to accurately estimate the likely incoming energy on the order of minutes ahead would allow devices to cease operations only when the severity of a particular wave group warranted it. This research path is both hardware and algorithm focused, since real-time inexpensive sensors would be needed to provide the shut-down algorithm with past data at least as rapidly as the wave-forecast algorithm is updated.
- Health and Diagnostic Monitoring and Controls: Component and subsystem failure can occur based on multiple causes: fatigue, extreme events, or random events. Health and diagnostic monitoring and controls should be able to address the first two causes. Once the life of a component or sub-system has been established, monitoring can occur to determine when a likely fatigue failure will happen. Furthermore, the maximum loads, voltages, etc. for each component and subsystem establish the extreme event threshold. Controls that can be used to manage the dynamic loads on the system and decrease both fatigue and extreme event failure rates could dramatically alter the LCOE of a device through decreased downtime (i.e., directly affecting both AEP and OpEx) and increased lifetime (i.e., directly affecting levelization of CapEx). Clearly, control strategies of this sophistication would require system-level performance models that continuously track the number and magnitude of cycles in order to predict when a fatigue failure is imminent. Additionally, the system-level performance model would need to feed into a cost model in order to optimize LCOE based on performance or on OpEx costs.

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. AEP enhancing controls are used to expand the range of frequencies over which efficient conversion is occurring. This has the effect of increasing the average converted power without increasing the peak converted power. This control is predicated upon foreknowledge of the incoming waves, or a proxy measurement. Although much of the literature focusing on reactive and bang-bang controls is applied to single body point absorbers or dual body point absorbers, there is nothing fundamentally limiting application of this research to WAB attenuator devices.[32,34–36] Reactive controls involve applying forces to the device in phase with the wave motion that can then be tuned for maximum energy absorption at the peak frequencies that correspond to different incoming wave spectra. Bang-bang controls include latching and clutching, and allow the control output to jump between two values, a low and a high. This research path is composed of two main thrusts:

- Wave Forecasting Eventually Leading to Wave Prediction: As described above, improved wave forecasting would be able to produce an estimated *energy spectrum* of a wave a few minutes to tens of minutes into the future. Wave prediction is the ability to predict the phase and amplitude of the free surface seconds to tens of seconds into the future. Wave prediction is the ultimate goal; however, the measurements, including the required sensors and the algorithm development, for both forecasting and prediction can be viewed as complimentary. Additionally, since the attenuator span is typically on the order of one wavelength, the information obtained about the resource at the beginning of the device can be used to enhance the controls at the end of the device. Hence, the wave forecast can be improved as the incident wave travels down the length of the device, with multiple opportunities to optimize the drivetrain's response. As a result, wave prediction may not be as important as wave forecasting to increasing the peak power from this device; however, the wave prediction will be able to yield the largest potential power increases by increasing the average converted power. This effort could be comprised of two components: wave measurement and wave forecasting and prediction algorithms. Both scaled device tank testing and full-scale ocean deployment would be needed to demonstrate this technology.
- PCC Control: Both reactive and bang-bang control strategies can be pursued for the attenuator devices.[28] Reactive control strategies require putting energy back into the device in order to achieve instantaneous and consistent phase matching. Alternatively, bang-bang 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 drivetrain control algorithm would 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 drivetrain and generator. To fully realize the potential of advanced nonlinear controls, more capable drivetrains and generators may be needed. Both scaled device tank testing and full-scale ocean deployment would be needed to demonstrate this technology.

Optimized Structural Design

Definition

The physical structure or the structural design refers to those 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 its shape are determined by power conversion requirements; the physical structure is determined by the loads that must be withstood. Optimizing the structural design must incorporate 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 and maintenance costs, while meeting the design life criteria. Optimized structural design seeks to minimize the safety factors used at the component and system levels while maintaining device performance and integrity.

Justification

The physical structure is the highest capital expenditure for the offshore WAB attenuator designs according to the industry interviews and literature survey. 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 attenuators and there are many examples, both in wind and aerospace, which indicate this area has a high potential for improvement. As consistently 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 the research for an optimized structural design 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 company will likely determine a unique solution for their design; thus, the thrust of this research would be to develop the tools that allow them to customize that design. Without accurately and fully understanding the loads acting on the structure, 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 attenuator, much greater understanding is needed regarding the loads which occur during extreme events. The loads originate from the mooring system and dynamic nonlinear loading on the structure. The dynamic nonlinear loading on the structure includes pressures on the submerged structure, inundation, greenwater loading (i.e., a significant amount of water on deck, usually caused by storm induced wave motion), slap events (i.e., water striking an un-submerged section), and slam events (i.e., the structure striking the surface of the water). Detailed device structural analysis, likely via Finite Element Analysis, should be coupled with more accurate load estimates. It is expected that the numerical technique identified to determine these loads would be 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, cyclic tension loading from the mooring lines and umbilical cables, and cyclic bending moments. Additionally, certain designs could result in cyclic greenwater, slap, and slam events. The development of modeling tools that can begin to address the fatigue of the structure would be very important to ensure the longevity of the design.
- WEC Design Standards: Offshore oil and gas standards are currently being applied to WEC designs in order to obtain the necessary insurance prior to deployments.[i] These standards employ high FoS owing to the fact that human lives are at risk if the structure experiences a catastrophic failure. The survivability modeling and fatigue

[i] Note: Standards specific to WEC designs are in initial stages through efforts in the IEC. However, these standards currently relate to nomenclature, resource, and power production. Standards specific to the structural design and anchor and mooring are not as developed.

modeling research paths could be employed to assemble new standards customized to WEC deployments. Additionally, instrumented WEC deployments could be utilized to obtain measurements with which to validate the modeling results.

- Manufacturing Procedures: Currently, the attenuator industry is using man-hour intensive fabrication facilities for prototype designs.[38] This manufacturing regime should be altered if the cost of the structure is to fall dramatically in scope. Since each device is, at this time, unique, we propose the development of a set of case studies to investigate how particular designs could be fabricated. Case studies would (1) identify the raw materials, labor, tooling, factory capital costs, and transportation costs associated with a particular design and (2) identify areas where better manufacturing and transportation costs could be achieved. These case studies would act as publically accessible procedures for determining how a new design could be similarly fabricated. These procedures would engage the manufacturing industry to determine how the survival and fatigue loading data (generated from models above) could be used to generate more simplified designs applicable to volume production and they may also identify the infrastructure development required to see volume production become a reality.
- Materials Case Studies: The use of alternative materials in the WECS may increase the expected lifetime of the structure, allow for unique repurposing of the structure, or allow for shape optimizations influencing the performance.[29] The specific materials chosen for a design will vary across the industry. Regardless of the material of interest, a process to qualify a particular material for a design application would advance the industry. Publically accessible case studies performed on material candidates would offer guidance on the best qualification process. The case studies would focus on maintaining the power performance of a particular device and investigate the ability of the newly required design to withstand the loads using alternative materials. Equally important, the manufacturing industry should be engaged to ensure that the materials and fabrication methodologies are conducive to high volume production. Unique influences from the marine environment, including saltwater uptake and biofouling, would need to be incorporated as these two processes can affect the integrity of the material over time; this has been observed in offshore wind gearboxes.[39] These case studies should generate structural designs incorporating the results from the survivability and fatigue modeling tasks proposed above and utilizing alternative materials. Data from these case studies would (1) seed a larger database containing material responses, considering environmental influences, to WEC-specific loading and (2) engage the manufacturing industry early to ensure volume production is possible with the desired materials.
- Structural Component Testing Facility: Every mature industry utilizing composites (wind, automotive, aerospace, etc.) has recognized the need for testing of structural components, and/or subcomponents fabricated of the new materials and of the joining features required to integrate them. When utilizing a new material in a design profile, the structural integrity of an entire component is often verified using substructural testing methodologies. Coupon testing is able to identify the material response and failure mechanisms required to begin structural design, but this knowledge must be expanded to include structural details and manufacturing processes in order to ensure the integrity of the entire component. Therefore, this industry would benefit from a facility 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.

Improved Power Conversion

Definition

Improving the PCC requires each component in the PCC 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 this research, the PCC grouping was used to obtain the over-all cost of realizable mechanical to electrical power conversion. However, during the webinars 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 WAB attenuator designs according to the industry interviews and literature review. 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, 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 research paths is presented below.

- Systems-Level Performance Model: Determining the requirements for each component of the power conversion chain necessitates a systems-level performance model. This model can assist the developer in understanding where commercial off-the-shelf components (COTS) are appropriate and where custom solutions may be necessary. This model will also assist in specifying the requirements for the custom solutions. Without such a model, it will be difficult to determine if the components selected are the best match for a particular design's operation.
- Drivetrain Design & Manufacturing: There are a limited number of ways in which mechanical power can be produced from the wave-activated body; however, optimizations of these designs would be beneficial. Incremental optimizations relating to efficiency losses and manufacturability of the drivetrain can be realized. Completely new drivetrain designs or the combination of the drivetrain with the generator would transform the power conversion chain and could lead to large improvements.
- Generator Design: The frequency of body oscillations is highly variable which causes the drivetrain to move 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 optimized for operation in this variable-rate environment could result in higher levels of grid-delivered power.
- Incremental Efficiency Improvements: The power conversion chain can be viewed as a series of efficiency losses from each component. At each step in the chain there is an opportunity to improve efficiency through improved components.
- Power Conversion Chain Scalability: Attenuators are theoretically expected to perform better as their size increases (see Optimized Device Profile section) raising the importance of the scalability of the power conversion chain. [40] Since the attenuator device is an emerging technology, it is logical that the current focus is on building smaller test-bed versions. However, as the industry grows, the size of these devices is expected to

grow. Hence, the selection criteria for components should include their inherent scalability. This research path should identify the limitations to scalability (is it manufacturing, voltage rating, or some other aspect?). This research path should also strive to identify those new components that will be required as the scale of the devices grows.

- Survivability: The loads on the power conversion chain in survival conditions will drive the required size of each of the components and, hence, the cost. Focus should be placed on methods to either remove the power conversion chain from the load pathway or to ameliorate the effects of large loads on it. Pelamis Wave Power has developed passive techniques to minimize the load transfer to the drivetrain during survival conditions, and attributes a cost-competitive advantage to this fact. [16] It is possible that additional components may be required for a particular attenuator in order to completely remove the power conversion chain from the load pathway, thus mitigating the savings due to reduced component size.

Planned Maintenance Scheduling

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 usually requires downtime for the device, thus negatively affecting availability. In general, the costs for planned maintenance are much less than for unplanned maintenance. However, the nascent WEC industry needs more experience with deployed devices to quantify costs for unplanned events. Instead, the planned maintenance interval is kept short to deal with failures and wear. 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. Also note that the Health and Diagnostic Monitoring and Controls research path discussed under Advanced Controls is also central to maintenance.

Justification

The contribution of planned maintenance to the LCOE of offshore WAB attenuator devices ranks it as one of the top five. Recent work by Dalton has shown that the cutoff for the weather window, often dictated by maintenance vessel size, can strongly affect the LCOE of the device.[21] Additionally, performing maintenance in forecast periods of low energy availability to minimize impact on turbine availability, lengthening the maintenance interval and avoiding unscheduled maintenance would greatly reduce the negative impact to AEP and the LCOE of the device. Since maintenance affects both the availability and the operational expenditures, the anticipated cost reduction is not surprising.

Research Paths

The underlying goal of this research path is to increase the accuracy of failure models and reduce 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. These efforts together can reduce the contribution of planned maintenance to the LCOE of 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 and develop failure models for key components. These models could integrate component failure/fatigue specifications, resource characteristics, number of cycles, and range of operation.

- Resource Classification: A classification scheme could be developed that not only identifies a site based on the incident power and survival conditions, but that also identifies opportunities for maintenance. Maintenance is dependent upon weather windows, distance to port, and availability of vessels and thus all of these aspects could be included in the resource classification. In addition, this classification scheme could 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 and help to establish realistic investor expectations. As mentioned above, the work by Dalton[21] 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.
- Monitoring Tools and Instrumentation: To facilitate improvements in planned maintenance schedules, diagnostic monitoring tools and instrumentation could be developed and employed on devices and their anchor and mooring. Fundamentally, data collection campaigns are needed to evaluate system performance under a variety of real operating conditions and gather data that can be used to validate the accuracy of component design models and failure models. Health monitoring campaigns from the wind and aerospace industry have helped to catapult the availability of these devices forward, and it is expected that similar results would occur with the attenuator industry. This instrumentation would feed directly into the Health and Diagnostic Monitoring and Controls path discussed under advanced controls.
- Designing for Maintenance: It is inevitable that failures will occur. Incorporating design practices that accommodate this philosophy would 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 and Recovery: The incorporation of design practices that promote ease of deployment and recovery of the device will be important to increasing the reliability of the device when servicing must occur. This can include improved locking/unlocking mechanisms, standardized methods of attachment for custom vessels, and lighter weight devices.

Optimized Device Profile

Definition

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

Justification

The offshore WAB in an attenuator configuration is distinct from other WEC types in that the device length can influence the theoretical energy absorption limits.[16,40] Other WEC types have their theoretical absorption limits set by the primary oscillation direction(s) and their size is not particularly important. Since there is a theoretical advantage to increasing the length of attenuators, optimizing the device profile has the potential to dramatically increase the AEP. Additionally, all devices can benefit from drag reduction and optimized cross-sectional shapes. Hence, optimizing the device profile is one of the most important changes that can be made to significantly reduce the LCOE for the offshore WAB in an attenuator configuration.

Research Paths

Although there is a theoretical advantage to scaling up the attenuator device, other factors become important in implementing larger devices. The research paths below focus on the more practical aspects of determining the most optimal profile for the attenuator device and could include modeling, techno-economic optimizations, and potential prototype testing.

- Optimization Tool: An optimization tool could be developed to assist in the investigation of an optimized device profile. A useful tool would include economic data, power optimization data, inputs for maintenance costs, as well as modeling the interaction of the device shape in the deployment environment. The model should allow variation in the parameters listed in the following research paths.
- Optimal Length: The theoretical absorption of an attenuator increases with increasing length. However, there are other techno-economic factors that come into play when determining the optimal length. Techno-economic optimizations by Costello and de Miguel both show that the most cost effective result is not the result that necessarily produces the most power.[20,23] Additionally, increased length will introduce more levels of complexity. Hence, research is needed to determine the optimal length whilst weighing the impact on OpEx and CapEx.
- Optimal Number of segments: Many attenuator designs are segmented into distinct pontoons with power conversion modules between the pontoons. The optimal number of segments influences the power.[20,23] Additionally, the number of segments will determine the number of power conversion systems required and, hence, also the planned maintenance schedule; both of these strongly influence the economics of the device. Again, the optimal power solution may not be the optimal economic solution, and, thus, research is needed to weigh these trade-offs.
- 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. 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 the structure.
- Optimal Cross-Sectional Design: The cross-sectional profile of the device will influence the hydrostatic restoring force upon variable submergence, the drag characteristics of the device, the total volume. Therefore, determining the optimal width/diameter and the shape of the cross-section will influence multiple aspects relating to the AEP of the device.

Second-Tier Cost-Reduction Pathways

These pathways also lead to lower LCOE but were not considered to be as promising for reducing LCOE as those in the previous list.

- Array Optimization
- Installation

- Improved Mooring Design
- Increased System Reliability

Array Optimization

Definition

Array Optimization refers to the spacing and orientation of offshore WAB attenuator devices within a large deployment containing multiple 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, but not so close as to compromise the performance of the individual units. The array layout will affect the power performance of each device individually as well as the power output from the array and the environmental impacts 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 by poor layout choices. With so many factors influenced through the array layout, this area has been identified as a promising pathway to minimizing the LCOE. However, due to the unique aspects of the offshore WAB attenuator device, this is not a first-tier prioritization.

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; this could dramatically reduce the cost of the mooring and anchoring system required. Footprint minimization is limited by the number and size of the WEC devices, and therefore it is linked to producing the target energy with the fewest devices possible. Thus the main goal of this research lies in developing the tools required to understand the performance implications of WEC-WEC interactions. Without this tool, it will not be possible to minimize the foot-print of the array while achieving the target energy with the fewest devices possible.

A nonexclusive and un-prioritized list of promising research paths is presented below. These paths include both model tool development and case studies that will further the industry knowledge. The wave energy development roadmap that outlines distinct WEC TRLs addresses array development as its own research and development process; most of the research paths identified below are introduced there.[11]

- Array 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 of other devices. Thus an array performance model, based on hydrodynamic interactions, could be developed so that the effect of wave interactions between attenuators can be understood. This model would 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 attenuators 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 attenuator devices. Models capable of capturing the full dynamical system could be developed in order to pursue high accuracy solutions. Current industry standard mooring models, like OrcaFlex,[41] cannot account for the hydrodynamics of interacting bodies and thus may only offer direction for preliminary studies.[ii] 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 large amounts of power to the grid. There are many valid optimization goals including storage optimization, maximizing power delivered, producing power continuously at a target level, producing high quality power, minimizing structural fatigue, and minimizing power conversion chain fatigue. This control strategy will require an accurate array performance model. A modeling tool capable of implementing these various optimization algorithms is needed.
- Environmental Modeling: This model would require 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.[42] Having such a model would be an important step for obtaining the appropriate licenses and permits for an array and could 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 to investigate an array's impact on infrastructure will be similar. The modeling tools developed above could 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 could 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 could be included in these case studies are very large WEC arrays vs. clusters of smaller arrays,[43] location and number of substations necessary, length of sub-sea cables, translatability to distinct deployment locations, number of connection points, and component redundancy requirements.
- Installation & Maintenance Procedures and Case Studies: In a similar manner to the Infrastructure Procedures and Case Studies, Installation & Maintenance Procedures and Case Studies could be developed from publically 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 would determine the procedures for systematically studying the effects of the array layout on distinct installation schemes and on expected maintenance patterns. Various aspects that could be included in this case study are very large WEC arrays vs. clusters of smaller arrays,[43] size of maintenance vessels, size of installation vessels, expected duration of installation, number of devices serviced at the same time, and, finally, rates and expected duration of

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

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 that 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.[44] Various technologies that could be included in these studies are power electronics, energy storage, and assorted generation sources (diesel, renewables, natural gas, etc.).

Installation

Definition

Installation of WEC devices includes the deployment of the device itself as well as the infrastructure required to support the device. Hence, vessel time and man hours required to set-up the electrical cable, mooring and anchoring configuration, the device itself, and interconnection of all of these components comprise the installation process. Additionally, the installation procedure strongly affects the maintenance costs since recovery and redeployment of the WEC will have to follow the same installation and interconnection procedure.

Justification

The capital investment as well as the strong overlap that the installation process has on planned maintenance costs raises this CBS component to the second tier. In general, servicing attenuator style devices *in situ* will not be common because the typical aspect ratio, narrow and long, is not conducive to onboard maintenance. Thus, more attention must be paid to installation and recovery procedures for attenuator devices than for other WEC devices that employ *in situ* maintenance techniques.

Research Paths

The goal of the installation research path is to focus on the design of the device, mooring connection points, and electrical cable connection points through the lens of installation. This is a process intensive exercise that can actually drive the design of each of the subsystems mentioned. Close and early collaboration with vessel operators, remotely operated vehicle (ROV) operators, and the research and design team within the company is necessary to find optimal solutions for each device. Below is an un-prioritized list of the considerations that drive the deployment and recovery costs throughout the life of a device.

- Device Profile: The device profile impacts installation costs through its demands on deployment vessel size and through the limitations and requirements of the port chosen for deployment. A longer device captures more energy, but would also require a larger, more powerful and more expensive deployment vessel. The port requirements could limit feasible deployment locations or the tow duration. These two factors combined may cause reconsideration of the device profile design.
- Mooring Connection Scheme: The location and number of mooring connection points will directly influence the dwell time and maintenance vessel requirements for the device. If each device in an array requires considerable man-hours or specialized equipment to attach the device to the mooring, the cost can quickly become unmanageable. If the connection points are below the surface, ROVs, supplementary buoyancy, or other

techniques will be required to complete the connections. Additionally, the number of attachment locations multiplicatively increases the cost, duration, and complexity of any deployment operation. These constraints may force the consideration of new mooring designs.

- Electrical Connection Scheme: In general, the umbilical cable attaches to the underside of WEC devices with wet-mate connectors at a point where the cable will experience minimal bend motions. In some cases the cable will pass through the device wall utilizing seals and will connect to the power electronics with dry connectors. These different connection schemes greatly influence the complexity and requirements for installation and recovery. Again, considering the process and its implications upon the installation and O&M costs on an array scale may motivate design alterations.

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 FoS. Currently, the offshore oil and gas industry practices are being used as a guide to WEC mooring designs; similar materials are being used, and the same design environment and conservative FoS are being applied. However, unmanned WEC operation and the deployment locations are fundamentally different from the manned structures being moored in the oil and gas industry; WECs are moored in much shallower water than oil and gas structures and WECs are designed to have large oscillation amplitudes in predominant frequency ranges whereas offshore platforms are designed to stay motionless.

Justification

The capital and the operational costs associated with the mooring and anchoring system combine to identify this subsystem as an important area 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 and more favorable environment interactions with the sea-floor. 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), and 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 and the unique deployment depths. This goal can be achieved through multiple research 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 should 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 require 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 these materials meet mooring requirements.[45–47] 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 concern for the WEC devices using steel construction is the effect of rust on mooring, since decreases on fiber strength have already been reported for lines coated with rust particles.[45] 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 all of interest. These new lines must be suited to the marine environment and capable of withstanding large loads. The operational and environmental testing would ensure appropriate fatigue properties to allow the establishment of operation and maintenance routines.
- Mooring Design Standards: This path would involve determining the guidelines and regulations that currently exist for mooring systems, critically assessing WECs similarities and dissimilarities to other moored marine structures, modeling WEC devices, and developing recommended guidelines for WEC mooring systems. It is expected that the most suited guidelines will result in lower FoS than those applied to oil and gas since WECs are unmanned and system failures will not result in large environmental catastrophes. These new standards should address both the design environment and the required FoS.
- Active Mooring Design: Current mooring systems are often 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.

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, the power conversion chain, and subsystem integration. There are many ways to tackle reliability concerns since they exist in each of the subsystems of a WEC device, including structure, power conversion, mooring, and grid connection components. Note that planned maintenance was identified as one of the most promising cost-reduction pathways and that related research paths may be found under that section.

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.[48] Since WECs are located in marine environments, their reliability is even more critical as access is typically more difficult than for 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 path 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. Recommended research paths to address this issue include modeling, design, testing and operation activities.

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 would further the industry knowledge, and development of testing facilities suited to examining the structural integrity of components.

- Full-Scale Power Conversion 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 and 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 hence, a more reliable device will naturally be developed. Reduction of system complexity can be achieved through higher accuracy modeling studies 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 and subsystem integration.
- Materials Testing and Failure Model Development: Failures of the structure and mooring system may arise as a result of the use of particular materials or coatings. Testing these materials in the marine environment under equivalent conditions (be it cyclic loading or marine growth) will help to classify the failure modes of the materials. This research program would help accurately develop failure models because often times these materials do not come with failure or fatigue specifications when subject to the unique conditions a particular to WEC devices.
- Sub-sea Electrical Infrastructure Testing Facilities: The sub-sea cable and substations within an array are potential points of failure that are catastrophic to an array’s performance. Thus, increasing the reliability of the sub-sea electrical infrastructure required to transport electricity back to shore is 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 could be developed.

Less Promising Cost-Reduction Pathways

Pathways that may also lead to lower LCOE that were considered to be less promising that those in the previous lists include:

- Infrastructure Improvements
- Minimize Unplanned Maintenance

- Optimized Subsystem Integration

Although these pathways were not considered to be of high priority, important strides can be made in these areas. These pathways 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.

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 and 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 gained 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. Another large aspect of subsystem integration is the interconnections between the mooring, umbilical cable, and device; again, this has already been addressed in the Installation section. As more experience is gained in designing, fabricating, assembling, deploying and recovering these devices, great gains are expected in the quality assurance procedures relating to subsystem integration.

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Conclusions

The WEC industry has yet to penetrate the U.S. electricity market despite the large potential resource available. Work by Weber [49] has effectively attributed this low penetration through the lens of low techno-economic performance; however, few concrete paths have been offered to alter the current state of the industry in order to bolster the techno-economic performance. This paper systematically prioritizes the technology developments that can alter this paradigm for an offshore WAB absorbing energy as an attenuator. Prioritization occurs through the whitepaper authors' 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 and the opportunity for improved AEP and power quality. Prioritization is based on evaluation of this data as well as the confidence of 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, with data from industry, literature searches, and experiences with other technologies such as wind and aerospace. It is unlikely that every research path could be pursued by any single company, institution, or government agency. Recommendations are intended to spur research across the industry in individual companies and institutions. The diverse strategic goals of companies, institutions, and government agencies hopefully will, when combined, cover the scope of the most valuable research path recommendations.

In general, conversations with the industry leaders in offshore WAB attenuator devices have indicated that there is a need to develop modeling tools, infrastructure, and standards specific to WEC devices. In lieu of having best practices specific to WECs, more costly or ineffective approaches, such as applying the high levels of FoS from the oil and gas industry to WEC mooring designs, is the default. This is equivalent to the wind industry applying blade designs from helicopters and windmills to modern wind turbines.

The diversity of designs that the industry is pursuing complicates the ability to develop standards specific to WEC devices. Each device type operates in distinct deployment locations with unique principles. Research programs are needed to focus on device - type 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 publically accessible data to the community at large. One of the largest barriers to the nascent WEC industry is the lack of publically 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: Based on a __ year device deployment period; ___ units with an installed capacity of circa ___ MW

	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	0		
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]	0	[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]		
	Availability	[Do not fill]		

Bibliography

1. Harris, R. E., Johanning, L. & Wolfram, J. Mooring systems for wave energy converters: A review of design issues and choices. *Heriot-Watt Univ. Edinb. Uk Retrieved Sept.* **19,** 2005 (2004).
2. Mørk, G., Barstow, S., Kabuth, A. & Pontes, M. T. Assessing the global wave energy potential. in *Proc 29th Int. Conf. Ocean Offshore Arct. Eng. Asme Pap.* **3,** 447–454 (ASME, 2010).
3. Jacobson, P., Hagerman, G. & Scott, G. *Mapping and Assessment of the United States Ocean Wave Energy Resource*. (Electric Power Research Institute, 2011).
4. *KEY WORLD ENERGY STATISTICS*. (International Energy Agency, 2012). at <http://ar.newsmth.net/att/633efe465236a/Key_World_Energy_Statistics(2007).pdf>
5. Haas, K., Fritz, H., French, S., Smith, B. & Neary, V. *Assessment of Energy Production Potential from Tidal Streams in the United States*. (Georgia Tech Research Corporation, 2011). at <http://www.tidalstreampower.gatech.edu/>
6. United States Department of Energy Wind and Water Power Program Funding in the United States: Marine and Hydrokinetic Energy Projects, Fiscal Years 2008–2011. (2011). at <www1.eere.energy.gov/water/pdfs/mhk-041812.pdf>
7. Price, A. A. New perspectives on wave energy converter control. (2009). at <http://www.era.lib.ed.ac.uk/handle/1842/3109>
8. Sullivan, G., Pugh, R., Melendez, A. & Hunt, W. Operations & Maintenance Best Practices A Guide to Achieving Operational Efficiency. (2010).
9. O'Sullivan, D., Mollaghan, D., Blavette, A. & Alcorn, R. *Dynamic characteristics of wave and tidal energy converters and a recommended structure for development of a generic model for grid connection*. (HMRC-UCC, 2010). at <http://www.iea-oceans.org/>
10. Reed, M., Bagbey, R., Moreno, A., Ramsey, T. & Rieks, J. Accelerating the U.S. Marine and Hydrokinetic Technology Development through the Application of Technology Readiness Levels (TRLs). in *United States Dep. Energy 'technology Readiness Levels Trls'* (2010). at <http://www1.eere.energy.gov/manufacturing/financial/trls.html>
11. Ruehl, K. & Bull, D. Wave Energy Development Roadmap: Design to commercialization. in *Oceans 2012* 1–10 (2012). doi:10.1109/OCEANS.2012.6404795
12. Vincent, C. L. Shallow water waves: A spectral approach. *Coast. Eng. Proc.* **1,** (1984).
13. Ochi, M. K. *Ocean Waves: The Stochastic Approach*. (Cambridge University Press, 2005).
14. Cruz, J. *Ocean Wave Energy: Current Status and Future Perspectives*. (Springer Verlag, 2008).
15. Wavestar. at <http://wavestarenergy.com/>
16. Yemm, R., Pizer, D., Retzler, C. & Henderson, R. Pelamis: experience from concept to connection. *Philos. Transact. A Math. Phys. Eng. Sci.* **370,** 365–380 (2012).
17. Falnes, J. *Ocean Waves and Oscillating Systems*. (Cambridge University Press, 2002).
18. Renzi, E. & Dias, F. Hydrodynamics of the oscillating wave surge converter in the open ocean. *Eur. J. Mech. - Bfluids* (2013). doi:10.1016/j.euromechflu.2013.01.007
19. Whittaker, T. & Folley, M. Nearshore oscillating wave surge converters and the development of Oyster. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **370,** 345–364 (2011).
20. De Miguel, B., Ricci, P., Touzón, I. & Ojanguren, M. New perspectives on the long term feasibility of wave energy conversion: a techno-economical approach. in (2012). at

<http://www.icoe2012dublin.com/icoe_2012/downloads/papers/day3/1.8%20Economics%20of%20Ocean%20Energy%202/Borja%20De%20Miguel%20-%20Oceantec%20Energias%20Marinas.pdf>

21. Dalton, G. J., Lewis, T. & O'Connor, M. Impact of inter-annual resource data variability on techno-economic performance of the WaveStar and Pelamis P1. (2012). at <http://www.icoe2012dublin.com/ICOE_2012/downloads/papers/day3/1.7%20Economics%20of%20Ocean%20Energy%201/Gordon%20Dalton%20-%20HMRC,%20University%20College%20Cork.pdf>
22. Dalton, G. J., Alcorn, R. & Lewis, T. Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America. *Renew. Energy* **35,** 443–455 (2010).
23. Costello, R., Teillant, B., Weber, J. & Ringwood, J. V. Techno-Economic Optimisation for Wave Energy Converters. *power* **2,** 1 (2012).
24. Ahn, K. K., Truong, D. Q., Tien, H. H. & Yoon, J. I. An innovative design of wave energy converter. *Renew. Energy* **42,** 186–194 (2012).
25. Brady, G., O'Loughlin, C., Massey, J., Griffiths, D. & Villegas, C. Design and test of a linear switched reluctance generator for use in wave-energy applications. at <http://www.icoe2012dublin.com/icoe_2012/downloads/papers/day1/POSTER%20SESSION%201/Garret%20Brady,%20Institute%20Of%20Technology%20Blanchardstown.pdf>
26. Kamizuru, Y. *et al.* Efficient Power Take-Offs for Ocean Energy Conversion. in 8 (2012). at <http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDAQFjAA&url=http%3A%2F%2Fwww.icoe2012dublin.com%2FICOE_2012%2Fdownloads%2Fpapers%2Fday2%2F3.4%2520Components%2C%2520Moorings%2520and%2520Materials%2FYukio%2520Kamizuru%2520-%2520Bosch%2520Rexroth%2520AG.pdf&ei=GA-NUfsrgf6LAoqygegC&usg=AFQjCNHfoIt25_JOf4QZOQIcqVr89AtAEg&sig2=Q_kcPU9SEZXy4j3pxJGBiw&bvm=bv.46340616,d.cGE&cad=rja>
27. Ricci, P. *et al.* Control strategies for a wave energy converter connected to a hydraulic power take-off. *Iet Renew. Power Gener.* **5,** 234–244 (2011).
28. Henderson, R. Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter. *Renew. Energy* **31,** 271–283 (2006).
29. Friis-Madsen, E., Sørensen, H. C. & Parmeggiani, S. The development of a 1.5 MW Wave Dragon North Sea Demonstrator. in (2012). at <http://www.icoe2012dublin.com/icoe_2012/downloads/papers/day1/1.1%20Wave%20Energy%20Convertors/Erik%20Friis-Madsen%20-%20WaveDragon.pdf>
30. Crestwing Development status. at <http://www.waveenergyfyn.dk/info%20Waveenergyfyn%20test%20rapport.htm>
31. Falcão, A. F. de O. Wave energy utilization: A review of the technologies. *Renew. Sustain. Energy Rev.* **14,** 899–918 (2010).
32. Hals, J., Falnes, J. & Moan, T. A Comparison of Selected Strategies for Adaptive Control of Wave Energy Converters. *J. Offshore Mech. Arct. Eng.* **133,** 031101 (2011).
33. Hals, J., Bjarte-Larsson, T. & Falnes, J. Optimum reactive control and control by latching of a wave-absorbing semisubmerged heaving sphere. in *21st Int. Conf. Offshore Mech. Arct. Eng.* (OMAE, 2002).
34. Kara, F. Time domain prediction of power absorption from ocean waves with latching control. *Renew. Energy* **35,** 423–434 (2010).
35. Li, G., Weiss, G., Mueller, M., Townley, S. & Belmont, M. R. Wave energy converter control by wave prediction and dynamic programming. *Renew. Energy* **48,** 392–403 (2012).

36. Mundon, T. R., Murray, A. F. & Wallace, A. R. Toward a Biologically Inspired, Neural Control Mechanism for Multiple Degree of Freedom Wave Energy Converters. in (EWTEC, 2011). at <http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/397.pdf>
37. WAVEWATCH III® Model. *Natl. Weather Serv. Environ. Model. Cent. Wavewatch Iii* (2009). at <http://polar.ncep.noaa.gov/waves/wavewatch/>
38. Slevin, C., Crerar, L., Whelan, M., Hart, R. & Doogan, E. Supply Chain for the West Wave Project. in (2012).
39. Jackson, M. How can the offshore wind industry overcome O&M obstacles? - Renewable Energy Focus. *Renew. Energy Focus.* (2009). at <http://www.renewableenergyfocus.com/view/3152/how-can-the-offshore-wind-industry-overcome-o-m-obstacles/>
40. Stansell, P. & Pizer, D. J. Maximum wave-power absorption by attenuating line absorbers under volume constraints. *Appl. Ocean Res.* **40,** 83–93 (2013).
41. Orcina: OrcaFlex. (2013). at <http://www.orcina.com/SoftwareProducts/OrcaFlex/>
42. Smith, H. C. M., Pearce, C. & Millar, D. L. Further analysis of change in nearshore wave climate due to an offshore wave farm: An enhanced case study for the Wave Hub site. *Renew. Energy* **40,** 51–64 (2012).
43. Borgarino, B., Babarit, A. & Ferrant, P. Impact of the separating distance between interacting wave energy converters on the overall energy extraction of an array. in *Proc. 9th Eur. Wave Tidal Energy Conf. Southampt. Uk* (2011). at <http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/EWTEC_CD/papers/40.pdf>
44. Halamay, D. A., Brekken, T. K. A., Simmons, A. & McArthur, S. Reserve Requirement Impacts of Large-Scale Integration of Wind, Solar, and Ocean Wave Power Generation. *Ieee Trans. Sustain. Energy* **2,** 321–328 (2011).
45. Davis, G. A., Huntley, M. B. & Correale, S. T. Long Term Performance of Mooring Lines Made with Spectra® Fiber. in *Oceans 2006* 1–6 (2006). at <http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4099179>
46. Fowler, G. & Reiniger, R. Mooring Component Perormance Kevlar Mooring Lines. in *Oceans 78* 297–301 (1978). doi:10.1109/OCEANS.1978.1151108
47. Jackson, D. *et al.* CFRP Mooring Lines for MODU Applications. in (2005).
48. Walford, C. A. *Wind turbine reliability: understanding and minimizing wind turbine operation and maintenance costs*. (United States. Department of Energy, 2006). at <http://www.preservethegoldencrescent.com/pdf/wind%20turbine%20reliability.pdf>
49. Weber, J. WEC Technology Readiness and Performance Matrix–finding the best research technology development trajectory. in *Int. Conf. Ocean Energy Dublin Irel.* (2012). at <http://www.icoe2012dublin.com/icoe_2012/downloads/papers/day2/3.6%20Evaluation%20and%20Standards/Jochem%20Weber%20-%20Wavebob.pdf>

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