FY19 Q4 FlexWEC Milestone

INTERNAL REPORT ON EVALUATION OF COST AND PERFORMANCE DRIVERS: KEY COST AND PERFORMANCE DRIVERS IDENTIFIED AND APPROXIMATELY QUANTIFIED

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1 DESCRIPTION AND EVALUATION

A Flexible Material Distributed Power Take-off Wave Energy Converter, or FMDP-WEC, is a device whose dynamic structural deformation – structural flexing, stretching, distension, et al. – is energy available for harvest by a continuously (or semi-continuously) distributed embedded power take-off (PTO) system. In this sense, a FMDP-WEC's PTO system is an integration of several power take-off units placed throughout FMDP-WEC's structure itself. With a distributed power take-off system, ocean energy deforming a flexible structure is dampened and is accomplished by converter the ocean energy into a another form; e.g. electricity. Hence, a plausible advantage of FMDP-WECs – over the more commonplace rigid body Wave Energy Converters (rigid body WECs) counterparts – is their ability to harvest ocean wave energy across the totality of their structure.

Such an ability could be a marked advantage beyond rigid body WECs as rigid body WECs often require a direct transference of ocean wave energy into a centralized PTO system and, in turn, into a single point of failure (e.g. a generator's shaft, hydraulic piston, bearings, gears, etc.). Put another way, if a FMDP-WEC power unit fails, then the majority of the FMDP-WEC's ocean energy conversion duties are still fulfilled. However, if a driveshaft of hydraulic member of a conventional FMDP-WEC fails, then it's likely not fulfilling any of its ocean energy conversion duties. Juxtaposing a FMDP-WEC with the more mainstream rigid body type WECs, therefore, means a potential paradigm shift in how WEC developers might effectuate their innovation strategies and concept development trajectories. To that end, this work aims to avail such FMDP-WEC technology possibilities to the larger marine renewable energy community by describing general FMDP-WEC technology and some of its primary cost-performance drivers.

1.1 ARCHETYPICAL FEATURES

By its very nature, a FMDP-WEC's structure leverages flexible, stretching, and distensible materials. Examples of such structures – having many archetypical features associated with FMDP-WECs – are: (i) SBM Offshore's S3™ concept; (ii) NREL's surge based FMDP-WEC; and (iii) NREL's point-absorber based FMDP-WEC. See Figure 1, Figure 2, and Figure 3 respectively for illustrations of these concepts. In common to these three concepts, is the embedment of electroactive polymers – principally based upon dielectric elastomer generators (DEGs) – that are distributed through a flexible structure.

Summarizing, therefore, the two primary archetypical features of most FMDP-WECs:

- Structure is made of base material(s) that enables flexing, stretching, distention and does so in a manner that is continuous – e.g. there is an absence of discrete joints and hinging mechanisms on FMDP-WECs.
- PTO systems are composed of integrated power take-off units that are embedded and distributed with the base material structure itself. These PTO systems, therefore, are a continuous or near-continuous means of harvesting ocean wave energy throughout the device structure.

1.1.1 Archetype Example: S3™ Concept

The S3™ concept is a long flexible tube, capped at both ends, and filled with fluid – typically a mixture of mostly water with some air or foam for buoyancy. It is freely floating beneath the free surface with its axis aligned in the direction of predominant wave progression – e.g. a floating line like attenuator. Oscillatory pressure variations in the surrounding fluid are transmitted through the flexible tubbed shelled structure into the fluid inside. This causes the fluid inside to slosh setting up standing “bulge” waves in the tube that induces alternate stretching and relaxing with the tube material.

The tube’s base material is an elastic polymer (e.g. synthetic rubber) and has – integrated within it – a semi-continuous PTO system. The PTO system is embedded at sequential intervals along the length and wrapped around the circumference of the tube. The S3™ PTO is based upon a series of interconnected and multilayered DEGs. SBM Offshore refers to S3™’s PTO system as “Electroactive Polymer Generators” or EPGs. The following figure gives an overview of the S3™ concept – aiming to illustrate S3™’s base material structure and semi-continuous PTO system. Typical dimensions of an S3™ device are: (i) tube length: 100 to 400 m; (ii) tube diameter: 2 to 5 m; and (iii) tube thickness: 5 to 10 cm.

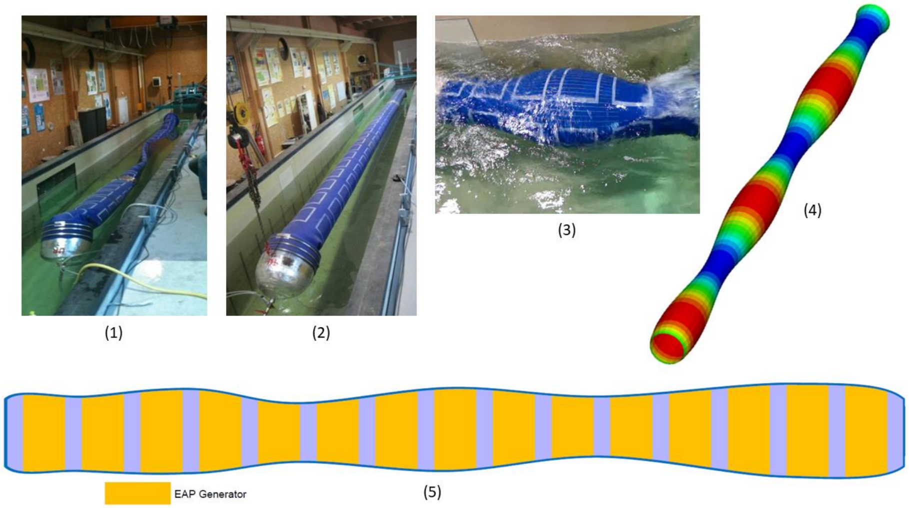
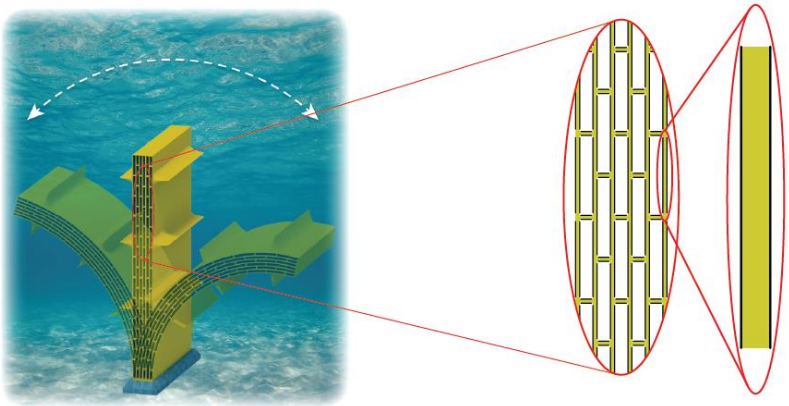


Figure 1: SBM Offshore’s S3™ concept; a representative FMDP-WEC. Describing, from upper left going clockwise: (1) S3™ concept ‘deflated’ configuration – used for deployment or possibly survival mode; (2) deployed configuration - S3™ concept is ballasted and ready for wave energy conversion; (3) section of the S3™ concept in wave environment – portion of converter located in a wave trough causing base material with embedded PTOs to bulge; (4) Numerical result of S3™ concept being subjected to wave crests and wave troughs along its length – red areas = tube distention due to wave troughs and blue areas = tube compression due to wave crests; and (5) cross section side view of S3™ concept – illustrating the various PTO sections made up of Electroactive Polymer Generators (EAPs), which themselves are likely made up of layered Dielectric Elastomer Generators (DEGs).

1.1.2 Archetype Example: NREL’s Surging Based FMDP-WEC

A surging based FMDP-WEC is a flexible structure that will actively deform – bend, contort, stretch – when subjected to, primarily, surging ocean energy. By damping the dynamic structural deformations, one can convert portions of the surging ocean energy into another form; e.g. electricity. Damping the structural deformation can be accomplished by embedment of power take-off units throughout the surging based FMDP-WEC structure. In aggregate, these power take-off units represent a distributed means to harvest ocean energy by curtailing structural deformation. Electro-active polymers are well suited as the embedded power take-off units for this type of FMDP-WEC. Being based upon integrated layers of DEGs, the electro-active polymers are, essentially, viscoelastic capacitors with specialized charging-discharging schemes – the electro-active polymers take surge based bending structural deformations as input and generates electricity as output. Accordingly, wherever structural deformation is induced by the surging ocean energy, the distributed power take-off system can resist the deformation through the generation of electricity. The following figure gives an overview of the surging based FMDP-WEC concept.



Cross section of flexible material distributed power take-off ocean energy converter.

Zoomed views: (i) layered configuration of electro-active polymers and (ii) a single dielectric elastomer generator.

Figure 2: NREL's Surging based FMDP-WEC – one that leverages the use of electro-active polymers to convert predominantly surging ocean wave energy into more usable forms such as electricity. In this example, electricity is generated via the distributed embedded electroactive polymers that made from layered interconnected dielectric elastomer generators. When this example surging FMDP-WEC deforms back and forth, the converter's dielectric elastomer generators dampen such deformation via the generation of electricity. This FMDP-WEC was developed at the National Renewable Energy Laboratory; provisional patent U.S. Application No. 62/888,685 (NREL PROV/19-98).

1.1.3 Archetype Example: NREL's Point Absorbing Based FMDP-WEC

A point absorbing based FMDP-WEC is based upon a structure that will actively deform – bend, contort, stretch – when subjected to (i) wave forces as it floats atop the ocean; (ii) forces caused by the motion of a heavy inertial mass contained within; and (iii) mooring loads. The flexible honeycomb based structure is an assortment of electro-active polymers that can dampen the resulting honeycomb dynamic structural deformations. Through such damping, the point absorbing based FMDP-WEC can convert portions of energy associated with i, ii, and iii into electricity. The damping itself is accomplished by embedment of power take-off units throughout the point absorbing based FMDP-WEC structure. In aggregate, these honeycomb power take-off units represent a distributed means to harvest ocean energy by curtailing structural deformation. As indicated before, electro-active polymers are well suited as the embedded power take-off units for this type of FMDP-WEC and are based upon integrated layers of DEGs. To reiterate, these layered/configured DEGs are, essentially, viscoelastic capacitors with specialized charging-discharging schemes – the electro-active polymers take surge based bending structural deformations as input and generates electricity as output. Accordingly, wherever structural deformation occurs within the honeycomb structure – being induced by i, ii, and iii – the distributed power take-off system can resist such deformation through the generation of electricity. The following figure gives an overview of the point absorbing based FMDP-WEC.

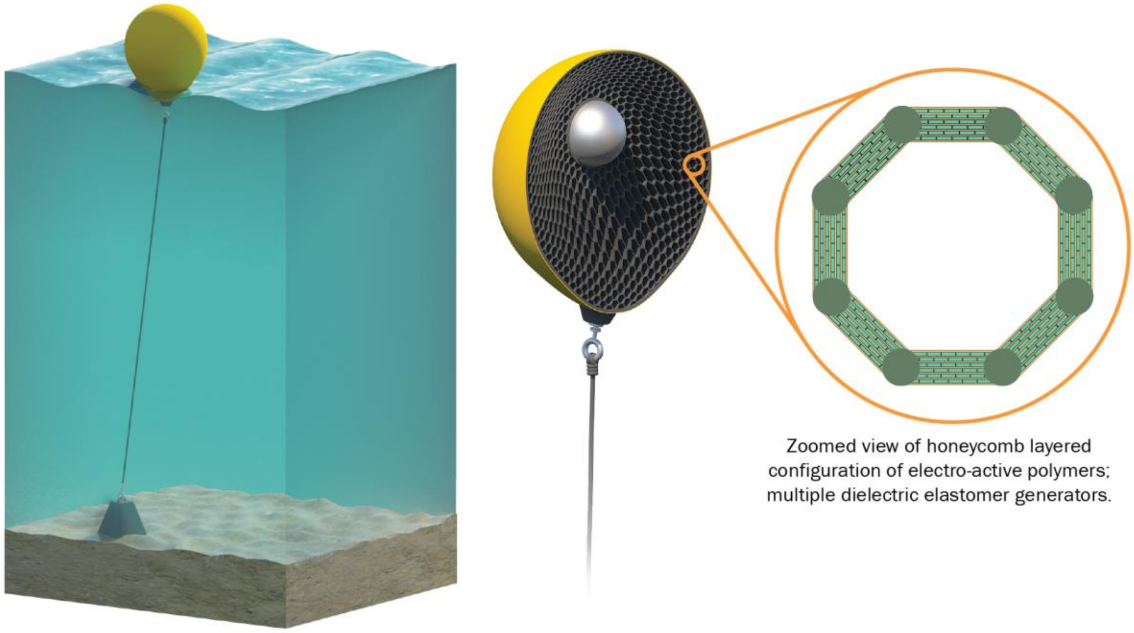


Illustration of conceptual deployment of a flexible material distributed power take-off ocean energy converter.

Cross section of flexible material distributed power take-off ocean energy converter.

Zoomed view of honeycomb layered configuration of electro-active polymers; multiple dielectric elastomer generators.

Figure 3: NREL's Point Absorbing based FMDP-WEC – one that leverages the use of electro-active polymers to convert the point absorbing relative motion of a flexible honeycomb hull and internal inertial mass into electricity. In this example, electricity is generated as the floating flexible hull – containing a honeycomb structure of electroactive polymers (dielectric elastomer generators) – is deformed due to wave forces and internal inertial mass forces. Damping of such deformation, via the honeycomb electro-active polymers, is the means of electricity generation. This FMDP-WEC was developed at the National Renewable Energy Laboratory; provisional patent U.S. Application No. 62/888,685 (NREL PROV/19-98).

1.1.4 Electro-Active Polymers

As indicated, a very common type of electro-active polymer are layers/configurations of dielectric elastomer generators. In terms of a single DEG – regardless of how it is layered, employed, or named – its operation is based upon the increased voltage potential due to the stretching and relaxing of a dielectric subjected to a pre-charged electric field that traverses its thickness. Thus, when a dielectric elastomer is strained, a pre-charged voltage potential is then applied across its dielectric material's thickness. When the now pre-charged and strained dielectric is allowed to relax, the aforementioned pre-charged voltage potential is concentrated and therefore amplified – because the charge is constrained to much smaller areas than when the dielectric was stretched and initial charged. It is the net difference in voltage potential – moving from strained pre-charged to non-strained (relaxed) concentrated charge – that electricity is generated. The following figure illustrates the basic operation of a DEG.

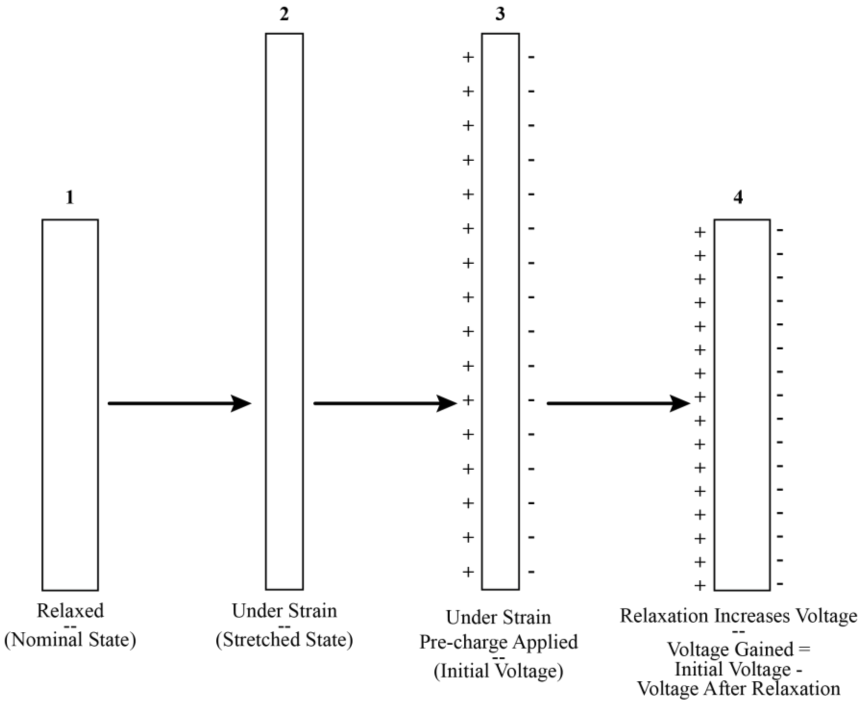


Figure 4: : Side view of a single Dielectric Elastomer Generator (DEG) at four main states; DEGs represent the basic form of most FMDP-WEC PTOs and are likely the constituent parts that make up S3™'s EPGs. State 1: The nominal relaxed state of the DEG; as the material would be without attachment to power electronics nor deformation. State 2: The stretched state; as the DEG would be if under some amount of deformation and without attachment to power electronics. State 3: Power electronics applied to stretched state of DEG; application of pre-charge to DEG under deformation. State 4: Having been deformed and under pre-charge, DEG is now relaxed causing the pre-charged initial voltage potential to be amplified and whose net gain represents the generated electricity of a dynamically stretched DEG.

1.2 BASE MATERIAL STRUCTURE

To enable flexing, stretching, and/or distention, most base materials for FMDP-WECs are composed of synthetic rubbers. In the case of the archetypical S3™ concept, its base material (aside from its EAP PTO system) appears to be made of neoprene rubber, ethylene propylene diene methylene (EPDM) rubber, or a composite of both. Beyond its flexing-stretching-distention requirements, a FMDP-WECs base material structure should also enable (at minimum):

- Proper sea worthiness – maintains ballast, endures ocean corrosion, mitigates biofouling, protected against UV radiation (if ocean surface penetrating), bears cyclic fatigue loading, etc.
- Has necessary connections points for mooring lines, power lines, ballast inlets/valves, deployment mounts, etc.
- Controllability; base material structure can alter its stiffness and/or allowed to be controlled in terms of how it flexes, stretches, and/or distends.

1.3 PTO-SYSTEM

Being integrated throughout the base material structure – in a continuous or semi-continuous manner – a FMDP-WEC's PTO system must also be able to flex, stretch, and distend. This directly implies that these types of PTO systems must be based upon energy available due to dynamic deformation. Dynamic deformation, in this instance, is intended to mean the back and forth (dynamic) deforming of materials whose properties transmutes ocean energy into electricity via the FMDP-WEC's power take-off systems. As mentioned, DEGs represent an archetypical feature capable of implementing the needed transmutation of dynamic deformation energy into electricity. Nonetheless, DEGs and their various arrangements (e.g. S3™'s EAPs) are not the sole means of dynamic deformation energy harvesting. Techniques such as those leveraging properties of magnetostriction or Hydraulically Amplified Self-healing Electrostatic (HASEL) based generators are also strong contenders for FMDP-WEC PTO systems.

1.4 POWER ELECTRONICS

DEG's and many other FMDP-WEC PTO systems must be pre-charged (with the notable exception being magnetostriction based fabrics). The basis for DEGs and HASEL operation is such that they take an already existing voltage potential and then – via dynamic mechanical straining – increase the pre-charged voltage potential from which, usable electricity can be harvested. In other words, without a continual source of pre-charge electric potential, DEGs and HASEL based generators will not generate electricity.

1.5 ACTIVE SYSTEM CONTROL

As shown in Figure 1, the DEG needs to be charged and discharged at the correct instants. The DEG itself can be used as a sensor to measure the stretch which can then be used as an input to the power electronics that charges and discharges the DEG (Jean, et al., 2012). Adjusting the applied voltage controls the level of PTO damping. This is useful in maximizing the energy produced while keeping the stretch under limit below material breakage. In survival mode, the DEG can be fully discharged and the hull completely relaxed – thereby "riding out the storm."

Other than these voltage controls incorporated in the power electronics, there are no other active controls like what one might find in rigid body WECs. The flexible hull has a semi-infinite number of degrees of freedom and is therefore capable of resonating across a broad band of wave frequencies. This obviates the need for controls supplying large reactive forces that aims to mimic resonant response in rigid body WECs that only have a limited number of degrees of freedom.

1.6 ELECTRIC POWER TRANSPORT TO SHORE

Augmenting utility power grids with renewable sources of electricity is of significant interest to both local and national governments. FMPD-WECs represent an opportunity, therefore, to be just such a source of renewable electricity. To accomplish this, however, FMPD-WECs needs an ability to transport their harvested ocean wave energy from sea to shore. As a brief overview, some methods of power transport to shore might include: (i) subsea cable – dredged or atop the seafloor; (ii) beamed power transmission – inductive power systems, directed laser-photovoltaic systems, and beamed microwave-heat-exchanger systems; or (iii) electrolyte regeneration with sea to shore transport – pumped or ferried.

Unless the power cable from shore is to an array of FMPD-WECs (a wave energy farm – the dominating cost of a FMPD-WEC is thought to be from those expenditures needed to establish a power cable existence as a means of transporting the harvested wave energy.

1.7 WAVE FARM

A wave farm is where several WEC's are deployed within a relatively close area and serviced by common infrastructure of substations, transmission lines, etc. Using SBM Offshore's S3™as an archetypical example whilst also drawing upon the reported results of their preliminary studies (see references), the expected layout of a SBM S3™ based wave farm can be roughly envisaged (Fig. 3).

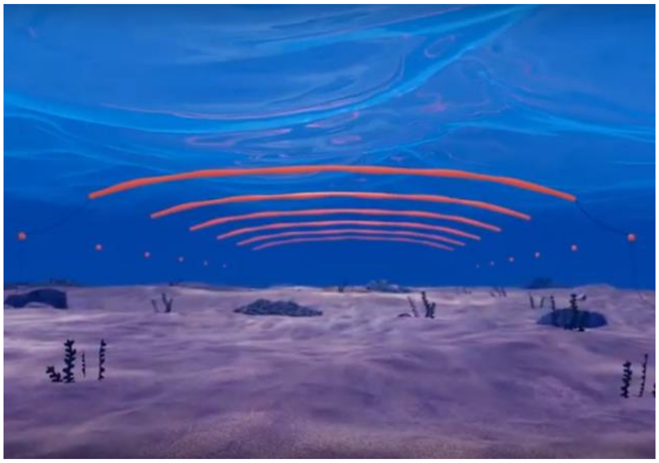


Fig. 3 Artist's impression of S3™farm (https://www.sbmoffshore.com/news/sbm-offshore-s3-wave-energy-converter-watch-the-video/)

Assume the incident wave energy flux to be 30 kW/m at the wave farm site. Also assume the most prevalent wave periods to be 5 to 10 s or equivalently the wave lengths to be 50 to 150 m. Theoretical and experimental studies by Babarit, et al. (2017) have shown that a 100 m long S3™ device can produce about 150 kW power in those wave conditions.

A single device of that size will find "blue economy" applications like powering sensors or supplying power to remote communities. A larger size device 400 m long and capable of producing 5 MW may be achievable. A farm of 10 such devices will produce 50 MW power and a farm of 200 such devices will produce 1 GW. Each device is moored with its axis parallel to the predominant wave direction, with one catenary line attached to the bow and another attached to the stern. If the transverse spacing between devices is 20 m, then a 1 GW array will stretch 4 km transversely. The substation servicing the farm can be housed on a floating barge spread moored to the lee of the farm.

1.8 MOORING SYSTEMS

The mooring system enables the wave farm to keep station within a desired localized area. Clearances between individual FMDP-WEC devices within a farm also need to be maintained. This may be to avoid entanglement plus collision, minimize destructive interference, or to promote constructive interference. The orientation of the FMDP-WEC devices with respect to the predominant wave direction may also have to be maintained (e.g. attenuator or terminator type FMDP-WECs).

An advantage of FMDP-WECs, is that they can be free floating, just beneath the ocean surface, and operate like an attenuator with their primary axis being parallel to the predominant wave direction (e.g. SBM Offshore's S3™). Likewise, they can be moored with conventional soft moorings (e. g. catenary single point or multi point moorings) thereby permitting the device to respond freely to the oscillatory forces of the waves while concurrently resisting only the higher-order steady and slowly-varying forces in the horizontal plane (e.g. waves and current). Furthermore, their windage area is practically nil and their projected area being exposed to currents can, if desirable, be minimized; meaning those forces to be resisted by the mooring system are relatively low.

1.9 PRINCIPAL PARAMETERS AND THEIR RANGES

The principal parameters of the FMDP-WEC archetypical example, SBM Offshore's S3™, are tabulated below. The ranges of parameter values and step sizes to be considered are also tabulated based on:

- ranges being broad enough to extend to upper and lower bounds, outside which benefits are likely negligible
- step sizes being small enough to identify optimums

Parameter bounds and step sizes are to be adjusted based on results obtained and sensitivities discovered. Though parameters are listed as they directly relate to SBM Offshore's S3™, the FMDP-WEC category encompasses other shapes and embodiments like those illustrated in Figs. 2-3, tubes in a horizontal V-shape, mat, etc.

#	Parameter	Units	Reference value	Range	Step size	Comment
1	Tube length	m	100	20-1,000	50-100	
2	Tube diameter	m	5.5	1-12	1	
3	Wall thickness	cm	10	2-50	5	
4	Material density	kg/m^3	1,500	950-2,300	500	natural rubber, neoprene, EPDM, CR, Silicone, polyurethane
5	Material elasticity	kPa	C_{10}=134, C_{20}=-22.2, C_{30}=7.3	TBD	TBD	coefficients in Yeoh model of hyper elasticity
6	Material damping coefficient	kPa-s	20	10-100	10	multiply material damping coefficient by rate of change of radius and divide by deflated radius to get contribution to hoop stress
7	Submergence	m	2.65	0.4-15	1	nearer the free surface, higher is the hydrodynamic pressure; deeper the submergence, the more fully exposed is the circumferential surface; deeper submergence with the help of extraneous added buoyancy may lead to innovative improvement of reference configuration

8	Inflated radius	m	130% of deflated	110%-200% of deflated	10% of deflated	
9	Distensibility	1/Pa	TBD	TBD	TBD	TBD from elasticity, tube size and inflated radius
10	Mooring stiffness	kN/m	50	0-5,00	50	steady and slowly varying forces not considered, so device keeps station even with zero horizontal stiffness
11	Regular waves: period	s	10	3-25	1	
12	Regular waves: height	m	1	0.5-10	1	
13	Irregular waves: energy period	s	10	3-20	1	
14	Irregular waves: significant wave height	m	2.5	1-10	1	
15	Wave heading	deg	0 (head seas)	-75 - +75	15	
16	Water depth	m	1,000	20-1,000	100	
17	Power take off (PTO) damping coefficient	kPa-s/m^2	40	10-100	10	linear PTO damping model
18	PTO stiffness	kPa/m^2	TBD	TBD	TBD	change in differential pressure to get unit change in cross sectional area

2 COST AND PERFORMANCE DRIVERS

2.1 INHERENT REDUNDANCY OF BASE AND PTO MATERIALS

The distributed PTO is made up of multiple DEGs spanning the length of the hull. There is therefore a natural segmentation of the system which provides a high degree of redundancy – all DEGs are electrically independent and can be disconnected from the rest of the system without altering its behavior. The loss of one of the generators would results in only a limited loss of output power.

2.2 COST – BASE MATERIAL

- Of possible base materials the following are highly anticipated to be used and/or incorporated into a FMDP-WEC's structure; anticipation is based upon current prevalence (gross manufacturing tonnage) in products and services related to the marine industry and including other large industries (e.g. chemical and petroleum industries):

- High Density Polyethylene
- A Thermoplastic produced by the ‘free radical polymerization’ of the monomer ethylene.
- Layman Analog: Heavy duty trash bag
- Approximate Cost: ~$5,000 per ton
- Approximate Tensile Strength: 0.20 to 0.40 N/mm^2
- Approximate Density: 0.944 to 0.965 g/cm^3
- Neoprene/Chloroprene
- A synthetic rubber produced by polymerization of chloroprene.
- Layman Analog: Wetsuit
- Approximate Cost: ~$3,000 per ton
- Approximate Tensile Strength: 500 to 3000 psi
- Approximate Density: 1.23 g/cm^3
- Silicone Rubber
- Elastomer of elemental silicon, carbon, hydrogen, and oxygen.
- Layman Analog: Door gaskets, O-Rings
- Approximate Cost: ~$7,000 per ton
- Approximate Tensile Strength: 2.4 to 5.5 MPa
- Approximate Density: 1.1 to 2.3 Mg/m^3

2.3 COST – PTO SYSTEM

Costs associated with FMDP-WEC PTO systems are not only governed by similar base materials as what is primarily used in a FMDP-WEC’s structure, but also by those materials needed to enable stretchable electrodes. In this sense, the cost of a FMDP-WEC’s PTO system, in part, is governed by those same costs already listed for the highly anticipated materials of a FMDP-WEC’s base material structure. The other significant FMDP-WEC PTO system cost would, therefore, likely stem from both development and the procurement of high conductivity stretchable electrodes. A stretchable electrode example – and likely the most common amongst DEG based PTO systems – is carbon grease applied to both surfaces of the stretchable dielectric.

2.3.1 Carbon Grease

Predominantly a petroleum-based jelly heavily infused with graphite.

- Layman's use: Often used in vibrating and rotating structures where electrical conduction is needed throughout the structure; e.g. for ensuring electrical grounding of the structure regardless of motion.
  Approximate Cost: ~$20 per 100 grams (inexpensive)

2.4 COST – POWER TO SHORE

If power is to be transmitted to an onshore utility grid, the infrastructure cost should cover:

- Array cables (collect power from individual devices in a wave farm and transmit to offshore substation)
- Export cables (connect offshore substations with onshore electrical infrastructure)
- Cable protection (dredging, scour protection, cable mattresses, protective sheath, etc.)
- Offshore substation
- Onshore transmission or conversion equipment

The cost is driven by:

- WEC array size and spacing
- Length, size and type of cables
- Water depth
- Distance to shore
- Seabed characteristics along cable corridor, and whether cable is to be buried

Quantitative cost estimates could be informed by knowledge of power transmission costs incurred by offshore wind farms (e.g. Green, et al., 2007).

2.5 COST – POWER ELECTRONICS

Fairly straightforward with the only caveat being the need for high voltage, minimal current, capacity for DEGs.

2.6 COST – MOORING SYSTEMS

An advantage of FMDP-WEC is that they are freely floating just beneath the free surface and operate like an attenuator with their primary axis parallel to the predominant wave direction (e.g. SBM Offshore's S3™). They can be moored with conventional soft moorings (e. g. catenary single point or multi point moorings) which permit the device to respond freely to the oscillatory forcing of the waves while at the same time resisting only the higher-order steady and slowly-varying forces in the horizontal plane (waves, current). Mooring system components are commercial off-the-shelf (COTS) comprising of:

- Hull attachment points or towheads, 2 nos./device
- Lines (e.g. synthetic light weight, length depending on water depth), 2 nos./device
- Mooring buoys, 2 nos./device
- Anchors (e.g. gravity, suction, auger, drag embedment, or other depending on bottom soil type), 2 nos./device
- Connecting hardware (e.g. shackles, pins)

2.7 MANUFACTURE, ASSEMBLY, INSTALLATION, MAINTENANCE

2.7.1 Manufacture

The mass production of DEG film would rely on roll-to-roll processes widely used in the manufacture of paper, capacitors, plastic films, etc. However, maintaining the required quality of DEG film at high production rates and very large volumes is a key remaining technical challenge (Wattez and van Kessel, 2016). Future research is necessary to develop high energy density elastomers which can be manufactured on a large scale with the desired performance and life expectancy.

2.7.2 Assembly

The DEG is embedded or otherwise wrapped around the hull in a multilayer arrangement with proper stretchable electrode placement and a deformable multilayer electrical connection. The general performance can be affected by external water channels creating direct connection between positive and negative sides. Therefore, special care must be taken in the design of the electrical connection as good material performance in wet environment is mainly dependent on a proper engineering solution for the protection of the electrical connections.

2.7.3 Installation

In the deflated condition, the FMDP-WEC can be reeled or folded. It can be unfolded or unreeled shoreside and then towed to site, or it can be unreeled on site from a reel barge. It is then inflated and hooked up to pre-laid mooring lines and power cables. These activities can be accomplished with equipment typically available in the marine construction sector.

2.7.4 Maintenance

Unlike rigid body WECs, the FMDC-WEC has no complex mechanical parts like hinges, gearboxes, turbines or hydraulics. Therefore only minimal routine maintenance is required, and the device can be run to failure, at which time it has to be repaired or replaced. Failure could result from:

- Structural failure of hull (e.g. mechanical fatigue)
- Electrical failure of DEG (e.g. electrical ageing or combined electromechanical fatigue of DEG simultaneously exposed to high electric fields and large strain)

In the latter case, loss of one of the generators would result only in a limited loss of output power, and a device can continue to operate as long as it has a sufficient number of healthy DEGs remaining.

2.8 WEC PERFORMANCE

With a 100 m long and 5.5 m diameter S3™ device, a capture width of 5 m is achievable per Babarit, et al. (2017) in 5 to 10 s waves which are the most prevalent periods. Assuming incident wave energy flux to be 30 kW/m, this means a single device will produce about 150 kW power. However, further optimization and improvements in materials could potentially enhance performance.

Performance is contingent upon the formation of standing ‘bulge’ waves inside the flexible hull set up by the oscillatory variations in the surrounding fluid pressure. This is achieved by an appropriate choice of hull dimensions, material, static inflation pressure, orientation with respect to waves, etc. matching the internal sloshing frequencies to the prevalent wave frequencies. Since FMDP-WECs can respond in a semi-infinite number of degrees of freedom, they are less sensitive to changes in their orientation with respect to waves. Nonetheless, their performance could degrade if their orientation strays far from optimal and consequently incident waves fail to excite resonant sloshing in the hulls.

The ability of the DEG to generate more energy with less volume or mass is also important. In particular, since the PTO damping is controlled by adjusting the DEG voltage, a large dielectric constant (or relative permittivity) and a large dielectric strength (or breakdown field) are two direct drivers of the energy output.

3 OPPORTUNITIES FOR CROSS-CUTTING TECHNOLOGIES

3.1 FLOATING BREAKWATER

Extracting the energy of the waves could leave a relatively calm shadow zone in the lee. Since the flexible hull of the FMDP-WEC can be deflated, folded or reeled for transporting, and re-inflated for redeployment, an FMDP-WEC can act as an easily transportable and deployable floating breakwater. It could serve, for example, as a temporary wave barrier during marine construction, or as a wave barrier enabling ship-to-ship cargo transfer in an open roadstead.

4 REFERENCES

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5 APPENDIX A – A REFERENCE STRUCTURE OF POTENTIAL COST-PERFORMANCE DRIVERS

The following was used to aid in the development of this document – a reference from which a perspective of potential cost-performance drivers for FMDP-WEC could stem from and be analyzed. The reference is not intended to be conclusive nor form fitting to all types of FMDP-WEC technology, but it does aid in setting those aspects and corresponding structures governing potential cost-performance drivers for general FMDP-WEC technology. The reader of this document is encouraged to go through this list with an eye towards the descriptions and primary cost-performance drives given above – that the reader may have a great context as to those aspects of FMDP-WEC technology driving and or potentially curtailing its further development.

- Plausible Configurations for Power Take-Off
- Failure Modes
- Single Device Control Strategies
- Multiple Device Control Strategies
- Rough Estimates on Conversion Efficiency
- Primary Factors Affecting Conversion Efficiency
- Device Illustrations/Drawings – Conceptual Archetypes
- Conceptual Archetype 1
- Conceptual Archetype 2
- Conceptual Archetype 3
- Layout and Dimensions
- Water Line
- Predominate Orientation Relative to Waves
- Nominal Displaced Volume
- Nominal Mass
- Frontal Area – Area Impacted by Incident Waves
- Configurations
- Operational Mode
- Maintenance Mode
- Survival Mode
- Deployment Mode
- Safe Mode
- Morphing Mechanisms for Mode Transitions
- Major Components
- Main Flexible Body Material
- Mass of Main Flexible Body Material
- Failure Modes – Main Flexible Body Material
- Power Take-off Material/Components
- Mass of Power Take-off Material/Components
- Failure Modes – Power Take-off Material/Components
- Embedded Systems and Controllers
- Mass of Embedded Systems and Controllers
- Failure Modes – Embedded Systems and Controllers
- Power Transmission Equipment
- Mass of Power Transmission Equipment
- Failure Modes – Power Transmission Equipment
- Lock-outs and Safety Equipment
- Mass of Lock-outs and Safety Equipment
- Failure Modes – Lock-outs and Safety Equipment
- Actuators
- Mass of Actuators
- Failure Modes – Actuators
- Redundant Systems
- Mass of Redundant Systems
- Failure Modes – Redundant Systems
- Docking Stations
- Mass of Docking Stations

- Failure Modes – Docking Stations
- Ballast Bladders/Tanks
- Mass of Ballast Bladders/Tanks
- Failure Modes – Ballast Bladders/Tanks
- Valves
- Mass of Valves
- Failure Modes – Valves
- Active System Control
- Sensors and Actuators Needed for Active System Control
- Environment and System Measurement Telemetry Need for Active System Control
- Manufacture and Assembly
- Farm Layouts – Multiple FMDP-WECs Deployed Together
- Active Farm Control
- Overview of Active Farm Control Principles
- Sensors and Actuators Needed for Active Farm Control
- Environment and System Measurement Data Needed for Active Farm Control
- Moorings
- Major Mooring Components
- Hull attachment points or tow heads
- Lines (e.g. synthetic light weight)
- Anchors (e.g. gravity, drag embedment, or other depending on bottom soil type)
- Connecting equipment (e.g. shackles, pins)
- Single Point Moorings
- Taut Single Point Mooring
- Catenary Single Point Mooring
- Multi Point Moorings
- Taut Multi Point Moorings
- Catenary Multi Point Moorings
- Hybrid Taut Catenary Multi Point Mooring System
- Active Mooring Systems
- Overview of Active Mooring System Control Principles
- Sensors and Actuators Needed for Active Mooring System Control
- Environment and System Measurement Data Needed for Active Mooring System Control
- Anchorage
- Gravity Anchors
- Suction Caisson
- Auger Anchors
- Power Electronics
- Power Smoothing and Conditioning
- Super Conductor Electricity Transport
- Discharge Systems and Safety
- Instrumentation
- Main Embedded Systems
- Major Sensors
- Instrumented Device Autonomy
- Transmission Equipment
- Marine Environment Certification
- Deployment and Logistics
- Power Transport and Logistics
- Electricity Transmission
- Substation – Power Smoothing and Transmission to Grid
- Undersea Cable
- Seafloor Resting Cable
- Applicable Ocean Wave Energy Resource
- Promising Site Locations
- Shallow Water Sites
- Deep Water Sites
- Applicable Permitting
- International Permitting
- National Permitting
- Local Permitting
- Finance
- Lobbyist – Acquisition of Subsidies
- Loan and Associated Interest Rates
- Cost-share/Cost-matching
- Insurance for Assembly
- Insurance for Deployment
- Insurance for Operation
- Insurance against Malpractice/Lawsuits

- Insurance for Decommissioning
- Public Relations
- Outreach to Public
- Community Awareness and Involvement
- Marketing the Idea
- Human Resource Management
- Union Negotiations
- Head-hunting/Recruitment Operations
- Safety and Protection Equipment
- Maintenance and Repair
- Anticipated Weak-links/Points-of-failure
- Recovery Operations
- Biofouling Abatement
- Hydraulic Fluid Abatement
- Decommissioning of Device
- Metal Component Decommissioning
- Plastic/Rubber Component Decommissioning
- Dangerous Material/Substance Abatement
- Survival Strategy
- Anticipated Survival Scenarios
- System Cutoffs
- Danger Mitigation
- General Risk Assessments
- Opportunities for Cross-cutting Technologies
- Floating Offshore Wind Turbines
- Seabed Foundation Wind Turbines
- Aquaculture Farm
- Aqua-mining Farm
- Disaster Relief
- Remote Power/Charging Station
- Floating breakwater
- Main Flexible Body Material
- Probable Materials
- Low-density Polyethylene
- High-density Polyethylene
- Neoprene/Chloroprene
- Fabric-Reinforced Neoprene/Chloroprene
- Polyurethane Rubber
- SBR (styrene butadiene rubber)
- Fabric-Reinforced SBR
- Silicone Rubber
- Fabric-Reinforced Silicone Rubber
- Buna-N (Nitrile) Rubber
- Fabric-Reinforced Buna-N (Nitrile) Rubber
- Ethylene Propylene Diene Methylene (EPDM) Rubber
- Fabric-Reinforced EPDM Rubber
- Butyl Rubber
- Viton® Fluoroelastomer Rubber
- Aflas Rubber
- Kalrez Rubber
- Mylar (BoPET; Biaxially-oriented polyethylene terephthalate)
- Kevlar/Aramid
- Carbon Fiber
- Fiberglass
- Copperized Fiberglass
- Carbon Fiber Zylon Hybrids
- Carbon Fiber Aramid Hybrids
- Ultra-High-Molecular-Weight-Polyethylene (UHMW)
- Glass-Filled UHMW
- Delrin®
- Nylon
- Polyvinyl Chloride (PVC)
- Polypropylene
- Polycarbonate
- Survivability of Primary Material vs. PTO Material