Distributed Embedded Energy Converters for Ocean Wave Energy Harvesting: Enabling a Domain of Transformative Technologies

Preprint

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Presented at European Wave and Tidal Energy Conference
Plymouth, United Kingdom
September 5–9, 2021

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5700-80484
September 2021

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Suggested Citation
Boren, Blake. 2021. *Distributed Embedded Energy Converters for Ocean Wave Energy Harvesting: Enabling a Domain of Transformative Technologies: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-80484. https://www.nrel.gov/docs/fy21osti/80484.pdf.

Conference Paper
NREL/CP-5700-80484
September 2021

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303-275-3000 • www.nrel.gov

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Distributed embedded energy converters for ocean wave energy harvesting: enabling a domain of transformative flexible technologies

Blake C. Boren

***Abstract*—Distributed embedded energy conversion technology (DEEC-Tec) is a very promising—but underdeveloped—domain in marine renewable energy research. The technology utilizes small distributed embedded energy converters (DEECs) that, in aggregate, form a much larger energy harvesting-converting structure. Each DEEC is a small transducer—an individual mechanism that converts one form of energy into another. A transducer's specific mode of operation can be based upon any number of physical phenomena, including variable capacitance, variable magnetic fields, or piezoelectrics. It is the dynamic deformation of a structure made from such DEECs (a DEEC-Tec structure) that provides the needed physical phenomena (the external energy source) for the underlying transducers to intake and convert energy into another form, such as electricity. DEEC-Tec structures designed specifically to dynamically deform in the presence of ocean wave energy—for the purpose of harvesting and converting that energy—can be called flexWECs. A flexWEC's gross shape (topology) and its compliant characteristics (morphologies) are chiefly determined by how the DEECs making up its structure are arranged and implemented. In turn, those corresponding topologies and morphologies will largely determine how a flexWEC interacts with—and dynamically deforms within—the presence of ocean wave energy. FlexWECs appear to have many attractive features, including broad-banded ocean energy conversion, in situ energy conversion throughout an entire flexWEC structure, inherent redundancy, and appealing material and manufacturing costs. To this end, the design and development of any particular flexWEC or flexWEC feature is a revolutionary opportunity for how we conceptualize and envision the future of ocean wave energy conversion.**

***Index Terms*—DEEC, DEEC-Tec, distributed embedded energy conversion technology, flexible transducer, flexWEC, manufacture, marine renewable energy, materials, wave energy conversion, WEC**

Paper ID number 2243; track ID: WDD. This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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I. Introduction

DISTRIBUTED embedded energy conversion technology (DEEC-Tec) combines many small energy converters together to form a compliant structure capable of both aggregated energy harvesting-converting and energized actuation throughout. The individual small energy converters themselves can be any transducer suitable for interconnection with other transducers such that an overall desirable compliant structure is created: a DEEC-Tec structure. When a conglomerate of DEEC-Tec structures are assembled to form an ocean wave energy harvesting-converting device, the conglomerate of DEEC-Tec structures is often called a flexWEC—a portmanteau representing (1) the compliant nature of most DEEC-Tec structures and (2) the conglomerated structure's intended purpose to harvest-convert ocean wave energy.

Given the numerous combinations and interconnected forms these transducers (the individual distributed embedded energy converters [DEECs] themselves) can obtain—and, in turn, the numerous forms a resulting DEEC-Tec structure could become as a flexWEC that harvests and converts ocean wave energy—-the DEEC-Tec domain could vastly broaden how we currently conceptualize and envision the use of ocean wave energy [1]–[3]. Indeed, being a conglomerate of DEEC-Tec structures and various types of DEECs (transducers), *flexWECs present a tremendous range of possibilities for developers and industry to advance a broad swath of very new and novel types of wave energy converter (WEC) technologies* [4], [5].

Some attractive features bringing flexWECs to light within the domain of WEC research and development include: (1) lack of highly loaded rigid bodies, (2) avoidance of force concentrations into singular mechanical or hydraulic power transmissions, and (3) absence of such features as high-pressure hydraulic seals, bearing loads, hull fractures, and worn gears. Indeed, of particular emphasis, flexWECs do not accumulate forces into or solely depend upon a centralized singular energy conversion and generation system—such as singular power take-off systems like a rotary electric generator or hydraulic piston. In other words, these attractive features arise from a flexWEC's ability to harvest ocean energy throughout its entire structure, via its many small distributed embedded energy converters.

What follows, therefore, is an effort to promote and broadcast to potential researchers and developers the expansive possibilities that the DEEC-Tec domain avails to the marine renewable energy sector. To that end, this paper presents a cursory overview of the DEEC-Tec domain, showcasing its basic principles and plausible applications within the field of ocean wave energy conversion—elucidating both the attractive features of flexWECs and their areas in need of further research and development.

Section II describes the underlying nature of what the many small distributed embedded energy converters could be—describing them in terms of transducer mechanisms. Section III describes how the distribution and embedment of those many small energy converters (DEECs) can be effectuated such that ocean energy conversion structures (flexWECs) can be realized—aiming to describe possible converter archetype topologies *and* morphologies. Lastly, Section V gives concluding remarks related to the current state of DEEC-Tec-based ocean energy conversion, in addition to those future pathways for continued flexWEC research and development.

II. DEEC-Tec

Fundamental to the domain of DEEC-Tec are the individual energy converters that make up any DEEC-Tec structure. These small distributed embedded energy converters can be combined, interconnected, and/or layered in any number of ways to create any type of DEEC-Tec structure. In this regard, individual DEECs are typically many orders of magnitude smaller than the aggregated DEEC-Tec structures they create. Each individual DEEC is a small transducer—a simple mechanism capable of converting one form of energy into another via some physical phenomena. Such phenomena could be variable capacitance, Faraday's law of induction, the piezoelectric effect, magnetostriction, or any others.

Each individual DEEC is typically designed toward one of three generalized categories: (1) generator transducers, , (optimized specifically to harvest energy through dynamic strain); (2) actuator transducers, , (optimized specifically to induce motion or to control a strainable mechanism); or (3) bidirectional transducers, , (optimized specifically for either harvesting of energy or to induce motion/control of some mechanism). Examples of current state-of-the-art transducers thought to be directly usable by the DEEC-Tec domain include dielectric elastomer generators (DEGs), dielectric elastomer actuators (DEAs), ionic dielectric elastomer generators/actuators, hydraulically amplified self-healing electrostatic (HASEL) generators, and the actuator version of HASELs [6]. As a specific example and type of DEEC, Fig. 1 gives an overview of operation of a DEG. Likewise, Fig. 2 illustrates a stretched/deformed sample volume of a DEEC-Tec structure with sections removed to reveal the layers of DEECs and their respective power conductors and interconnects.

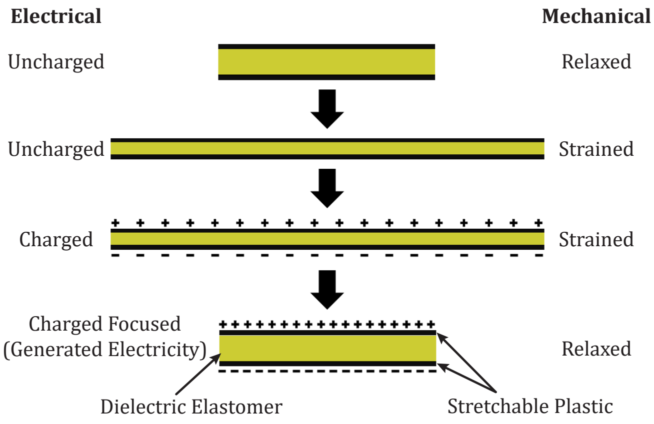

Fig. 1. An example DEEC generator transducer, : a dielectric elastomer generator. This figure illustrates the general modes of operation for such a DEEC: uncharged-relaxed, uncharged-strained, charged-strained, and charged-focused-relaxed. This sequence represents the dynamic straining and corresponding charging of this transducer [7]. DEGs leverage variable capacitance to harvest dynamic strain energy and convert portions of that energy into electricity. In whole, DEGs take an initial applied electrical charge and then amplify it through application of mechanical energy (the dynamic strain energy). The net gain of the resulting focused charge is then converted energy—the generated electricity.

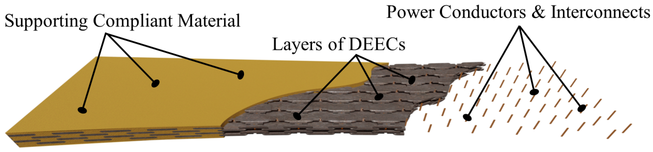

Fig. 2. A stretched/deformed sample volume of a DEEC-Tec structure illustrating basic use of DEECs to create such a structure. The sample volume has sections where material is removed to clarify their respective arrangements. (Left) the complete structure, including power conductors, interconnects, and layers of DEECs embedded within a supporting compliant material; (middle) supporting compliant material is removed revealing the layers of DEEC transducers; and (right) both supporting compliant material and layers of DEECs are removed, showing only the power conductors and interconnects that help link everything together. In sum, the figure showcases how the combined semi-continuous interconnected nature of DEECs can produce a deformable DEEC-Tec structure.

An individual DEEC is not merely a small transducer converting one form of energy into another, but also a linkage to interconnect and/or build upon with other DEECs—thereby creating a larger DEEC-Tec structure. Therefore, design, development, and implementation of the needed DEEC interconnections can be facilitated by leveraging several extant manufacturing methods. These methods include (1) direct embedment fabrication of DEECs into compliant substrates—similar to lithography etching techniques; (2) creation of singular strands of DEECs, or fiber-like tows, made of sequentially linked DEECs that could then be woven into cloths or fabrics; and (3) roll-to-roll assembly processes that are often found within the paper and plastic printing industries. Moreover, there are likely many nonexisting methods that could be directly developed to produce the needed interlinking of DEECs—much of which will likely leverage the more burgeoning contemporary fields of modern automated manufacturing techniques such as fused deposition modeling, stereolithography, and multi-filament/material additive manufacturing.

A key feature of any DEEC-Tec structure is its inherent ability to harvest and convert external sources of energy throughout the entirety of its structure. In other words, where those individual DEECs are being dynamically strained due to their host structure being acted upon by external energy sources, then those individual DEECs themselves will directly harvest and covert their portion of that external energy in situ. This means that wherever and whenever an underlying DEEC generator transducer, , or a DEEC bidirectional transducer, , is actively being distorted, twisted, flexed, or deformed (i.e., dynamically strained), then that energy will be harvested and converted within that immediate specific DEEC's location. In this way, DEEC-Tec structures: (1) do not depend upon whole device collection and concentrating of external energy sources—e.g., ocean wave energy, (2) do not depend upon focusing energy through a centralized delivery system, and (3) do not depend upon transmitting energy through a singular conversion system.

Moreover, through use of DEEC actuator transducers, , and/or bidirectional transducers, , there is the ability to alter an entire DEEC-Tec structure's morphology—enabling the ability for a DEEC-Tec structure to adapt its shape and form toward optimal operational effectiveness (e.g., per variable environmental conditions). Fig. 3 illustrates the principal manner of operation that DEEC-Tec structures utilize to harvest-convert an external energy source—dynamically straining its DEECs to convert portions of that external energy into something else (e.g., electricity) at each DEEC location, in situ, within such a DEEC-Tec structure.

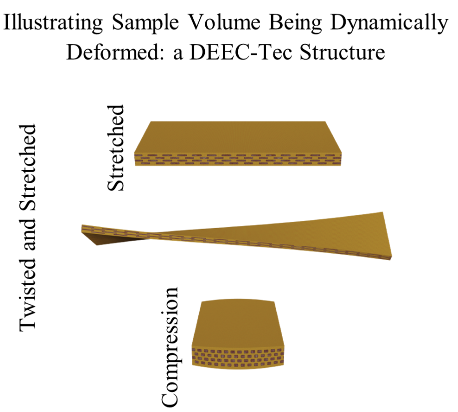

Fig. 3. Principal manner of operation, illustrating a sample volume of a DEEC-Tec structure (see Fig. 2) being dynamically deformed by some external source of energy, thereby enabling the sample volume's numerous interconnected DEECs to harvest and convert the external source of energy into a more usable form, such as electricity.

These aforementioned features of DEECs and their resulting DEEC-Tec structures create an energy harvesting-converting structure that is inherently redundant. If groups of DEECs fail, then there would still be other groups of functioning DEECs that could allow the overall DEEC-Tec structure to maintain the majority of its purpose and function. Likewise, these features also inherently circumvent the need for singular funneled concentrated power transmission, thereby avoiding singular transmission chains that could otherwise be required to endure extreme loadings and/or be bottlenecks in terms of both harvesting and converting an external source of energy. In other words, DEEC-Tec structures have no need to focus harvested energy into mechanisms like a gearbox, a rotational generator, or a hydraulic piston.

Ultimately, the DEEC-Tec domain is centered upon the interconnection of DEECs—the amalgamation of various transducer types—to create DEEC-Tec structures that can convert external sources of energy into more usable forms (e.g., electricity) throughout that resulting, aggregated, DEEC-Tec structure.

III. FlexWECs

Those DEEC-Tec structures designed specifically for harvesting and converting ocean wave energy can be called flexWECs, a portmanteau word representing: (1) the compliant nature of DEEC-Tec structures and (2) the structure's designed purpose for harvesting and converting ocean wave energy. Although research into the flexWEC domain is still nascent, it nevertheless stands to be a disruptive step change away from the status quo and current state of the art for harvesting and converting ocean wave energy into more usable forms. Hence, research into the flexWEC domain enables a new opportunity—a paradigm shift—in not only how developers might conceptualize ocean wave energy converters, but also how ocean wave energy, as a whole, is viewed and evaluated as a viable source of renewable energy.

FlexWECs expand the landscape of possibilities for ocean wave energy harvesting and conversion. FlexWECs accomplish this by: (1) avoiding dependence upon large monolithic rigid bodies, (2) avoiding dependence upon singular forms of power transmissions (e.g., drive shafts, gearboxes), and (3) avoiding dependence upon a solitary power conversion and generation systems (e.g., a rotary generator or a hydraulic generator/pump). Moreover, flexWECs can harvest and convert ocean wave energy wherever and whenever any of its distributed embedded energy converters (DEECs) are actively being deformed by ocean wave energy. In this way, a flexWEC's DEECs that are generator transducers, , and/or bidirectional transducers, , that can directly harvest and convert ocean wave energy—in situ—into more usable forms wherever they are being dynamically strained by that ocean wave energy. Additionally, a flexWEC's actuator transducers, , can actively help to adapt a flexWEC's form and function for optimal performance per a given wave state (e.g., small vs. large ocean waves) or mode of operation (e.g., adapting to seasonal weather, maintenance schedules, failure to some groups of DEECs).

Given the aforementioned properties, a flexWEC structure need not be entirely grossly actuated by ocean wave energy for effective harvesting and conversion to occur. FlexWEC structures could be designed to actuate, move, and gesticulate in very different manners dependent upon, for example, the type of encountered ocean wave environment. In this way, flexWECs have the inherent possibility to be highly effective harvesters and converters of ocean wave energy across a wide bandwidth of wave amplitudes and frequencies and, likewise, across a wide bandwidth of circumstances and operational conditions. In realizing this ability, it is helpful to recognize that it could be, in large part, the ocean wave environment itself that is directly dictating a flexWEC's form of function—for example, altering the flexWEC's compliant structure into "operational modes" highly optimized per an encountered ocean wave environment.

In general, the optimized operational modes are made possible by way of the flexWEC's topology and/or morphology. A flexWEC's topology is its general geometric shape and form. A flexWEC's morphology is its structure's changeability—its ability to alter specific aspects of its shape and form. These topological and morphological alterations could, for example, occur: (1) naturally, by way of how a flexWEC's gross physical structure is designed to "passively" respond to various types of ocean waves; (2) artificially, by way of how a flexWEC "actively" responds to various types of ocean waves via direct control of its transducers (, , and); or (3) by an implementation of both 1 and 2—likely the norm of most flexWEC topological and/or morphological alterations.

FlexWECs are true amalgams of distributed embedded energy converters (transducers: , ,), manufacturing methods (techniques needed to construct the distribution and embedment of transducers to create structures), and control strategies (enabling operational modes for optimal device performance). Given this amalgamation, the flexWEC domain grants developers the ability to conceptualize ocean wave energy converters that heretofore have never been possible; converter designs with nearly complete control over their topologies and morphologies. As a result, not only are there many distinct possible flexWEC designs and archetypes, but there are likely innumerable topologies and/or morphologies that those archetypes could employ. Fig. 4 illustrates three possible representative flexWEC archetypes—flexWECs that are, by no means, comprehensive in representing every possible design, but are, nevertheless, showcasing some possibilities for flexWEC concepts.

A. Preexisting technologies and methodologies

Design and development for flexWEC topologies (their gross shape and forms) and morphologies (their compliant and flexible characteristics)—via coordinated distribution and embedment of the many small energy converters (DEECs)—is a vast and open area of research. Nonetheless, such research and development can leverage several preexisting technologies and/or methodologies such as soft robotics, compliant mechanisms, origami mechanics, inflatables, and metamaterials. In whole, these preexisting technologies need not be conclusive nor thoroughly useful for conceptualizing flexWEC designs. They are, nevertheless, insights into the current state-of-the-art that can directly accelerate development of overall flexWEC research.

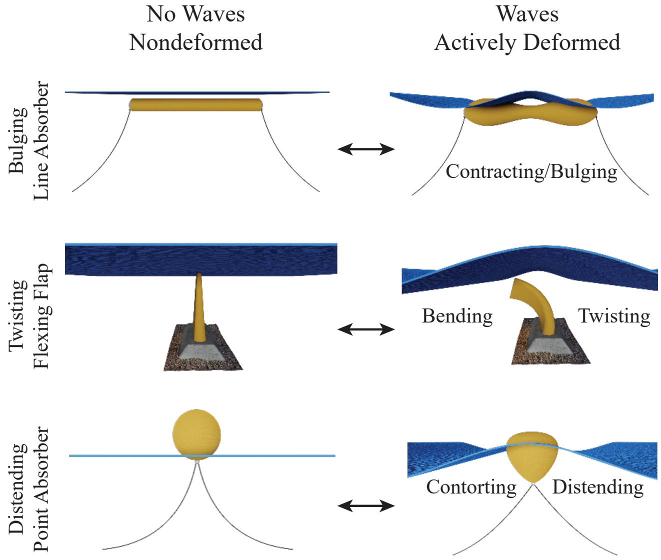

Fig. 4. Three possible FlexWEC archetypes showcasing the dynamically deformed states of flexWEC structures. The yellow flexible bodies of each archetype represent the DEEC-Tec structures illustrated in Fig. 2 and Fig. 3. (Note that these flexWEC archetype figures and scenes are solely illustrative and not to scale.)

1) Soft robotics: This technology domain centers upon non-rigid-body actuators. The applicability of soft robotics in support of flexWEC advancement stems from the notion of "reverse power flow." Namely, the actuators in soft robotics are merely transducers converting electrical signals into actuation and could, therefore, conceivably be used in reverse; absorbing some external energy through its actuators and generate electricity from it. Thus, by reversing the power flow used by soft robotic actuator designs, one has a means to investigate soft robotic technologies explicitly for the purpose of flexWEC development. One particular soft actuator already identified as promising for flexWECs are HASEL actuators [8]–[10].

2) Compliant mechanisms: This technology domain develops structures, often bio-inspired, designed to perform functions without the need of rigid-body or discrete joints [11]–[15]. Applying the compliant mechanism domain to advance flexWEC research, centers upon the inherent need for *flexible substructures* such that the individual DEECs of a flexWEC move relative to each other when the larger overall flexWEC structure is subjected to ocean wave energy.

3) Origami mechanics: This technology domain uses properties of foldable patterns to create mechanical structures and systems [16], [17]. Applying origami mechanics into the domain of flexWECs would likely give focus into how such structures can morph from one mode of operation (e.g., a mode for flexWEC shipping, transport, and deployment) into another mode (e.g., a mode for standard ocean energy harvesting-converting or, even, a survival mode for enduring excessive large energetic ocean wave environments). Ostensibly, there is a strong synergy between distributed groups of DEEC transducers (that make up a flexWEC's overall structure) and how that resulting structure can be manipulated—by those distributed/arranged groups of DEECs that can, therefore, create foldable origami patterns—patterns that can enhance operational modes and, in general, the overall efficiency of ocean wave energy conversion. In short, origami mechanics—coupled with actively controlled DEECs—could readily enable a flexWEC to alter (fold or unfold by some amount) its topology, in real time, to increase its operational effectiveness.

4) Inflatables: This technology domain leverages the expansion of fluids, contained within a barrier, to create structures [18]. The inflatable technology domain could facilitate the flexWEC domain in several ways, including: (1) because flexWECs are nominally compliant, inflatable technologies could provide the general flexible structure-substrate for DEEC application; this would also allow for collapsibility, thereby enabling ease of flexWEC transport and deployment; and (2) many inflatable chambers themselves could be the actual DEECs of a flexWEC—numerous distributed embedded inflated compressible chambers could be the direct means by which ocean energy is harvested (the resulting pressurized fluid/gas could be utilized to generate electricity or for desalination). Of particular note, a business incubator group known as "Otherlab"—an independent research and design laboratory—has developed inflatable technologies ranging from shelters to robotic arms [19].

5) Metamaterials: Metamaterials represent a domain within which developing structural properties is governed not by their material composition(s), but rather by way of said structure's layout, arrangement, and pattern [20]–[22]. The metamaterial domain could facilitate design and development of flexWECs by way of the metamaterial domain's ethos itself. In other words, flexWECs need not be viewed solely as some aggregated mixture of materials, nor would flexWECs be viewed as clumsy glued-together DEECs. Rather, flexWECs can leverage both the ethos and the actual technological know-how from the metamaterial domain to generate concepts that function intrinsically with multiple combinations of properties dependent upon how a flexWEC's structure is configured.

IV. Example

DEEC-Tec enables a very broad domain of possible ocean wave energy converters—much broader than what has historically been visited by WEC designers and developers. In this regard, it is important to recognize that: (1) there is no singular representative type of DEEC transducer, (2) there is no singular representative distribution type for those transducers to form DEEC-Tec structures, and (3) there is no singular representative type of flexWEC that can be created by those DEEC-Tec structures. Therefore, there are many possible types of DEECs, there are many possible types of DEEC-Tec structures and materials, and there are many possible types of flexWECs that could be created (by those varying types of DEECs and DEEC-Tec structural components). Ultimately, the DEEC-Tec domain centers itself upon the ideology of distributing and/or embedding many very small transducers to create larger building materials—DEEC-Tec structures—that can then, in turn, be used to create whole energy harvesting and converting devices, such as flexWECs.

With there being no particular manner in which one can leverage the DEEC-Tec domain to create flexWECs, there is therefore no representative amount of energy a flexWEC can harvest and convert per a given ocean wave energy resource environment. Likewise, there is no representative size any particular flexWEC structure could (or should) be for "cost-effectiveness," "performance-effectiveness," or "otherwise-effectiveness." Quantities such as ocean wave energy extraction rates, surface areas and/or volumes sizes for DEEC-Tec structures, and overall flexWEC environmental impacts would all be dictated (at minimum) by a particular flexWEC design, a corresponding purpose (e.g., utility grid-scale flexWECs vs. autonomous underwater vehicle-based flexWECs), and a corresponding ocean wave energy resource environment. Nevertheless, there is a company, SBM Offshore, that has developed a type of flexWEC from which one can reference and garner further insights into how distribution and embedment of energy converters can be accomplished.

SBM Offshore's "S3 device" is based upon a flexible tube that bulges and contracts as successive ocean wave troughs and crest pass by [23]. The S3 device utilizes transducers with a proprietary design that SBM Offshore calls "Electro-Active-Polymer" (EAP) generators [24]. SBM Offshore developed a *rudimentary proof-of-concept* small-scale version of the S3 device. The small-scaled S3 device was tube 11 meters long, by 40 centimeters in diameter, aramid fiber reinforced, with 25 of SBM Offshore's EAP generators wrapped around the tube and sequentially along the tube's length [24]. For this, the small-scaled S3 proof-of-concept, SBM Offshore evaluated it in a wave basin composed of irregular waves (significant wave height of 20 centimeters with peak period of 3 seconds) and measured a mean power output of approximately 0.45 watts [24].

V. Conclusion

FlexWECs are made from DEEC-Tec structures. These structures are composed of many small distributed embedded energy converters (also known as DEECs). DEECs are simple transducers that can leverage any number of physical phenomena to convert one form of energy into another (e.g., dynamic strain energy into electricity). How best to develop, co-design, and combine DEECs to create a DEEC-Tec structure that can then be used to create an effective ocean wave energy converter (to create an effective flexWEC) is still very much an unanswered question and an open area of research. However, it is thought that the degree to which one can engineer DEECs into an amalgam of materials suitable for a flexWEC's topology and morphology designs—leveraging preexisting technologies and methodologies—will determine how effective any given flexWEC's performance will be. Consequently, this work promotes the DEEC-Tec/flexWEC domain as a disruptive step change, in not only how we conceptualize and develop ocean wave energy converter designs, but also how we can newly consider the potential availability and viability of using ocean wave energy as a usable source of renewable energy.

Moreover, from industry, SBM Offshore already shows an exemplified application of DEEC-Tec for ocean wave energy harvesting and converting: SBM Offshore developed their S3 concept—a flexWEC that utilizes their SBM Offshore's special variety of DEEC transducers (EAPs) that are placed around (and along) a flexible buoyant tube [23]. The S3's primary means of ocean wave energy harvesting and conversion appears to be based upon the bulging and contracting of the aforementioned tube due to successive ocean wave troughs and crests that ultimately cause the dynamic deformation of the tube and corresponding EAPs (DEECs).

In the end, the key to the DEEC-Tec domain's potential, for its use to realize flexWEC concepts, is centered upon the distribution and embedment of many small energy converters (small transducers: , , and ). The DEEC-Tec flexWEC domains present many desirable features for ocean wave energy harvesting and conversion—features such as inherent redundancy, broad-banded ocean energy absorption, and ease of transport and deployment. Meaning, in this light, the DEEC-Tec flexWEC domains could revolutionize how ocean wave energy converters are conceptualized, developed and employed.

Acknowledgement

The author acknowledges the vision, advocating, and support from Jochem Weber—Chief Engineer, Water Power Program, National Renewable Energy Laboratory—crediting him for his guidance, insights, and impetus of this work, without which such research and development would not be possible. This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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