A review of flexible membrane structures for Wave Energy Converters

Ieuan Collins, Mokarram Hossain, and Ian Masters

Abstract— **Flexible working devices take many forms. In this paper, we have proposed a methodology for classification based on the working surface. Three operational classifications have been devised based on the developments to date: Membrane Cell, Bulge Wave and Membrane Carpet. Additional operational classifications may be added following the same methodology. A review of all the technological developments for each of the operational classifications has been presented. Three devices are now entering Stage 3 (TRL 5-6) of development after proving to be a promising concept. The devices have all used hyperelastic rubber-like materials (elastomers) as their working surface, due to the low modulus of elasticity and excellent durability. The advent of dielectric elastomers has allowed for the Power Take-Off (PTO) to merge with the primary mover, further simplifying the design, although it may also replace the PTO for traditional devices. The use of these materials aims to improve reliability, survivability and maintainability which should lower the levelized cost of energy (LCOE) to a competitive level. As for device development, the novelty of materials has permitted new computational modelling and experimental techniques. Although, further research is needed into the expected fatigue behaviour for more accurate reliability predictions.**

Keywords—Flexible Structures, Dielectric Elastomers, Membranes, Levelized Cost of Energy (LCOE), Device Classification, Power Take Off (PTO), Technology Readiness Level (TRL), Fatigue

I. INTRODUCTION

WAVE energy is an untapped abundant renewable energy source. Since the 1970s, there has been a renewed interest in the technology which has seen a myriad of different designs. The original design philosophy of using large metallic based devices such as the Salter Duck [1] has carried on through to the later designs such as Pelamis [2]. However, while the levelized cost of energy (LCOE) has reduced significantly for other renewable energy resources to a competitive level, wave energy has lagged behind. Currently, recent studies have suggested it to be as high as 325 €/MWh [3]. One possible reason for the high levelized cost of energy is due to the lack of convergence in the wave sector compared with tidal and wind which are more mature technologies. As a result, there is no market leader, and more designs are continually being developed [4]. Therefore, it is commonly said that wave energy is 25 years behind wind regarding technological development.

The stage of technological development is classified by the technology readiness level (TRL). For wave energy devices, it is classified as a 5-stage process. The initial 3 stages focus on developing laboratory tests and computational models to scaled sea trial testing (TRL 1-6). Stage 4 (TRL 7-8) focuses on a full-scale prototype sea trial testing and the Stage 5 (TRL 9) is an economic validation whereby several units are tested at sea for an extended period [5], [6]. In 2008, Pelamis reached stage 5 with the world's first commercial wave energy farm located off the Agucadoura coast in Portugal [7]. Since 2012, the Wello Penguin has also worked off the coast of Orkney and more recently has provided power to the National Grid, also reaching stage 5 on this scale [8], [9]. These are the only devices which have reached this stage to date.

Reliability, survivability and maintenance requirements are integral for wave energy converters (WEC). Traditional wave energy converters have struggled in this regard due having highly complex mechanical systems which have been costly, poorly adaptable to the wave climate, subject to failure and the efficiency has been low due to a narrow operational bandwidth [10].

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A WEC design can be split into three areas:

1) Primary Mover: The mechanical interface between the device and waves, which converts incoming wave energy into useful mechanical motion.
2) Power Take-Off (PTO): The conversion of fluidic energy to useful electrical energy which is linked to the primary mover.
3) Non-harvesting sub-components: The other components which make up the system such as mooring tethers, structural connections etc.

To address the problems associated with traditional devices, flexible structures using elastomeric composites has been suggested in these three key areas of design. Earlier devices such the Lancaster Bag and Sea Clam used flexible membranes as the primary mover [11], which has seen a renewed interest of late with new designs such as the Bombora and Anaconda [12], [13]. As for the PTO, the use of a novel dielectric elastomer generators (DEGs) has grown interest in the wave energy literature due to its design simplicity and the ability to merge the primary mover and PTO together as one. Other devices have used elastomers as other sub-components, two notable examples include the Symphony and Qoceant devices. The Symphony device is a point absorber using a rubber membrane as a roller mechanism, allowing for sub-structure movement inside a larger shell structure [14], and the Qoceant device which uses a flexible hull structure that can be inflated and deflated corresponding to the wave climate [15].

This paper presents a review and classification method for a range of wave energy converters with flexible working surfaces. These are devices in which the primary mover or PTO incorporate flexible membranes. Further discussion of flexible membranes in other sub-components of wave energy devices is beyond the scope of the present work. A discussion is then made on the elastomeric composites these structures are using, providing an insight into the modelling approaches and expected fatigue behaviour in a marine environment. Finally, a review on the DEGs for wave energy conversion is presented.

II. Device Classification

A. *Classification*

Currently, the European Marine Energy Centre (EMEC) has identified 8 different wave energy device types [16]. Elastomers have permitted many radically different designs which can be difficult to classify under the traditional scheme. In the forthcoming years, there is a high probability that many new designs will utilise flexible structures. In this paper, we propose a novel operational classification system that may be applied to all flexible structure wave devices by considering their working surface. This classification will accompany other descriptions based on location and orientation to waves. To date, there have been multiple membrane cell devices where the operational principle remains similar. However, some have been on the surface (attenuator) while others have been fully submerged (submerged pressure-differential). Therefore, a full classification description can be achieved by reference to Table 1, first a working surface is selected and then a device configuration.

B. *Membrane Cell*

A membrane cell device (Fig.1) is one with a deformable membrane that has pinned boundary conditions covering an air-filled volume (cell). A hydrodynamic pressure is applied to the surface which results in the deformation of the membrane forcing air out of the cell. The pressurised

TABLE I
DEVICE CLASSIFICATION BASED ON WORKING SURFACE

Working Surface	Possible configurations based on EMEC classification [16]
Membrane Cell	Attenuator Point Absorber Terminator Submerged Pressure-Differential
Bulge Wave	Attenuator Submerged Pressure-Differential
Carpet Membrane	Attenuator Submerged Pressure-Differential

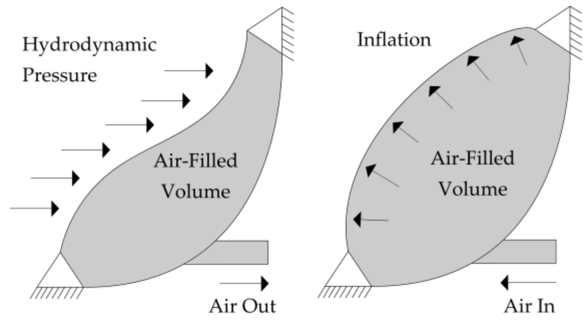

Fig. 1. Schematic of Membrane Cell: (a) Membrane deflation, (b) Membrane inflation.

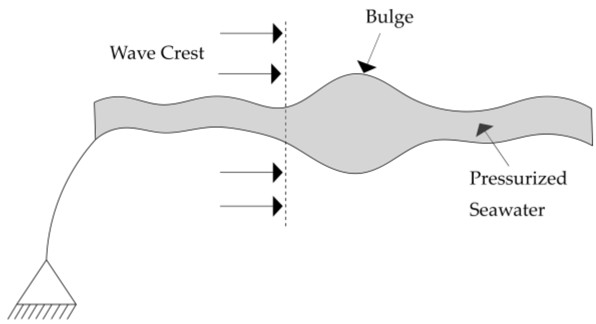

Fig. 2. Schematic of Bulge Wave.

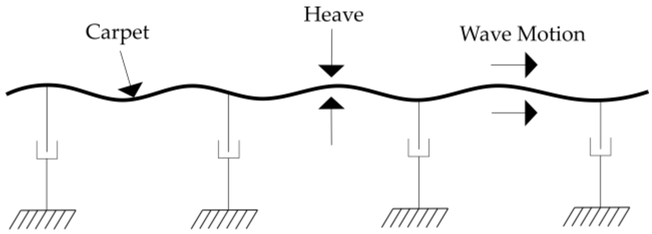

Fig. 3. Schematic of Carpet Membrane.

air is then captured by a PTO, typically pneumatic. Membrane cell devices so far have been in the form of an attenuator, point absorber, terminator and submerged pressure-differential.

C. Bulge Wave

A bulge wave device (Fig.2) is a tube filled with pressurised seawater moored to the seabed. The tube is orientated perpendicular to the wave crest. As the wave crest passes alongside the tube, a bulge forms in front of the wave crest that grows progressively larger along the length of the tube, a idea conceived by Rainey and Farley [17]. The theory from Lighthill [18] states that a longitudinal pressure wave of the same velocity as the incident wave results in a transfer of energy to the tube which has later become known as a 'Bulge Wave'. The bulge wave can be harvested using a hydro turbine PTO. However, more recently dielectric elastomers have been suggested as the sole PTO [19].

D. Carpet Membrane

A membrane which takes the form of a carpet (Fig.3) that has free end boundary conditions. It is held in place via either tethers or hydraulic pistons. The carpet attenuates the wave's motion by rising and falling with the wave peaks and troughs. It occupies a large surface area, and the free end boundary conditions allow for a high absorption efficiency. The heaving action of the carpet at various locations along its length can be captured with a hydraulic PTO. From the two devices proposed to date, one floats on the surface, and the other is held under water [20], [21].

III. Membrane Cell Devices

E. Lancaster Bag – Attenuator

Professor Michael French conceived the first known concept of a deformable device at Lancaster University in 1977. The design aimed to have an affordable, durable working surface at the rough sea surface; the concept used rubber bags attached to a long buoyant concrete spine. These rubber bags would result in a high ratio of swept volume to the overall structural volume of the device. The concrete spine would orientate perpendicular to the wave crest, like an attenuator [11], [22]. French suggested this configuration would result in lower energy capture than a terminator *'broached-to'* configuration, however, from a structural economic standpoint, it would be cheaper. The spine of the device would contain many high and low-pressure ducts along the length of the interior. Pressure from incident waves compresses air through a high-pressure duct via a series of non-return valves. A conventional air turbine system is placed between the high and low-pressure ducts, acting as the PTO. Air is then vented from the low-pressure ducts which cause the bags to reinflate before the next wave peak. The proposed full-scale length of the device was 257 m [23]. The device always remained at the concept stage, mainly due to the high structural costs associated with the design, at 63% of the overall cost [24].

F. Sea Clam – Terminator (1978-1984) & Attenuator

The design, developed by Sea Energy Associates, originated from 1978 and was initially called the Linear Sea Clam. It was similar in design to Lancaster Bag with a proposed length of 275 m [25], [26]. The significant difference was the orientation of the device to the waves. Initially, it opted for a terminator configuration as opposed to an attenuator. In 1985, the design changed to a circular configuration for stability reasons, where it has remained since then [27]. The operation is similar to the Lancaster Bag, except the turbine rectifying system was changed to a Wells air turbine for each cell.

The membrane working surface material needs to be: *'robust for environment, requires vertical strength coupled with horizontal elasticity to give multimillion buckle free cycles.'* For this reason, the rubber was reinforced with Kevlar. Suggestions were also made for emergency systems should a membrane fail due to a rupture. One suggestion was an inflatable bag on the interior which would isolate the affected cell if the presence of water is detected. A portable press could then be lowed to vulcanise a new patch of rubber over the affected membrane. For an economically viable system, the membrane lifespan would need to be a minimum of 5 years [28]. Work stopped between 1992 and 2007 but has since continued in 2008. The significant change since then has been an increase in the ring diameter from 60 m to 80 m, and an OWC has been suggested in place of the air-filled chamber. More recently in 2016, structural integrity tests were performed using a fluid-structure interaction approach [29], [30].

G. AWS III – Attenuator

AWS is currently developing multiple devices, one of which is a multi-cell device initially similar to the Circular Sea Clam. More recently, it has adopted a new linear configuration: 6 cells facing the wave crest at an angle between 20 to 40 degrees and 3 cells on the other side. The membrane cells facing the wave crest deflate, forcing air to the other side of the device through a bi-directional air turbine. The device is expected to have a length of 120 m and weigh a total of 2500 tonnes (4400 tonnes after it has been ballasted). To ensure good survivability, the membrane can be deflated, meaning all the loading is directed to the cassette structure [31].

H. Bombora – Submerged Pressure-Differential

The Ryan brothers from Australia invented the Bombora mWave device, inspired from watching breaking waves on the shore [32]. Unlike the other membrane cell devices, the device is fully submerged operating at a depth of several metres nearshore. A fully submerged configuration avoids exposure to high impact loads found at the free surface. Submersion provides a large reduction in loads for only a small reduction in available energy, which should help to reduce the LCOE [13]. The device has 8 cells, 4 on either side of a concrete structure fixed to the seabed, aligned 60 degrees to the oncoming wave crest. It operates on the principle of a pressure differential between the cells caused by wave motion at the surface. The concrete structure contains a closed air circuit, with a pneumatic PTO operating analogously to the Lancaster Bag.

Like the AWS III, the device can deflate the membrane for each of the cells meaning all the forces are directed onto the fixed concrete structure [13]. Experimental modelling has been undertaken in the wave tank at the Australian Maritime College Model Test Basin. The power production validation was achieved by firstly measuring the wave intensity, then the internal and flow pressure inside the membrane was used to validate a numerical power performance model. In additional, videogrammetry was chosen to validate the finite element modelling of membrane deformation during submerged inflation and deflation [33].

Further numerical modelling has also been undertaken using field data for a proposed location in Portugal. The power output was found to be good over a broad range of sea-states, suggesting that the device has the potential to provide commercial-scale power generation, while retaining good survivability at the subsea location [34]. Bombora is currently building an mWave demonstrator for open ocean deployment in 2020, in Wales, UK. This project aims to validate LCOE predictions made for the Portugal wave farm study [35] and demonstrate open ocean operation and survival during a winter deployment [36].

I. *Plymouth Air Bag – Point Absorber*

Plymouth University, and partners, have been working on the design of a ballasted floating air bag which resembles the appearance of a squid. The main motivation for this design is the deformable structure allows for a reduction in the resonance period due to a lower hydrostatic stiffness. The device can therefore be made smaller than the traditional heaving buoy point absorber. The bag breathes under wave action forcing air through a tube to another volume [37] with a pneumatic PTO between the two volumes. Elastomeric fabric-based composites with reinforcing tendons have been investigated as the choice of material [38]. At this current time analytical modelling has been used to validate the concept as well as small-scale tank tests at the wave basin in Plymouth University [39].

IV. BULGE WAVE DEVICES

J. *Anaconda – Attenuator*

The Anaconda was invented by Farley and Rainey in 2006, later developed by Checkmate Seaenergy [17], [40]. The tube is made from rubber and is closed at both ends. In 2010, physical modelling of the device was undertaken to validate the bulge wave principle, and numerical models were developed at the University of Southampton [41].

The design consists of a rigid nose cone attached to the tube which is the tethering point for the anchor. Operating on the bulge wave principle, the speed of the bulge is determined by the tube distensibility (the tube's capability of stretching or swelling). An important design parameter is matching the resonance of the bulge wave to the incident wave which is controlled by the material stiffness. The PTO is at the stern of the tube where the bulge wave causes water to flow through the high-pressure accumulator then through check valves before flowing to a low-pressure accumulator. Between each accumulator is a hydro-turbine which is the PTO method for this device. The accumulators have been designed to allow for a large amount of water storage, therefore resulting in smooth power delivery between the two accumulators [17], [40], [42]. More recently, Wave Energy Scotland has awarded funding to Checkmate Seaenergy to develop the Anaconda further through tank testing and numerical modelling. A new configuration *'Mark 2'* Anaconda has been tested at the Kelvin Lab in Strathclyde University. Checkmate plans on deploying a prototype device with a sea-going test platform at 1:4 scale at Scapa Flow [43].

K. *SBM S3 – Attenuator*

The SBM S3 is similar to the Anaconda, a 100m tube filled with seawater and the wave action causes a bulge in the same way. Instead of a mechanical PTO, the S3 contains DEG rings located along the length of the tube, spaced between a traditional elastomeric material. The stretching and relaxing of the DEG rings result in energy generation without the need for external or internal moving parts. Wave flume tests have been undertaken in Monaco to validate the concept [19] and numerical models have been developed for an insight of the expected tube performance [44].

L. *AWS Electric Eel – Attenuator*

The AWS Electric Eel provides continuous energy extraction along the length of the tube, using a continuous DEG PTO. Actuators and sensors are integrated into the membrane which allows for the material stiffness to be altered depending on wave climate. A candidate device has been sized at 155 m in length for a power production of 750 kW. However, large devices have been sized to a rating of 5.25 MW. The device remains at the early stage of development where patents have been granted [45], [46].

V. CARPET MEMBRANE DEVICES

M. *CalWave Wave Carpet – Submerged Pressure-Differential*

The *'Wave Carpet'* was an idea conceived at the Berkley University of California, inspired by strong wave attenuation caused by seafloor mud. The device is a submerged carpet sitting slightly above the seabed, held in place by linear springs and using a hydraulic PTO. This location has been said to have a number of benefits for reliability and survivability, including resilience against storm surges. The carpet has a broad operational bandwidth and is omnidirectional, as it absorbs wave energy from above and below its surface, resulting in maximum theoretical efficiency of unity [47]. The device has also said to be dual purpose, acting as a breakwater and providing a sheltered region in stormy seas [47]. There has been analytical modelling focusing on the hydrodynamics and viscoelastic response of the carpet [48], [49]. The modelling has been validated by wave flume experiments showing a peak absorption efficiency of 99.3%, but a lower PTO efficiency of 42.3% [47]. In the experiments, the carpet required multiple materials: rubber as the carpet absorber due to its low Young's modulus, fibreglass as the bending beam and aluminium as the connection point between the fibreglass beam and the PTO [50]. Currently, CalWave is performing experimental tank testing of a scaled prototype. The experimental testing aims to assess wave structure conversion efficiency and validate numerical device modelling for different sea states [51].

N. *LilyPad – Attenuator*

The LilyPad is similar in configuration to the wave carpet, but works at the sea surface rather than the seabed. The device consists of a dual membrane carpet configuration connected with multiple cables. The upper membrane rides the sea surface like an attenuator, acting against the lower, more rigid, membrane. An extendable hose pump can be used to create pressure to drive a hydraulic PTO. Like the wave carpet, it can also act as a breakwater for coastal protection [53]. To date, there are no publicly known experimental results or analytical modelling of this device and it remains a patented concept.

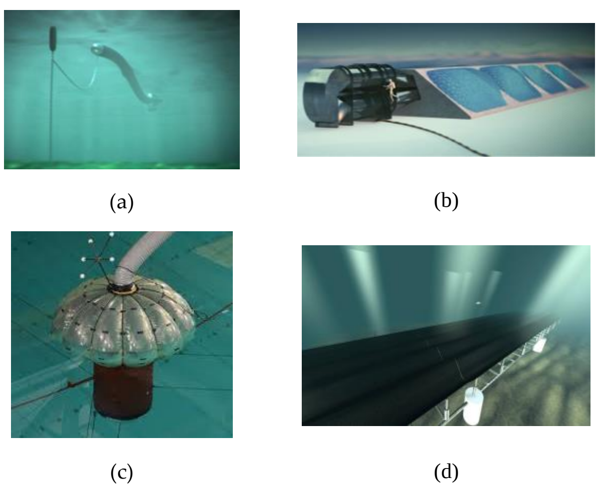

Fig. 4. Flexible Structure Wave Energy Converters: (a) Anaconda [41], (b) Bombora [10], (c) Plymouth Air Bag [37], (d) Wave Carpet [52].

VI. Design of Elastomeric Structures

O. *Design Enhancements and Considerations*

Wave Energy Scotland and the European Commission have released reports on the potential benefits of elastomers as the working surface of WEC designs [54], [55]. The main benefits of these materials are potential cost reductions, achieved through improved reliability and survivability without compromising on the performance.

Reliability is related to the operational lifespan and maintenance requirements. Elastomers fare well in this regard by having non-corrosive properties, but the fatigue of these materials in a seawater environment remains largely unproven. Survivability is related to the ability to survive under a varied wave climate which may be improved through deflation of the structure under harsh loading conditions.

Other cost reduction areas include improved transport and deployment requirements, due to the flexible and lightweight nature of elastomers; less than 20% of the density of marine structural steel [56]. Elastomers can also allow the size of some devices such as the Plymouth Air Bag to be reduced, by decreasing the resonance period [39].

As part of the design process, material selection, followed by experimental and computational modelling of the device is required to validate the early concepts through to later sea trials. The novelty of these devices has required a new design approach which is discussed in this section.

P. *Material Properties*

Elastomers are viscoelastic, meaning there are two material components: an elastic component acting as a spring and a viscous fluid component acting as a dashpot. Viscoelasticity is commonly observed as stress relaxation, which is time dependent behaviour. It is the defined as the reduction in stress in the material for a constant strain applied. As a consequence of viscoelasticity there are various phenomena which may occur such as hysteresis, stress-softening and strain induced crystallization.

Hysteresis is heat dissipation caused by internal friction of the polymer chains. It may be observed on a stress-strain curve; the elastic component is perfectly recovered during unloading, however, the viscous component results in energy loss through heat dissipation, showing as a lower unloading path. Hysteresis is unwanted in WECs due to it reducing the transfer of fluidic energy of the waves to potential harvesting energy caused by a greater amount of damping [57], [58].

Stress-softening (referred to as Mullins effect) is the change in the material response after the maximum previous loading encountered. Virgin materials are typically stiff, but after loading they become softer. Eventually, the stress-strain response stabilises [58], [59], similar to the *'bedding in'* of mooring ropes.

Strain induced crystallization (SIC) occurs under high amplitude loading conditions. The elastomeric material strengthens due to the alignment of polymer chains [59]. Therefore, WEC designs should ensure the onset of SIC for optimum structural performance.

Reinforcement particles are added to improve the mechanical properties of elastomeric materials, such as the tensile strength and modulus of elasticity. This can have consequences such as an increased amount of hysteresis and Mullins effect, as well as resulting in a lower degree of strain-induced crystallization [59]. Therefore, filler composition is an essential parameter as part of the design process for these wave energy devices.

Q. Material Modelling

Elastomers can be modelled through hyperelastic models, viscoelastic models, or a combination of both. Hyperelastic models assume a non-linear path dependant deformation process based on a strain energy function, an example being the Mooney-Rivlin model [60]. However, these models assume a perfectly elastic material with the same loading and unloading paths. Viscoelastic models do not share this assumption, by considering time-dependant and hysteretical behaviour. Two common examples are the Maxwell and Voigt-Kelvin models; the prior has the spring and dashpot in series, the latter has them in parallel. More complex arrangements of these springs and dashpots may represent linear and nonlinear viscoelastic material behaviour [61]. The combination of hyperelastic and viscoelastic models results in visco-hyperelastic models which take into account the nonlinear stress-strain relationship whilst considering the viscoelastic behaviour of rubber. All these models are semi-empirical, requiring experiments to determine material parameters. More complicated models are often difficult to implement and may suffer from convergence problems when performing finite element analysis (FEA) [62].

R. Fluid-Structure Interaction

A fluid-structure interaction analysis combines computational fluid dynamics (CFD) with a structural model (typically FEA), and allows wave energy developers to validate their concept without outlaying large costs associated with the manufacturing and testing of prototype devices. The novelty of these devices is a challenge, as traditional WECs are modelled on the assumption the device is rigid using one-way coupled analysis. The reviewed devices use thin-wall membrane structures which undergo large deformations under loading, affecting the fluid flow around the membrane. Therefore, developers have had to develop their own in-house models for the problem; two examples in the literature are from Bombora and SBM.

Bombora developed a range of membrane fluid-structure interaction models for early proof of concept simulations of a single cell problem and of the complete system operation. An FEA/CFD model (coupled in both directions) was developed and used for assessment of dynamic loads on the membrane [63], [64]. For power performance modelling, an FEA membrane model loaded by a hydrostatic external pressure field was used to determine the hydrostatic stiffness of the membrane, while simplified membrane deformation shapes were used for the calculation of membrane hydrodynamic coefficients using a boundary element method (BEM) solver [65]. This performance model was validated through tank experiments mentioned previously [33].

SBM have developed a wave to wire simulation for their bulge wave device. The simulation couples modelling of internal fluid flow, the structural wall and outer fluid flow problem using simplifications that allow for modal decomposition. The structural wall model was based on a visco-hyperelastic model determined from experimental data. Modification of the wall model allowed for predictions of the power production. This simulation was found to have good predictability for the response of the membrane to the ocean waves. However, the authors suggested further improvements could be made by taking more nonlinearities into account [44].

Recently, a new general modelling approach has been proposed for all membrane-based WECs [66]. The approach aims to become a standard tool to validate new designs, in a similar manner to WAMIT, InWave and WEC-Sim for rigid devices. It aims to overcome the limitations of these packages which includes the inability to consider the effect of membrane dynamics, the changes in membrane shape from equilibrium position and effects of an internal working fluid. The tool uses static analysis to determine the device or membrane shape and stress under static loads. This feeds into a dynamic analysis which extends the standard frequency domain analysis used for traditional rigid-body devices by including additional terms to account for the mass, stiffness and damping associated with the membrane, internal working fluid effects, and either a turbine or DEG PTO. A case study bulge tube analysis was performed and compared with the previous analysis for the SBM S3 [44]. Similar wave response results were found to occur after the damping and mass components had been normalised using the maximum value for each mode shape. These initial results prove promising, although further improvements are suggested to be possible with the extension of the method to the time domain to allow for the inclusion of nonlinear terms.

S. Fatigue

The effect of cyclic fatigue on elastomers in a marine environment is not yet well understood, although data from the automotive and aerospace sectors suggests good general performance. Factors which influence the fatigue life of rubber include loads, environmental conditions and chemical formulation [67]. Most fatigue studies of rubber use uniaxial loading, however biaxial is a more representative of expected loadings from the waves and internal working fluid, which may lead to a lower expected fatigue life if the control parameter is based on maximum strain [68]. Waves vary in amplitude and frequency, which will subject the membrane to variable loadings. The adaptation of the cumulative damage approach such as the Palmgren-Miner rule has been used in the literature [69], [70], although not yet to the same extent as for metallic structures.

Extensive high cycle fatigue multiaxial loading has been performed in the past, suggesting rubber should not be relaxed to small strains, with the optimum fatigue life being under non-relaxing conditions [71].

Based off data in [71], the developers of Anaconda device examined the fatigue life for 8 second waves and strain range of 200-300%, which suggested a fatigue life of 100 million cycles or 25 years [17]. Note that this prediction does not consider the degradation mechanisms and complex biaxial loading conditions.

The effect of seawater can be split into two areas: ageing (degradation of the material caused by oxidation and other chemical processes) and submersion (the affect seawater has on the crack propagation of the material). The material stiffness of rubber has been proven to increase after long term exposure to seawater [72], [73]. Limited previous fatigue studies have shown that water immersion has little effect on the crack growth, and short-term ageing is similar for both air and seawater [74], [75]. The effect of submersion has been analysed more recently by Ifremer, using new equipment which allows testing to take place in both air and seawater conditions. No difference in fatigue life for relaxing conditions was found, however there was a significant decrease in fatigue life in seawater compared to air for non-relaxing conditions [76]. In follow up work, a more comprehensive study took place for non-relaxing conditions. For large stretch amplitudes the fatigue life was better in seawater, contradicting the previous study. They hypothesised the change could be due to a reduction in the degree of SIC at higher temperatures caused by cycling - as the seawater reduces the temperature of the samples allowing an enhanced degree of SIC [77]. For more accurate fatigue life predictions, future work needs to closely mimic the biaxial loading conditions encountered through the device operation whilst taking into the account ageing and submersion effects of the seawater environment.

VII. DEG Power Take-Off Systems

T. *Operational Principle*

Since the 1990s, dielectric elastomers have been investigated for artificial muscles. More recently they have been investigated for energy harvesting, which has been of interest among the wave energy industry [78]. Electroactive polymers using piezoelectric materials have previously been suggested [79], [80], however DEGs aim to overcome the limitations of both these materials and electromagnetic generators by operating over a much broader frequency range. Recent studies have suggested DEGs have energy densities as high as 400 J/kg, an order of magnitude greater than piezoelectric ceramics and electromagnetic generators [81], with a mechanical efficiency conversion for DEGs speculated to be up to 90% [81], [82].

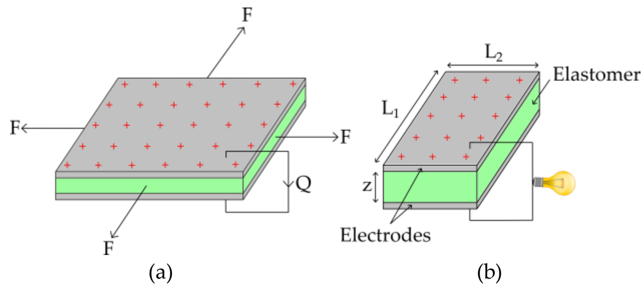

Fig. 5. Schematic diagram of a dielectric elastomer for: (a) stretched and (b) unstretched.

Dielectric elastomeric materials work on the principle of varying capacitance, where capacitance is the stored charge per unit voltage as shown in Equation 1. In a traditional capacitor, an insulator separates two parallel plates. In a dielectric elastomer, an elastomer is sandwiched between flexible electrodes [81], [82], [83], [84]. Capacitance varies with both the surface area and distance between the electrodes. The capacitance of a simple example dielectric elastomer (as shown in Fig. 5) is given in Equation 2, where L_1, L_2 are the areas of the electrodes, z is the distance between them, ϵ_d is the relative permittivity of the dielectric elastomer and ϵ_0 is permittivity of free space [83].

$$C = \frac{Q}{V} \quad (1)$$

$$C = \frac{\epsilon_d \epsilon_0 [L_1 L_2]}{z} \quad (2)$$

An example configuration would be a constant charge cycle, as used by the SBM S3. The harvesting cycle can be explained in 4 steps [19], [83]:

1) The pressure increase from a bulge wave stretches the elastomer. This increases the effective area of the electrodes and decreases the distance between them, increasing capacitance (Eq. 2).
2) A charge is placed over the electrodes.
3) The pressure reduces after the bulge wave has passed, allowing the elastomer to relax to its initial shape. As charge remains constant, the voltage increases (Eq. 1).
4) The gained electrical energy is stored.

U. *Wave Energy Applications*

The earliest known application of DEGs has been in a buoy by SRI International [85], with a similar but more recent concept under investigation by Bosch and partners [54], [86]. In both cases, the DEGs form a vertical stack, and the heaving motion of the buoy causes compression and expansion of the DEG films, resulting in energy generation. Two of the Bulge Wave devices discussed above have merged the PTO and the primary mover by embedding DEGs into the membrane working surface; a significantly less complex design compared with traditional attenuators [19], [41].

One project which has provided a comprehensive study on the use of DEGs in WEC design is PolyWEC. PolyWEC have suggested three WEC configurations: Poly-Buoy, Poly-OWC and Poly-Surge [87]. Poly-Buoy works similarly to the buoy configurations discussed above. Poly-OWC replaces the Wells turbine in a traditional OWC with an inflatable circular DEG membrane. As the water rises and falls in an enclosed air filled channel, the pressure change deforms a dielectric membrane, resulting in energy generation. Fixed shoreline and buoy configurations have been tested so far [87]. Poly-Surge operates in shallow water, using wave motion to oscillate and compress a DEG membrane in place of a traditional PTO. Poly-Surge uses a lozenge-shaped dual-DEG membrane either side of the oscillating flap [88].

Alongside testing of the Poly-OWC device, novel three-way coupled Multiphysics models were developed for validating the experimental results [89], [90]. A techno-economic analysis of the device suggested DEGs could reduce the LCOE by at least a factor of 2 compared with traditional pneumatic systems [91]. Scaled 1/20-1/30 testing of the revised Poly-A-OWC device has been undertaken, which suggests a peak power of 3.8W, corresponding to hundreds of kilowatts at a larger scale [89], [90].

In [54], [55], some of the benefits and drawbacks of DEGs are discussed. One of the main benefits is the simplification of the overall design through merging the primary mover with the PTO allowing for fewer components, improving reliability and maintenance costs. Having an electrical surface integrated on the membrane should allow for advanced functions such as sensing and surface monitoring or the ability to change the material stiffness to respond to different wave climates like suggested in the AWS Electric Eel [46]. Other benefits are related to the durability of elastomers in the marine environment and the silent operation due to reduced friction. The energy generation is proportional to the amount of stretch and electrical field, but larger stretches, charges or voltages imposed on electrodes will reduce their fatigue life. Therefore, finding a suitable compromise between energy generation and material fatigue life is essential. Little is known on the effects on capacity of the dielectrics when scaling up WEC devices, as the concepts have only been proven on a smaller scale. There are also the manufacturing challenges associated with building large DEGs, both areas requiring further investigation [54], [55].

VIII. Discussion

This paper has proposed an additional operational classification to accompany others based on location and the orientation to the waves. New future designs may take different forms than the three operational principles listed here, however, future categories could be incorporated into this classification methodology.

Based on this classification, a technology review collating major wave energy developments using flexible structures has been presented. Of these, three devices are currently at or near development Stage 3 (TRL 5-6): Bombora, Anaconda and SBM S3. The other devices currently in development remain at Stage 2 (TRL 4).

Elastomers have permitted a new design philosophy for wave energy devices. Some designs are still utilising traditional PTO systems but using the elastomers as the working surface to the benefit of overall design simplification. The use of DEGs allows the PTO to be merged with the primary mover, simplifying the design significantly.

Elastomeric materials aim to address the three critical areas for a wave energy device: reliability, survivability and maintainability with the overall aim to lower the LCOE to a competitive level. For device development, the novelty of these materials has required new computational modelling and experimental techniques, but there are still limited studies for fatigue behaviour under realistic loading conditions. A better understanding of this behaviour is required for more accurate reliability predictions.

The next stages for these devices are scaled prototype sea trials (Stage 3, TRL 5-6) before moving onto full-scale prototypes (Stages 4-5, TRL 7-9). These stages are critical for a better understanding of reliability, survivability and maintenance requirements in real-world conditions. From this, more accurate cost predictions can be made which will validate the competitiveness of these devices.

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References

[1] Salter S. Wave power. Nature. 1974;249(5459):720-724.

[2] Ocean Power Delivery Ltd. Pelamis WEC – Main Body Structural Design And Materials Selection. Crown Copyright; 2003.

[3] Astariz S, Vazquez A, Iglesias G. Evaluation and comparison of the levelized cost of tidal, wave, and offshore wind energy. Journal of Renewable and Sustainable Energy. 2015;7(5):053112.

[4] Collins K, Meng M, Le H, Greaves D, Bellamy N. Modelling of the buckling of a diaphragm–spine structure for a wave energy converter. Materials & Design. 2017;119:159-170.

[5] Heller V. Technology Readiness Level approach for the development of WECs. Presentation presented at; 2012; 4th CoastLab Teaching School, Wave and Tidal Energy, Porto, 17-20th January 2012.

[6] Technology Readiness Levels: EMEC: European Marine Energy Centre [Internet]. Emec.org.uk. [cited 4 February 2019].

[7] Pelamis, World's First Commercial Wave Energy Project, Agucadoura - Power Technology | Energy News and Market Analysis [Internet]. Power Technology | Energy News and Market Analysis. [cited 7 February 2019].

[8] Projects - Wello Oy [Internet]. Wello Oy. [cited 7 February 2019].

[9] Wello reports wave testing progress [Internet]. Marine Energy. 2017 [cited 7 February 2019].

[10] Koca K. et al. Recent Advances in the Development of Wave Energy Converters. European Wave and Tidal Energy Conference. 2013.

[11] Moss J. Technology. New Scientist. 04/021982;308.

[12] Checkmate Seaenergy [Internet]. Checkmateukseaenergy.com. [cited 4 February 2019].

[13] Bombora Wave Power | Ocean Energy [Internet]. Bomborawave.com. 2019 [cited 4 February 2019].

[14] How does it work? [Internet]. Symphony Wave Power. [cited 25 April 2019].

[15] Quoceant. Marine Automatically Stowable & Inflatable Volume (MASIV). Wave Energy Scotland; 2017.

[16] Wave devices: EMEC: European Marine Energy Centre [Internet]. Emec.org.uk. [cited 7 February 2019].

[17] Farley F, Rainey R, Chaplin J. Rubber tubes in the sea. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2011;370(1959):381-402.

[18] Lighthill M. Waves in fluids. Cambridge [et al.]: Cambridge University Press; 1980.

[19] Jean P, van Kessel R, Wattez A, Fourmon A. Challenges of using Electroactive Polymers in Large Scale Wave Energy Converters. IEEE; 2012.

[20] Energy Island [Internet]. Energyisland.com. [cited 4 February 2019].

[21] Lehmann M, Elandt R, Shakeri M, Alam R. The Wave Carpet: Development of a Submerged Pressure Differential Wave Energy Converter. 30th Symposium on Naval Hydrodynamics. 2014.

[22] French M. Conceptual Design for Engineers. 2nd ed. New York, Tokyo: Springer-Verlag Berlin Heidelberg; 1985.

[23] Brooke J. Wave Energy Conversion. Elsevier Ocean Engineering Series, Volume 6. 1st ed. Oxford: Elsevier Science & Technology; 2003.

[24] Huang M, Aggidis G. Developments, expectations of wave energy converters and mooring anchors in the UK. Journal of Ocean University of China. 2008;7(1):10-16.

[25] Sea Energy Associates Limited. Wave Energy Project, The SEA Clam. Rendel Palmer & Tritton; 1992 p. 3.

[26] Sea Energy Associates Ltd. Development Of The Sea Clam Wave Energy Converter. p. 2. (9 sea clam)

[27] Bellamy, N.W., "An Alternative Design of the SEA Clam Wave Energy Converter", Proc. of the ASME Fourth International Offshore Mechanics and Arctic Engineering Symposium, Vol 1, Dallas, February 1985.

[28] Duckers L. Reinforced rubber membranes for the 'Clam' wave energy device. Polymers in a Marine Environment. 1989; (Paper 30).

[29] Bellamy N, Bucchi A, Hearn G. Analysis of the SEA-OWC-Clam wave energy device – Part A: Historical development, hydrodynamic and motion response formulations & solutions. Renewable Energy. 2016;88:220-235.

[30] Bucchi A, Hearn G. Analysis of the SEA-OWC-Clam wave energy device part B: Structural integrity analysis. Renewable Energy. 2016;99:253-269.

[31] AWS Ocean Energy. Technology Description and Status AWS-III. Wave Energy Scotland 2016.

[32] Bombora: Taking a new direction on the renewable energy wave [Internet]. RenewEconomy. [cited 7 February 2019].

[33] Orphin J, Fleming A, Algie C. Physical scale model testing of a flexible membrane wave energy converter: Videogrammetric analysis of membrane operation. International Journal of Marine Energy. 2017;20:135-150.

[34] Algie C, Ryan S, Fleming A. Predicted power performance of a submerged membrane pressure-differential wave energy converter. International Journal of Marine Energy. 2017;20:125-134.

[35] Bombora Wave Power. Bombora prepares for Portugal Wave Farm after Strong LCOE Results. 2016.

[36] Bombora Wave Power. Bombora expands operations in Europe. 2017.

[37] Greaves D, Hann M, Kurniawan A, Chaplin J, Farley F. The Hydrodynamics of Air-Filled Bags for Wave Energy Conversion. 2016. Paper presented at International Conference on Offshore Renewable Energy, Glasgow, United Kingdom.

[38] The University of Edinburgh. A feasibility study on Elastomeric based WECs (ELASTO). Wave Energy Scotland; 2018.

[39] Kurniawan A, Chaplin J, Greaves D, Hann M. Wave energy absorption by a floating air bag. Journal of Fluid Mechanics. 2016;812:294-320

[40] Checkmate Seaenergy. WES Novel Wave Energy Converter, Stage 1 Project, Project Report. Wave Energy Scotland; 2017 p. 1-10.

[41] Heller V, Chaplin J, Farley F, Hann M, Hearn G. Physical Model Tests Of The Anaconda Wave Energy Converter. 1st IAHR European Congress, 4 - 6. 2010.

[42] Choplain N. Interactions of a submerged membrane with water waves and its use in harnessing nearshore wave power [PhD]. University of Southampton; 2012

[43] Anaconda WES NWEC Stage 2. Presentation presented at; 2018; SuperGen Marine Annual Assembly, Edinburgh.

[44] Babarit A, Singh J, Mélis C, Wattez A, Jean P. A linear numerical model for analysing the hydroelastic response of a flexible electroactive wave energy converter. Journal of Fluids and Structures. 2017;74:356-384.

[45] AWS Ocean Energy. Technology Description and Status Electric Eel. Wave Energy Scotland; 2016.

[46] Flexible Wave Power [Internet]. AWS Ocean Energy - Electric Eel Flexible Wave Power Attenuator [cited 7 February 2019]

[47] Lehmann M, Elandt R, Shakeri M, Alam R. TheWave Carpet: Development of a Submerged Pressure Differential Wave Energy Converter. 30th Symposium on Naval Hydrodynamics. 2014;.

[48] A Flexible Seafloor Carpet For High-Performance Wave Energy Extraction. Proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering.

[49] Alam M. Nonlinear analysis of an actuated seafloor-mounted carpet for a high-performance wave energy extraction. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2012;468(2146):3153-3171.

[50] Lehmann M, Elandt R, Pham H, Ghorbani R, Shakeri M, Alam M. An artificial seabed carpet for multidirectional and broadband wave energy extraction: Theory and Experiment. European Wave and Tidal Energy Conference. 2013.

[51] MHKDR: CalWave Device Behavior in Different Sea States from Scaled Tank Testing [Internet]. Mhkdr.openei.org. [cited 5 February 2019].

[52] Wave Carpet: An Efficient and Multidirectional Ocean Wave Energy Converter – TAF Lab [Internet]. Taflab.berkeley.edu. [cited 25 April 2019].

[53] Energy Island [Internet]. Energyisland.com. 2019 [cited 17 January 2019].

[54] Wave Energy Scotland. Materials Landscaping Study. Wave Energy Scotland; 2016

[55] European Commission. Workshop on identification of future emerging technologies in the ocean energy sector. Luxemborg: European Union; 2018

[56] Densities of Solids [Internet]. Engineeringtoolbox.com. [cited 6 February 2019].
[57] Heller V. Dynamic mechanical analysis of rubber used in Anaconda testing. 9th European Wave and Tidal Energy
[58] Suphadon N. The Viscoelastic Properties of Rubber Under A Complex Loading [Ph.D]. Queen Mary University of London; 2010.
[59] Bauman P. Fatigue, Stress, and Strain of Rubber Components. München: Hanser, Carl; 2012.
[60] Steinmann P, Hossain M, Possart G. Hyperelastic models for rubber-like materials: consistent tangent operators and suitability for Treloar's data. Archive of Applied Mechanics. 2012;82(9):1183-1217.
[61] Findley W, Lai J, Onaran K. Creep and relaxation of nonlinear viscoelastic materials. New York: Dover; 2010.
[62] Tobajas R, Elduque D, Ibarz E, Javierre C, Canteli A, Gracia L. Visco-Hyperelastic Model with Damage for Simulating Cyclic Thermoplastic Elastomers Behavior Applied to an Industrial Component. Polymers. 2018;10(6):668.
[63] King A. Numerical modelling of the bombora wave energy conversion device. In 19th Australasian Fluid Mechanics Conference, Melbourne, Australia 2014 Dec 8.
[64] King A, Algie C, Ryan S, Ong R. Modelling of fluid structure interactions in submerged flexible membranes for the bombora wave energy converter. In 20th Australasian Fluid Mechanics Conference, Perth, Australia 2016 Dec 5.
[65] Algie C, Fleming A, Ryan S. Experimental and numerical modelling of the Bombora wave energy converter. In 3rd Asian Wave and Tidal Energy Conference (AWTEC 2016) 2016 (Vol. 2, pp. 719-725).
[66] McDonald A, Xiao Q, Forehand D, Smith H, Costello R. Initial Development of a Generic Method for Analysis of Flexible Membrane Wave Energy Converters. RENEW2018. Lisbon, Portugal: IST Congress Centre; 2018.
[67] W. V. Mars and A. Fatemi Factors that Affect the Fatigue Life of Rubber: A Literature Survey. Rubber Chemistry and Technology: July 2004, Vol. 77, No. 3, pp. 391-412.
[68] Roberts BJ, Benzies JB. The relationship between uniaxial and equibiaxial fatigue in gum and carbon black filled vulcanizates. Proceedings of rubbercon. 1977 Mar;77(2):1-3.
[69] Jardin A, Leblond JB, Berghezan D, Portigliatti M. Definition and experimental validation of a new model for the fatigue of elastomers incorporating deviations from Miners linear law of cumulative damage. Procedia Engineering. 2010 Apr 1;2(1):1643-52.
[70] Zarrin-Ghalami T, Fatemi A. Multiaxial fatigue and life prediction of elastomeric components. International Journal of Fatigue. 2013 Oct 1;55:92-101.
[71] Cadwell, S. M., Merrill, R. A., Sloman, C. M. & Yost, F. L. 1940 Dynamic fatigue life of rubber. Ind. Eng. Chem. Anal. Ed. 12, 19–23.
[72] Gordelier T, Parish D, Thies PR, Weller S, Davies P, Le Gac PY, Johanning L. Assessing the performance durability of elastomeric moorings: Assembly investigations enhanced by sub-component tests. Ocean Engineering. 2018 May 1;155:411-24.
[73] Rabanizada N, Lupberger F, Johlitz M, Lion A. Experimental investigation of the dynamic mechanical behaviour of chemically aged elastomers. Archive of Applied Mechanics. 2015 Aug 1;85(8):1011-23.
[74] P. H. Mott and C. M. Roland Aging of Natural Rubber in Air and Seawater. Rubber Chemistry and Technology: March 2001, Vol. 74, No. 1, pp. 79-88.
[75] Selden R. The effect of water immersion on fatigue crack growth of two engineering rubbers. J Appl Polym Sci 1998;69(5):941–6.
[76] Le Gac P, Arhant M, Davies P, Muhr A. Fatigue behavior of natural rubber in marine environment: Comparison between air and sea water. Materials & Design (1980-2015). 2015;65:462-467.
[77] Narynbek Ulu K, Huneau B, Le Gac P, Verron E. Fatigue resistance of natural rubber in seawater with comparison to air. International Journal of Fatigue. 2016;88:247-256
[78] Chiba S, Waki M, Wada T, Hirakawa Y, Masuda K, Ikoma T. Consistent ocean wave energy harvesting using electroactive polymer (dielectric elastomer) artificial muscle generators. Applied Energy. 2013;104:497-502.
[79] Taylor G, Burns J, Kammann S, Powers W, Welsh T. The Energy Harvesting Eel: a small subsurface ocean/river power generator. IEEE Journal of Oceanic Engineering. 2001;26(4):539-547.
[80] Techet A, Allen J, Smits A. Piezoelectric Eels for Energy Harvesting in the Ocean. Proceedings of The Twelfth International Offshore and Polar Engineering Conference. Department of Mechanical and Aerospace Engineering; Princeton University Princeton, New Jersey, USA.; 2002.
[81] Yin G, Yang Y, Song F, Renard C, Dang Z, Shi C et al. Dielectric Elastomer Generator with Improved Energy Density and Conversion Efficiency Based on Polyurethane Composites. ACS Applied Materials & Interfaces. 2017;9(6):5237-5243.
[82] Cao J, E S, Guo Z, Gao Z, Luo H. Electromechanical conversion efficiency for dielectric elastomer generator in different energy harvesting cycles. AIP Advances. 2017;7(11):115117.
[83] Thomson, G., Yurchenko, D., & Val, D. V. (2018). Dielectric Elastomers for Energy Harvesting. In (Ed.), Energy Harvesting IntechOpen. DOI: 10.5772/intechopen.74136
[84] Mehnert M, Hossain M, Steinmann P. On nonlinear thermo-electro-elasticity. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science. 2016;472(2190):20160170.
[85] US Patent No. 8183739 B2, "Electroactive polymer actuated devices" (2005), SRI International
[86] AG W. Electricity from the Ocean Waves - Wacker Chemie AG [Internet]. Wacker.com. [cited 25 April 2019].
[87] Final Publishable Summary Report. PolyWEC. New mechanisms and concepts for exploiting electroactive Polymers for Wave Energy Conversion. 2017.
[88] Moretti G, Fontana M, Vertechy R. Model-based design and optimization of a dielectric elastomer power take-off for oscillating wave surge energy converters. Meccanica. 2015;50(11):2797-2813.
[89] Moretti G, Papini GP, Righi M, Forehand D, Ingram D, Vertechy R, Fontana M. Resonant wave energy harvester based on dielectric elastomer generator. Smart Materials and Structures. 2018 Feb 20;27(3):035015.
[90] Moretti G, Rosati Papini GP, Daniele L, Forehand D, Ingram D, Vertechy R, Fontana M. Modelling and testing of a wave energy converter based on dielectric elastomer generators. Proceedings of the Royal Society A. 2019 Feb 13;475(2222):20180566.
[91] Teillant B, Vicente M, Papini G, Moretti G, Vertechy R, Fontana M et al. Techno-economic comparison between air turbines and dielectric elastomer generators as power take off for oscillating water column wave energy converters. European Wave and Tidal Energy Conference. 2015.