Distributed Embedded Energy Converter Technologies for Marine Renewable Energy: A Technical Report

Nicole Mendoza,* Blake Boren,* and James Niffenegger

National Renewable Energy Laboratory

**These are the first authors of this report, and they contributed equally to this work.*

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List of Acronyms

DEEC	distributed embedded energy converter
DEEC-Tec	distributed embedded energy converter technologies
FEA	finite-element analysis
FSI	fluid-structure interaction
HexDEEC	hexagonal distributed embedded energy converter
MEMS	micro-electro-mechanical systems
TENG	triboelectric nanogenerator
WEC	(ocean) wave energy converter

Executive Summary

The domain of distributed embedded energy converter technologies (DEEC-Tec) is a nascent and underexplored paradigm for harvesting and converting marine renewable energy. The paradigm distinguishes itself through its use of many small distributed embedded energy converters (DEECs) that, ultimately, are assembled through the creation of “DEEC-Tec metamaterials” to create an overall larger structure for harvesting and converting marine renewable energy. As an example, such a structure could be an ocean wave energy converter—an energy converter whose structure is made from various types of DEEC-Tec metamaterials that harvests ocean wave energy and converts that energy into something more useful such as electricity. To that end, DEEC-Tec can be viewed at three different levels of hierarchy: (1) individual distributed embedded energy converters, also known as DEECs; (2) DEEC-Tec metamaterials—essentially, pseudo-material-frameworks made from the interconnection of many DEECs; and (3) overall larger complete marine renewable energy harvesting-converting structures made from DEEC-Tec metamaterials.

DEEC-Tec Hierarchy Level 1: An individual DEEC is often no more than several centimeters in characteristic length and has both the role of energy transducer and structural mechanism. As an energy transducer, an individual DEEC leverages at least one physical phenomenon (e.g., Faraday’s law of induction, variable capacitance, piezoelectric effect, etc.) to convert external sources of energy into a desirable energy output such as electricity. As a structural mechanism, an individual DEEC houses and/or is part of the energy transducer and enables an interconnection and/or integration into other DEECs such that a pseudo-material is created—called a DEEC-Tec metamaterial.

DEEC-Tec Hierarchy Level 2: DEEC-Tec metamaterials are an aggregation and integration of many individual DEECs. DEEC-Tec metamaterials are the general building blocks that are used to create an overall marine renewable energy harvesting-converting structure. In this way, a DEEC-Tec metamaterial need not be composed of the same types of DEECs nor have the same layout/configuration of such DEECs throughout the metamaterial. In other words, DEEC-Tec metamaterials could include combinations of different DEEC types and be combined in different ways (e.g., layers vs. latices vs. embedded in substrates).

DEEC-Tec Hierarchy Level 3: An overall DEEC-Tec-based energy harvesting-converting structure is made from the assemblage of various DEEC-Tec metamaterials. A DEEC-Tec-based ocean wave energy converter, for example, is a specific category implemented at DEEC-Tec hierarchy level 3. This category—DEEC-Tec-based WECs—typically has two defining characteristics: (1) topology and (2) morphology. Specifically, topology is a DEEC-Tec-based WEC’s description of its general form and shape characteristics. And morphology is a DEEC-Tec-based WEC’s description of its deformable parameters such as stiffness, hysteresis, plasticity, etc.

Arising directly from the application of DEEC-Tec to harvest and convert ocean wave energy are several noteworthy benefits, some of which include (but not limited to): (1) the lack of load concentrations into singular components or subsystems, (2) broad-banded ocean wave energy frequency harvesting and conversion, and (3) inherent redundancy—failure of some individual DEECs does not represent failure of an entire DEEC-Tec-based WEC.

This report describes DEEC-Tec by way of descriptions of the above three hierarchy levels: individual DEECs, DEEC-Tec metamaterials, and DEEC-Tec-based WECs. Moreover, the report describes corresponding research approaches and methodologies for related concepts such as DEEC-Tec-based WEC topologies and morphologies in addition to manufacturing and fabrication techniques found suitable for

the application of DEEC-Tec within the *general* domain of marine renewable energy—moving beyond only ocean wave energy conversion.

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1 Introduction

Distributed embedded energy converter technologies (DEEC-Tec) is a domain that is relatively nascent and underexplored for marine energy conversion (Boren et al. 2019; Boren et al. 2020; Boren 2021). The domain is predominantly characterized by the construction of larger energy harvesting-converting structures through the distribution and/or embedment of numerous smaller energy transducers. These small energy transducers are the distributed embedded energy converters (DEECs) making up the grounding foundation and ethos that *is* the DEEC-Tec domain.

At a high level, individual DEECs could convert energy sources—directly or indirectly—such as motions, forces, moments, pressures, thermal gradients, ion gradients, etc. into other more desirable energy forms such as electricity or fluidic pressures (e.g., for desalination, reflow batteries). Thus, being the basic building block of DEEC-Tec, these individual DEECs represent the first hierarchy level of the DEEC-Tec domain. When many individual DEECs are combined, then a DEEC-Tec metamaterial is created. Such metamaterials are the second hierarchy level of the DEEC-Tec domain. DEEC-Tec metamaterials, in turn, are used to construct larger overall energy conversion structures. When used to harvest and convert ocean wave energy, the created structure can be called a DEEC-Tec-based wave energy converter (WEC). Figure 1 gives an overview and description of the DEEC-Tec hierarchy levels in terms of a DEEC-Tec-based WEC made from DEEC-Tec metamaterials. Likewise, Figure 2 gives a pictorial overview and example of those hierarchy levels being applied to form an actual DEEC-Tec-based WEC design: a bottom-fixed surging flexible WEC, or flexWEC.

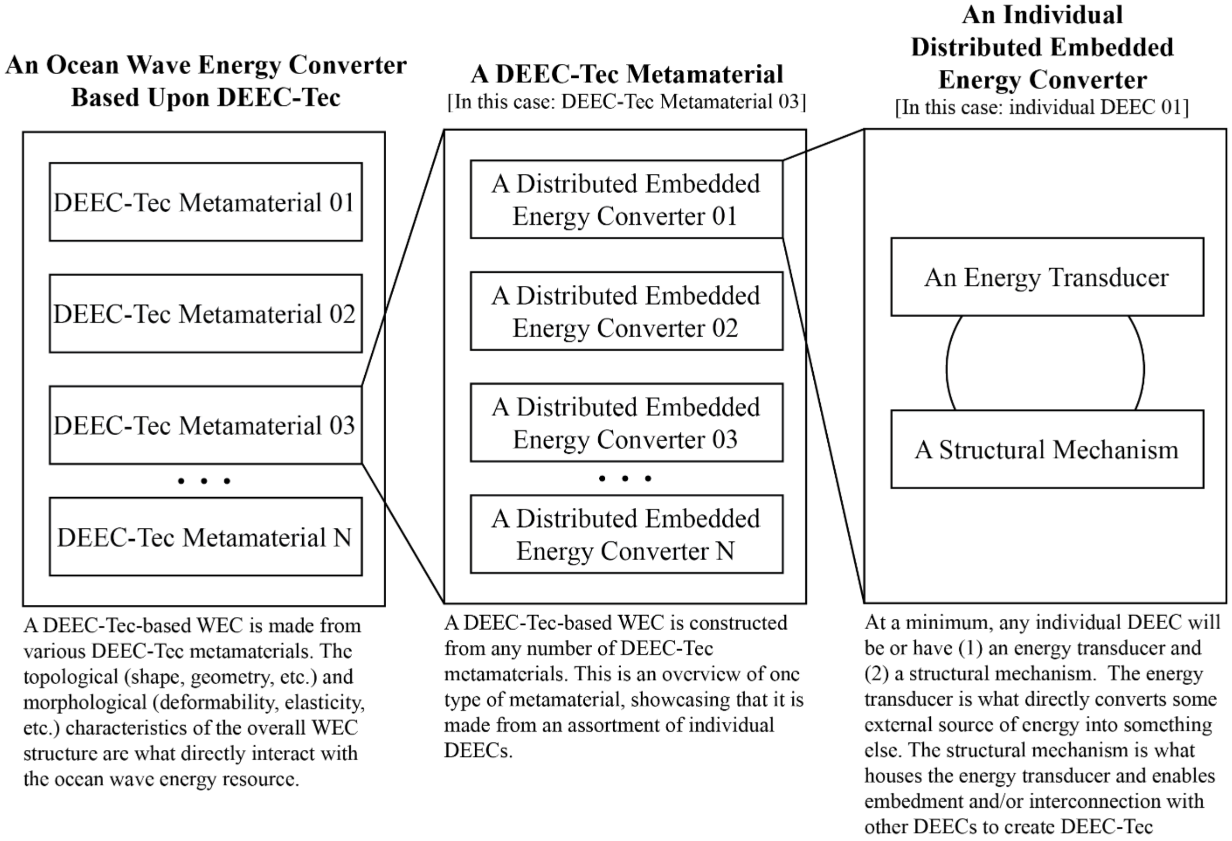


Figure 1: An overview of the DEEC-Tec domain as applied to ocean wave energy conversion, demonstrating the three hierarchy levels of the DEEC-Tec domain

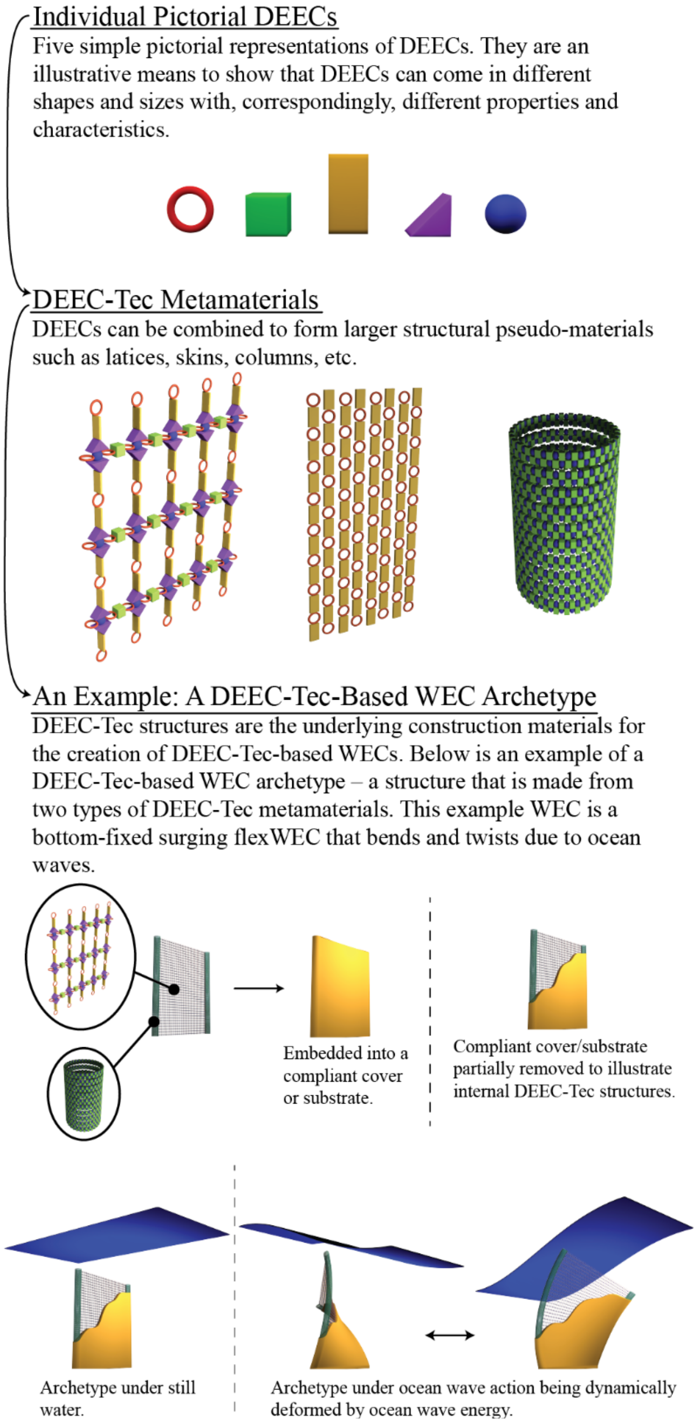
DEEC-Tec-based WECs inherently do not concentrate harvested energy into a singular generator, prime mover, or a lone power take-off system. Moreover—and of note—DEEC-Tec-based WECs can be constructed from one or more types of individual DEECs and, correspondingly, various types of DEEC-Tec metamaterials. Arising from such inherent qualities, the DEEC-Tec domain provides DEEC-Tec-based WECs with some of the following advantages:

- Supports broad-banded energy capture
- Has built-in mechanical redundancy
- Eliminates force and load concentrations into singular forms of energy transmission (e.g., a single rotary generator or hydraulic piston system)
- Removes the need for large, highly loaded, monolithic rigid bodies.

Many of these advantages could minimize the need for maintenance, lower the operations and maintenance costs, and extend the operational lifetime of an overall DEEC-Tec-based WEC than what would otherwise be possible. Likewise, when using DEEC-Tec for marine renewable energy, the following advantageous characteristics and abilities are possible:

- Resilient (e.g., failure of a few DEECs does not mean failure of the entire DEEC-Tec-based WEC)
- Can directly employ favorable materials
- Near-continuous structural control
- Easier installation
- Reduced maintenance.

In this way, DEEC-Tec offers a paradigm shift in how ocean wave energy conversion can be conceptualized by way of the employment and amalgamating of many smaller distributed energy converters, which are then aggregated to form a DEEC-Tec metamaterial, which is used to build an ocean wave energy converter structure—also known as a DEEC-Tec-based WEC. The following sections describe research methodologies needed for the application of DEEC-Tec into the domain of marine renewable energy, especially in terms of ocean wave energy conversion.



Five simple pictorial representations of DEECs. They are an illustrative means to show that DEECs can come in different shapes and sizes with, correspondingly, different properties and characteristics.

DEECs can be combined to form larger structural pseudo-materials such as latices, skins, columns, etc.

DEEC-Tec structures are the underlying construction materials for the creation of DEEC-Tec-based WECs. Below is an example of a DEEC-Tec-based WEC archetype – a structure that is made from two types of DEEC-Tec metamaterials. This example WEC is a bottom-fixed surging flexWEC that bends and twists due to ocean waves.

Figure 2. A pictorial overview and example of hierarchy levels being applied to form an actual DEEC-Tec-based WEC design: a bottom-fixed surging flexWEC

2 Research Methodologies for Individual DEECs

Designs of individual DEECs—and corresponding development strategies—will enable effective energy conversion and interconnections with other DEECs. In pursuit of such designs, it is helpful to explicitly state what an individual DEEC is:

> **<u>Distributed Embedded Energy Converter (DEEC)</u>** – *a relatively small energy transducer (often having a characteristic length of a few centimeters) that converts one or more form(s) of energy into another form of energy and also serves as a structural mechanism by which other DEECs can be connected to and interact with—this interconnection ultimately forms a DEEC-Tec metamaterial.*

Individual DEECs represent the first hierarchy level of the DEEC-Tec domain. Individual DEECs can use a variety of physical phenomena to convert (transduce) one form of energy (such as dynamic mechanical strain) into another form of energy (such as electricity). Therefore, it is fundamental to model a potential DEEC design's ability to respond to different forms of dynamic mechanical strain caused by external loading. From those DEEC design concepts found most effective for their corresponding role as an energy transducer (e.g., by evaluation of their efficiencies, material usage, power densities, and robustness), prototype DEECs can be manufactured and experimentally evaluated and characterized.

A DEEC has two primary functions: energy transducer and structural mechanism.

2.1 Energy Transducer

The energy transducer mechanism of a DEEC converts some input energy (motion, forces, moments, general deformations, etc.) into a more desirable output energy type (e.g., electricity to power electronics or fluidic pressures for desalination of water). The implementation of such energy transduction could be enabled by any number of physical phenomena. Some of the main candidates for such physical phenomena include but are not limited to:

- Faraday's law of induction
- Variable capacitance
- Piezoelectric effect
- Triboelectric effect
- Microfluidic power (microhydraulics and micropneumatics)
- Magnetostriction
- Micro-electro-mechanical systems (MEMS)
- Thermoelectric effect.

Following are brief descriptions of those physical phenomena.

2.1.1 Faraday's Law of Induction

If a changing magnetic field occurs by way of some applied external source of energy—while being in range of an electrical conductor—then an electromotive force will be induced into that electrical conductor and electricity will be generated. The advantages and disadvantages vary depending on how Faraday's law of induction is used:

Advantages

- No external voltage source required (Wang and Yuan 2008)
- Relatively inexpensive and well-known power electronics (Pelrine et al. 2001).

Disadvantages:

- Likely more appropriate for large-scale systems (Invernizzi et al. 2016)
- Most implementations result in efficiency reductions as scale is reduced—for example, dielectric gaps become difficult to maintain (Invernizzi et al. 2016)
- Overall lower energy density (Kornbluh et al. 2011).

2.1.2 Variable Capacitance

If a capacitor's capacitance is varied by way of some form of external energy, then portions of that external energy can be converted into electricity.

Examples of variable capacitors include dielectric elastomeric generators (Invernizzi et al. 2016; Pelrine et al. 2001; Kornbluh et al. 2011), ionic electroactive polymers (Invernizzi et al. 2016), reverse electrowetting devices (Invernizzi et al. 2016), and hydraulically activated self-healing electrostatic actuators (Kellaris et al. 2018). The advantages and disadvantages vary among the different implementations of variable capacitance-based energy transducers.

Dielectric Elastomeric Generators

Advantages

- Can be used under large activation forces (Invernizzi et al. 2016; Kornbluh et al. 2011)
- Can use low-cost *non*-rare earth materials (Kornbluh et al. 2011)
- Can have higher energy densities than piezoelectric or electromagnetic systems (Invernizzi et al. 2016; Murray and Rastegar 2009).

Disadvantages

- More complex and expensive to control/implement corresponding power electronics (Kornbluh et al. 2011; Pelrine et al. 2001)
- Need high input voltage to create very strong electric fields near dielectric breakdown limit (Invernizzi et al. 2016)
- Shorter lifetimes for large film areas (e.g., dielectric breakdown) (Kornbluh et al. 2011)
- Risk of dielectric breakdown increases with larger electrode areas (Kellaris et al. 2018).

Ionic Electroactive Polymers

Advantages

- Work directly under wet conditions (Invernizzi et al. 2016)
- Need low activation voltage (avoids risk of dielectric breakdown) (Invernizzi et al. 2016).

Disadvantages

- Slow response and require electrolytes (Invernizzi et al. 2016)
- Require protection against component evaporation to operate in ambient conditions (Invernizzi et al. 2016).

Reverse Electrowetting Devices

Advantages

- Potential to produce very high-power densities (Invernizzi et al. 2016)
- Can use a wide range of forces and displacements as energy inputs (Invernizzi et al. 2016)
- Can produce power across a broad range of currents and voltages without up or down conversion (Invernizzi et al. 2016).

Disadvantages

- Require a bias voltage (Invernizzi et al. 2016)
- Research is still needed to isolate those dielectric materials with both high permittivity and high dielectric breakdown strength while also able to withstand large mechanical stresses (Invernizzi et al. 2016)
- Perform best using toxic liquid metals (Invernizzi et al. 2016).

Hydraulically Activated Self-Healing Electrostatic Actuators

Advantages

- Composed of low-cost materials and can be developed via standard low-cost manufacturing processes (Kellaris et al. 2018)
- Fast response to stimuli (Kellaris et al. 2018)
- Do not require highly stretchable electrodes (Kellaris et al. 2018)
- Self-healing after a dielectric breakdown.

Disadvantages

- Currently designed as energy transducers for actuation rather than energy transducers for electricity generation (Kellaris et al. 2018)
- Require high voltage (highly charged electric fields) and materials with high dielectric breakdown strengths (Kellaris et al. 2018).

2.1.3 Piezoelectric Effect

Some substances (mainly crystalline materials), when subjected to an applied dynamic external force, will produce an electromotive force; the piezoelectric substance will generate electricity when actively strained.

Advantages

- High energy density (Invernizzi et al. 2016)
- Ease of fabrication (Invernizzi et al. 2016)
- No external voltage source required for operation (Wang and Yuan 2008).

Disadvantages

- Some forms of piezo-crystals, can be brittle, especially with aging (Wang and Yuan 2008)
- Constituent piezoelectric substances (the piezo crystal and supporting electrodes) can be rather expensive and are often composed of toxic materials (Kornbluh et al. 2011)
- Typically has high output impedance and can leak electrical charge (Wang and Yuan 2008; Invernizzi et al. 2016).

2.1.4 Triboelectric Effect

The triboelectric effect occurs when certain materials become electrically charged after they have been in physical contact with and subsequently separated from another, different material. The common phenomenon of static electricity is an example of triboelectricity. It is an electrostatic attraction, not chemical bonding, that yields an electromagnetic force. The greater the surface contact, the greater the resulting net charge will be. Some commonly used triboelectric materials span a wide range of polymeric, metallic, and inorganic materials, such as nylon, polytetrafluoroethylene (PTFE), wool, polyvinyl chloride (PVC), polyethylene terephthalate (PET), fluorinated ethylene propylene (FEP), and many more.

The fundamental phenomena—converting relative motion (contact and separation) between two different dielectric materials (micromechanical energy) into electricity—is both applicable and relevant for DEEC-Tec-based transducers. One type of actuator that employs the triboelectric effect is the triboelectric nanogenerator (TENG). Wang et al. (2021) have claimed the possible feasibility of TENGs for wave energy conversion. The overall device configuration, described mainly by its topology and morphology, varies considerably across the published literature. Some examples of triboelectric materials in different configurations include tower, whirling-folded, and seaweed-like arrangements (Wang et al. 2021) as well as swing, buoy, and book configurations.

Advantages

- Potential advantages in harvesting relatively low-frequency energy (Wang et al. 2021)
- Simple structure, low cost, lightweight, robust (Wang et al. 2021)
- Applicable and relevant in low-energy wave energy resources.

Disadvantages

- Considerations regarding matching wave resources to material properties
- Material durability and degradation, survivability in extreme weather events
- Relatively low power density.

2.1.5 Microfluidic Power

Originating from the biological world of cardiovascular systems and osmotic pressure phenomena, this transducer mechanism centers itself upon hydraulic and/or pneumatic concepts at a micro (or nano) scale. These systems involve an actuator system to pump fluid through energy harvesters (De Volder and Reynaerts 2010; Raisigel et al. 2005; Nguyen et al. 2013). The actuators can be made of elastic membranes, balloons, or bellows (De Volder and Reynaerts 2010). Alternatively, small hydraulic or pneumatic piston cylinders can be used (De Volder and Reynaerts 2010). When a force is applied to these pressurized actuators, they flow fluid past either microturbines (that connect to electromagnetic generators and are hard to manufacture) or bluff bodies that induce Karman vortices whose pressure fluctuations oscillate piezoelectric or electromagnetic generators (Raisigel et al. 2005; Nguyen et al. 2013). Since the energy-generating methods rely on previously discussed phenomena, the advantages and disadvantages of the actuator methods are discussed below.

Elastic Actuator

Advantages

- Easy to fabricate (De Volder and Reynaerts 2010)
- No leakage issues, wear, or friction (De Volder and Reynaerts 2010).

Disadvantages

- Trade-off between stiffness and force output (De Volder and Reynaerts 2010)
- Lower power density and stroke length than those of piston cylinder actuators (De Volder and Reynaerts 2010).

Piston Cylinder Actuator

Advantages

- Large stroke length (De Volder and Reynaerts 2010)
- Can produce high velocities and actuation forces (De Volder and Reynaerts 2010).

Disadvantages

- More difficult to manufacture (De Volder and Reynaerts 2010)
- Require proper sealing, which is still under development (De Volder and Reynaerts 2010).

Applied Examples of Microfluidic Power

- *Microhydraulic power*: The working fluid is an incompressible liquid, such as water, oil, etc.
- *Micropneumatic power*: The working fluid is a gas, such as compressed air.
- *Flow batteries*: A flow battery typically consists of two tanks of liquids separated by a membrane where the fluids are pumped through the system. Employing the working fluid in a flow battery could add new capabilities while minimizing additional complexity.
- *Energy storage*: The working fluid can also be used as a form of energy storage, such as compressed air energy storage and pumped hydropower.
- *Combinations*: Any combinations of these principles and applications could produce higher-performing, higher-potential devices when integrated together.
- *Others*: The working fluid can perform a number of other innovative tasks, including those not specified herein.

2.1.6 Magnetostriction

Magnetic materials, when actively strained by some applied dynamic external force, will pivot and shift their internal magnetic domains, which are nominally aligned. The pivoting and shifting of the internal magnetic domains can create a changing magnetic field, from which the aforementioned physical phenomenon, Faraday's law of induction, can be leveraged to generate an electromotive force within an electrical conductor, thereby generating electricity.

Advantages

- No depolarization or aging (Wang and Yuan 2008; Deng and Dapino 2017)
- High flexibility and mechanical strength (Wang and Yuan 2008; Deng and Dapino 2017)
- Low output impedance (Deng and Dapino 2017).

Disadvantages

- Highly nonlinear (Deng and Dapino 2017; Wang and Yuan 2008)
- May need bulky bias magnets and pickup coils (Deng and Dapino 2017; Wang and Yuan 2008).

2.1.7 Micro-Electro-Mechanical Systems

MEMS are microscopic (or nanoscale) devices that use electricity and/or micromechanical to nanomechanical systems. Essentially, MEMS are very small machines, with those machines being any number of micro- to nano-sized versions of their larger everyday counterparts (e.g., links, motors, generators, actuators, hydraulic pistons/cylinders). Indeed, the other listed transducer mechanisms could all be (or be a member of) some MEMS.

Transducers Compatible With MEMS

- Variable capacitance (Wang and Yuan 2008)
- Piezoelectric (Wang and Yuan 2008)
- Microfluidic (De Volder and Reynaerts 2010; Nguyen et al. 2013; Raisigel et al. 2005).

Transducers Difficult To Integrate Into MEMS

- Electromagnetic (Faraday's law) (Wang and Yuan 2008)
- Magnetostriction (Wang and Yuan 2008).

2.1.8 Thermoelectric Effect

The thermoelectric effect is the direct conversion of a temperature gradient into a voltage potential. Moreover, the effect can be reversed—an applied voltage potential can create a temperature gradient. The thermoelectric effect is commonly used in measurement devices such as thermocouples, hot wire anemometers, and automotive thermoelectric generators. In general, the greater the temperature gradient, the greater the voltage potential generated, and vice versa.

Like both the piezoelectric and triboelectric effects, certain classes of materials exhibit thermoelectric properties in various ways, with, correspondingly, varying degrees of effectiveness. Some examples of thermoelectric materials include bismuth telluride alloys and other metallic alloys that often contain lead tellurides, silicone-germanium, tin selenide, magnesium compounds, and others.

When used for ocean wave energy conversion, the thermoelectric device generates electricity from the temperature gradients present in the marine environment (e.g., the entire water column, the water-air interface, the thermal ocean wave particle orbitals). To maximize the conversion efficiency, large temperature gradients are required, which in turn typically require a cold reservoir.

A notable example of such thermal gradients would be ocean thermal energy conversion of an ocean water column. In this example, a mechanism would be implemented to draw/pump colder water from deeper in the ocean's water column than the warmer ocean water near or at the surface. Alternatively, a thermoelectric system could use the temperature gradient above and below the surface of the water in warm regions with cold ocean water (e.g., Southern California), or use wave motion to generate cavitation bubbles and convert the heat generated by these phase changes (Gevari et al. 2019).

Advantages

- Reduced complexity; no moving parts
- Convert waste heat to energy, thus making the overall system more efficient.

Disadvantages

- Cold reservoir must stay cold (maintain temperature, avoid heat transfer)
- Low efficiencies and performance at low temperature differences
- Expensive and strong potential for use of exotic rare earth materials (e.g., platinum and palladium).

The various energy transducers based on the thermoelectric effect can differ significantly in their corresponding ranges of frequencies, stresses, strains, etc. Depending upon how well such thermoelectric effect energy transducers match ocean waves, they may have relatively strong advantages or disadvantages. (Jbaily and Yeung 2015; Collins et al. 2021).

2.2 Structural Mechanism

A DEEC's structural mechanism often facilitates interconnecting (and interfacing) with other DEECs, either directly or indirectly. A DEEC's structural mechanism often has a key role in the creation of the second hierarchy level of the DEEC-Tec domain: DEEC-Tec metamaterials. In this manner, the structural mechanism primarily accounts for the transfer of loads, power, and communications between neighboring DEECs. Overall, a DEEC's structural mechanism can serve several functions ranging from the provisioning of interconnection with other DEECs to the housing of a DEEC's transducer mechanism and interconnection with other subsystems.

There are different types of mechanical, chemical, and physical interfaces and connections that are suitable for interconnecting homogenous or heterogenous types of DEECs. Some examples are:

- Mechanical joints and connectors (e.g., flanges, fins, bolts/screws, nails)
- Chemical bonds (e.g., adhesives, thermoplastic welding)
- Fabric processing (e.g., weaving, twisting, braiding)
- Layering (e.g., sandwich structure)
- Folding (e.g., origami).

2.3 Functional Requirements

In addition to acting as an energy transducer and structural mechanism, a DEEC must possess additional characteristics to have high techno-economic, environmental, and social potential:

- Be survivable and durable
- Have minimal environmental and social impacts and maximal environmental and social benefits
- Have minimal risks: does it require a new material or new/underdeveloped method or process that does not yet exist?

2.4 Numerical and Computational Methodologies for Individual DEECs

There are many applicable and relevant numerical methods for designing and studying individual DEECs. The following subsections are not a comprehensive list but rather identify research tools and methods found to be insightful and useful for most DEEC energy transducer mechanisms and/or DEEC structural mechanisms.

2.4.1 Electric-Fluid-Structure Interactions

Numerical modeling of fluid-structure interactions (FSI) would likely be a key (and even necessary) component of DEEC development, given their multiphysics nature. Moreover, when electricity is the output of a DEEC's operation, the FSI modeling becomes electric-fluid-structure-interaction modeling. Many textbooks have been written describing the assortment of algorithms, boundary conditions, and methods needed to model such multiphysics phenomena.

2.4.2 Digital Twins and Hardware in the Loop

There are numerical tools that can create digital twins (or virtual models) of real-time actuators, sensors, and generators. If a digital twin involves direct interaction with hardware (that is likely a facsimile of an actual completed product), then the numerical tool can be called hardware-in-the-loop modeling.

2.4.3 Finite-Element Analysis

Finite-element analysis (FEA) tools have been extensively developed and used in a wide variety of industries. FEA tools perform complex structural and mechanical calculations over complex geometries subject to various loads to generate structural quantities (strain, stress, fatigue, etc.) used in design. FEA is often a core component of the FSI and electrical-fluid-structure interaction numerical methods.

2.4.4 Concluding Thoughts – Research Methodologies for Individual DEECs

There are likely numerous manners in which an individual DEEC could be conceptualized; such broadness is thought to be a major advantage for the DEEC-Tec domain's application into the realm of marine renewable energy. Overall, this section presents a series of available and relevant options for individual DEEC research and development. However, the section's contents should not be regarded as comprehensive because they do not present an exhaustive list of every research method for individual DEEC development; rather, the section lists methods found strongly relevant via the examinations of case studies and expected applications of established technology domains such as soft robotics, MEMS applications, etc. Likewise, it should be clear that there is a need to directly link a DEEC's initial conceptualization and innovation with its numerical and simulated developments. DEEC designs should be assessed concurrently via numerical modeling.

Furthermore, it should be noted that there are a variety of software packages and tools that can be used to assess the response of a conceptualized DEEC. For example, SolidWorks can be used to create solid models of DEECs while SolidWorks Simulation can be used for basic static and dynamic FEA. In similar fashion, the software package Abaqus can also be used for FEA and has strengths for evaluating large deformations and properties of nonlinear or hyperelastic materials. ANSYS can also be used for FEA. For FSI and general multiphysics simulations, Star-CCM+ is a good option for DEEC developments.

Ultimately, the ability to numerically model largely nonlinear materials, coupled with multiphysical domains (fluid, structure, electromagnetism), would be used with corresponding empirical efforts and with cross-validation, experimentation, and well-rounded characterization of DEEC concepts. The next section links the analytical and theoretical innovation phases for individual DEECs with their empirical counterparts.

2.5 Experimental and Empirical Methodologies for Individual DEECs

Experimental and empirical efforts for individual DEEC research should involve the characterization of a DEEC's material(s) usage, supplement a DEEC's numerical models, and assess a DEEC's general performance metrics (power density, efficiencies, fatigue life, etc.).

To empirically characterize a DEEC's material properties, one should implement static, dynamic, and fatigue testing systems; rheology testing systems; torsion testing systems; and thermal testing systems, among others, as appropriate for the type of DEEC. The listed material characterization types are not exhaustive; some materials could very well have more nuanced or niche types of characterizations such as ultrasonic testing, thermal imaging (inferred thermography), and/or digital image correlation.

Notably, digital image correlation appears to be well suited for many individual DEEC concepts, as it encompasses many of the deformation features that individual DEECs would encounter and engage in (e.g., highly three-dimensional dynamic straining). Digital image correlation analyzes the displacement of randomized markers on a surface to determine strain. This method can be implemented with black spray paint on the material or DEEC with a white background, or it can employ other visual cues.

Of course, those experimental and empirical methods for individual DEEC research will require physical DEECs to be created or acquired. Such DEEC prototypes could be made through a variety of methods, some of which are discussed in Section 5. Individual DEEC designs should correspond to the relevant numerical models as listed in the previous section, thereby enabling a proper comparison between the experimental/empirical individual DEEC results and their numerical/analytical results.

The survivability of the different DEEC designs should also be directly assessed, aiming toward understanding their lifespans and possible rates of performance degradation over time. To this end, fatigue testing can be done with various load frames on materials used in the DEECs and on the DEECs themselves. Moreover, for DEECs directly exposed to seawater, tests should be conducted to assess the need for and performance of marine protective coatings around the DEECs. In like manner, DEECs that will be directly exposed to the sunlight should be evaluated against laboratory ultraviolet radiation to characterize how they will perform under extended ultraviolet radiation conditions. Also, biofouling tests should be conducted on the DEECs exposed to seawater to quantify and understand the level of sea life growth that could occur. Finally, individual DEECs could generate acoustic noise during their operation and should be assessed with respect to how the noise could impact the marine environment they are deployed in.

2.6 An Example: Design of an Individual DEEC (a HexDEEC)

At the National Renewable Energy Laboratory, an experimental design and development effort for an "in-house-DEEC" is underway. The hexagonally shaped DEEC is called a HexDEEC and leverages the physical phenomenon of variable capacitance to enable its transducer mechanism to convert dynamic deformations into generated electricity (see U.S. Patent No. 11,522,469 B2). HexDEECs are nominally composed of a hyperelastic hexagonal housing (most designs use silicone rubber) with six electrodes attached to the inner side of the hexagonal faces; the hexagonal housing is the HexDEEC's structural mechanism. Figure 3 illustrates an example HexDEEC with some of its key dimensions.

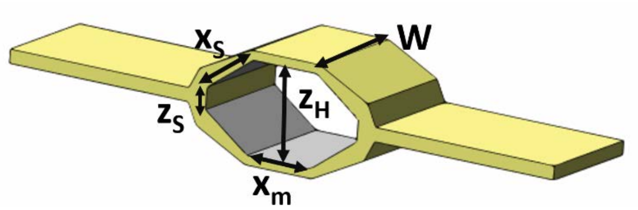


Figure 3: An archetypical HexDEEC showcasing its general geometry and dimensions

The upper three electrodes share the same charge (e.g., positive electrical charge), while the lower three electrode charges oppose (e.g., negative electrical charge) the upper electrode charges. Externally, the HexDEEC has two arms extending away from the middle vertices of the hexagon that, when pulled, deform the internal hexagonal space so that all six plates become parallel in the now rectangular internal space. From the variable capacitance phenomena that HexDEECs leverage, there is a relationship between electrical capacitance and electrical potential (voltage and charge) of the opposing HexDEEC electrodes. Thus, electricity is generated when the HexDEEC's arms are dynamically pulled or released under tensile loading, as doing so causes the distance between the upper and lower sets of opposing electrodes to change, thereby adding to the converter's overall charge—a net gain in charge is generated. In other words, the energy that causes a HexDEEC to dynamically deform also causes its electrical charge to be amplified. The increase in electrical charge is the electricity generated from a HexDEEC undergoing dynamic deformation. As with other dielectric elastomeric generator transducers, either the voltage, electric field, or charge on the plates needs to be held constant in the energy-generation process. For the current HexDEEC design, constant voltage is used due to its more simplified control requirements (Invernizzi et al. 2016).

Analytical modeling and numerical modeling of HexDEEC designs are being implemented to evaluate the mechanics and electrical energy generation of those designs. Equations to describe the capacitance and electrostatic forces acting on the unique HexDEEC systems have been developed (Niffenegger and Boren 2022). This capacitance could then be used to determine the electric potential energy generated from the HexDEEC deformations. Approximating those deformations, the capacitance equations were coupled with the multiphysics modeling software tool STAR-CCM+ to account for the hyperelastic nature representing a HexDEEC's structure via a Mooney-Rivlin three-parameter model scheme (Bergström 2015; Doman et al. 2006).

For the in-house DEEC development, which included the innovation, design, and empirical evaluation of HexDEECs, Star-CCM+ was chosen over other numerical modeling software tools due to its ability to incorporate multiphysics models and custom functions—abilities that enabled the examination of the mechanical loadings of DEECs, the resulting electrical energy generated, and the loading of the structure due to fluid interactions. Moreover, Star-CCM+ has compatibility with high-performance computing systems, thereby enabling analysis of very complex deformations across all hierarchy levels of DEEC-Tec: hyperelastic DEECs (such as the HexDEEC),

DEEC-Tec metamaterials, and DEEC-Tec-based WECs. Software packages that are more typically used for ocean wave energy converter developments (such as WEC-Sim) lack the capability to model flexible and/or elastic structures. Though STAR-CCM+ was used to investigate the deformation and energy production of the HexDEECs, it is primarily useful for fluid-structure interaction. Meanwhile COMSOL is a multiphysics software that is also compatible with high-performance computing systems and can simulate hyperelastic materials. Consequently, STAR-CCM+ and COMSOL are some of the best software options for DEEC-Tec development across all of its hierarchy levels.

In terms of fabrication, individual HexDEECs have been fabricated by drawing uncured liquid silicone rubber into molds via vacuum pressure. The molds were designed with SolidWorks and manufactured via fused deposition modeling (a type of 3D printing). To simplify manufacturing, HexDEEC subcomponents such as electrodes and electrode wiring can be placed within the molds such that they are directly embedded into the hexagonal housing during the silicone rubber curing process. Furthermore, DEEC-Tec metamaterials—made from HexDEECs—can be created through the interweaving and/or sequential layering of multiple HexDEEC strands. Such a HexDEEC-based metamaterial could then generate electricity through its gross dynamic deformations. Ultimately, HexDEECs represent a specific type of energy transducer that can be leveraged by the DEEC-Tec domain to create metamaterials used to construct novel DEEC-Tec-based WECs while also informing the community at large of processes and methods for overarching DEEC-Tec research and development.

3 Research Methodologies for DEEC-Tec Metamaterials

As previously discussed, a DEEC-Tec metamaterial is defined as follows:

> **<u>DEEC-Tec metamaterial</u>**—*a structural framework created from, or consisting of, various combinations and/or interconnections of one or more types of individual DEECs, the arrangements and compositions of which determine the properties and characteristics of the structural framework. DEEC-Tec metamaterials are the primary construction components for DEEC-Tec-based ocean wave energy converters.*

DEEC-Tec metamaterials represent the second hierarchy level of the DEEC-Tec domain, and because they are made up of many individual DEECs, they can have qualities arising from those DEECs and/or from how the DEECs are interconnected—emergent qualities arising from the combining of many DEECs together. In this way, a DEEC-Tec metamaterial could be designed to be very flexible or very rigid; one could even design DEEC-Tec material properties to be a function of the external loadings acting upon it (e.g., a non-Newtonian fluid).

Other considerations for conceptualizing DEEC-Tec metamaterials can include the level at which certain functions are performed across and throughout a given DEEC-Tec metamaterial—functions such as collecting converted energy to power aggregation, actuator mode vs. generator mode, and/or passive vs. active mode throughout a DEEC-Tec metamaterial. To reiterate, a DEEC-Tec metamaterial may or may not be homogenous in terms of the individual DEECs used in its creation. Moreover, a DEEC-Tec metamaterial generally exhibits different properties than its constituent DEEC materials. Likewise, there are no real restrictions as to the form and shape a DEEC-Tec metamaterial could be. For example, a DEEC-Tec metamaterial could be 2D (e.g., a thin fabric), quasi-2D (e.g., a honeycomb layer), or 3D (e.g., icosahedron scaffolding).

3.1 Functional Requirements

When interconnecting DEECs to create a DEEC-Tec metamaterial, it could be highly desirable to maximize functionality of the overall DEEC-Tec metamaterial while minimizing cost, complexity, and losses of all types (number of failure points/modes, number of parts, etc.). Likewise, it could also be preferrable that the individual DEECs act synergistically (e.g., enhancing the deformation and motion of the surrounding DEECs or one set of DEECs within the DEEC-Tec metamaterial, providing initial charging power for another set of DEECs within the metamaterial). Synergy is preferred over the outright opposition and/or meddlesome nature that interconnecting DEECs might cause (e.g., restricting or obstructing the performance of the surrounding DEECs).

Some additional concepts to consider for DEEC-Tec metamaterial development and implementation:

- Failure mode analysis—if an individual DEEC fails, will it cascade across the metamaterial or would it be an isolated failure?
- Provide an intermediate level of energy aggregation.
- Repairability—if some portion of a DEEC-Tec metamaterial fails (or is near failure), what would be required to repair it?

3.2 Numerical and Computational Methodologies for DEEC-Tec Metamaterials

Methods for numerical and computational models of DEEC-Tec metamaterials can span techniques, but typically fall between two approaches: (1) the actual modeling of each interconnected DEEC that makes up the DEEC-Tec metamaterial and (2) the “lump-parameter” modeling of DEEC-Tec metamaterials, which approximates a metamaterial by way of its overall gross properties as opposed to the individual modeling of its internal constituent parts. Facilitating those approaches are computational models such as finite-element methods, finite-differencing methods, and finite-volume methods. The choice of method would be dictated by the needs and/or known characteristics of interest for the DEEC-Tec metamaterial. Some of these characteristics of interest could include properties related to plasticity, elasticity, hysteresis, energy harvesting, damping, electromagnetism, thermal conductivity, fluid flow, controllability, etc.

Specific software packages found particularly useful for the numerical and computational modeling of DEEC-Tec metamaterials include StarCCM+, COMSOL, ANSYS, and Abaqus. Such software packages are useful for modeling the multiphysics features common to DEEC-Tec metamaterials. In particular, these software packages can allow for the multiphysics mixing of electrical current and elasticity, which are the current predominant features of known DEEC-Tec metamaterials. Using the numerical and computational methodologies outlined above, DEEC-Tec metamaterial models can be developed and corroborated via their empirical experimental prototype counterparts.

3.3 Experimental and Empirical Methodologies for DEEC-Tec Metamaterials

Experimental and empirical testing at the DEEC-Tec metamaterial scale not only presents opportunities to validate numerical models but also grants an ability to experiment in ways that would otherwise not be possible if solely depending on numerical techniques and capture nonlinear behavior. Some of those experimental and empirical methods include rapid trial and error of DEEC integration materials, such as evaluation of various elastomer stiffness DEEC interconnects, evaluation of interconnected electric systems techniques, evaluation of thermal losses as varied between material types, and evaluation of casting techniques for the embedment of DEECs to form DEEC-Tec metamaterials.

Other forms of experimental and empirical methodologies for DEEC-Tec metamaterials fall into the more common realms of load testing of material samples: tensile and compressive axial load testing, multiaxial load testing, cruciform sample geometry testing, biaxial bubble inflation testing, biaxial load testing, and out-of-plane testing, to name a few (Laustsen et al. 2014; Viljoen 2018). Collapsible/hinged square testing methods are also possible, which would enable complex yet controlled deformations to DEEC-Tec metamaterials—a DEEC-Tec metamaterial would be clamped in a square frame with hinged corners, and the hinging mechanism could be loaded to a degree defined by the test's purpose and goals. For the experimental and empirical methods outlined, custom test fixtures could be designed and manufactured for use in a uniaxial load frame, thereby granting the ability to apply controlled loads and displacements to the DEEC-Tec metamaterial specimens.

Additional aspects of experimental and empirical methodologies for DEEC-Tec metamaterials include assessment of the reliability and load-carrying capacity of the interconnections between individual DEECs, assessment of the ability to connect an array of DEECs together, and failure assessment of both static and dynamic fatigue DEEC-Tec metamaterial interconnects, which will depend on the overall metamaterial architecture. In addition, the magnitudes, time-varying properties, and continuous vs. discrete nature of the type of testing are important to consider and align with the type of DEEC and/or DEEC-Tec metamaterial.

Ultimately, such experimental and empirical methodologies enable refined DEEC-Tec metamaterial designs aimed at optimizing reliability, power output, and feasibility, which would provide insights and metrics for further down-selection of the best DEEC-Tec metamaterials and corresponding architectures.

4 Research Methodologies for DEEC-Tec-Based WEC Topologies and Morphologies

A DEEC-Tec-based WEC is the third and highest level of the DEEC-Tec hierarchy; it is a structure designed to harvest and convert ocean wave energy into more usable forms (e.g., electricity or fluidic pressure). A DEEC-Tec-based WEC can be defined as follows:

> **DEEC-Tec-based WEC** – *an overall energy harvesting/converting structure that is made from one or more types of DEEC-Tec metamaterials for the purpose of harvesting and converting ocean wave energy into more desirable forms such as electricity.*

A DEEC-Tec-based WEC's *topology* represents those general forms, shapes, and geometries defining its structure. Likewise, a DEEC-Tec-based WEC's *morphology* represents the flexible and compliant characteristics—properties such as stiffness, damping, plasticity, and other deforming abilities.

Research methodologies for DEEC-Tec-based WEC topologies and morphologies are inherently multidisciplinary and will likely require iterative methods as well as multi-fidelity and multi-physics approaches that invoke a combination of theoretical, analytical, numerical, computational, and empirical work. Moreover, DEEC-Tec-based WECs can exhibit a strong coupling between their topologies and morphologies.

As a brief example, consider a DEEC-Tec-based WEC designed to flutter in the presence of ocean and/or tidal currents (see Figure 4). If such a DEEC-Tec-based WEC's topology were to be squished into a pyramid with a base affixed to the ocean floor, then such a topology would not enable the DEEC-Tec-based WEC's needed morphology to flutter in the presence of the ocean and/or tidal currents. As such, this example DEEC-Tec-based WEC's topology and morphology are strongly coupled and should be researched and developed accordingly, which implies a need for concurrent research mechanisms between DEEC-Tec-based WEC topological and morphological developments.

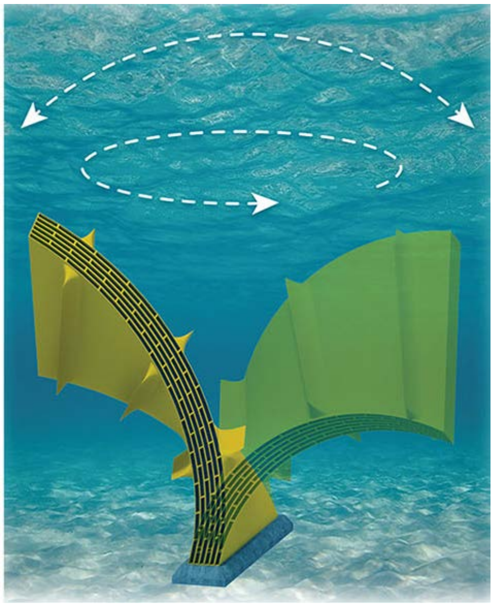


Figure 4: An example bottom surging flexWEC design

4.1 DEEC-Tec-Based WEC Topology Discovery, Design, and Innovation

To capture ocean wave energy using a DEEC-Tec-based WEC, what geometries or general forms should such a WEC take? What are some of the more advantageous research and discovery methods to aid in the identification of useful DEEC-Tec-based WEC geometries, shapes, forms, etc. for optimal converter performance per the desired ocean energy resource environment (e.g., onshore, nearshore, offshore, ocean waves, ocean currents, ocean tides)? This section aims to address such questions and to give direction to research methods and pathways most suitable to the task.

The following are several ways to discover advantageous and optimal topologies for DEEC-Tec-based WECs:

- Developing flexible analogs to classical rigid-body WECs
- Considering active-variable shapes and forms for different WEC orientations
- Applying miniaturization, then multiplication, of classical mainstream WEC systems to create the DEECs needed to compose a DEEC-Tec-based WEC
- Investigating the use of flexible undulating surfaces and strings
- Acquiring inspiration from evolution and biology (bio-inspired design).

These methods can produce the various advantages of the DEEC-Tec domain, as discussed in the beginning sections of this report.

4.1.1 Flexible Analogs to Classical WEC Rigid-Body Systems

One research pathway for DEEC-Tec-based WEC topology development is to consider the flexible analogs to well-known classical rigid-body WECs. There are advantages and disadvantages to pursuing this approach. One advantage is that there is no longer a direct need to conceptualize and flesh out a DEEC-Tec-based WEC's topology from scratch—the pressure to develop a completely novel DEEC-Tec-based WEC is ameliorated by basing the design on classical, familiar rigid-body WEC concepts. Nevertheless, by leveraging classical notions of what a WEC "should" be and/or what it should look like, the development of a corresponding DEEC-Tec-based WEC could be heavily biased toward those classical notions, possibly curtailing some of the new and promising aspects that DEEC-Tec brings to the forefront of marine renewable energy research and development.

4.1.2 Active-Variable Shapes per DEEC-Tec-Based WEC Orientation

Similar to the first research method suggested above is the examination of existing classical rigid-body WEC topologies and the enabling of active-variable geometry along different axes of a WEC's predominant orientations. For example, an ocean wave energy resource that also has strong cross-flow (ocean current action orthogonal to the ocean wave front) could be harvested/converted by a DEEC-Tec-based WEC if the WEC has active-variable shapes in those corresponding directions. Thus, the ability to have independent topologies for various DEEC-Tec-based WEC body orientations—having the ability to intelligently and actively change topology configurations—can further maximize WEC performance in marine renewable energy environments, including those that could have multimodal but distinct forms of marine renewable energy available for harvesting and conversion. Ultimately, what is being described is using DEEC-Tec to give classical rigid-body WECs the ability to have additional modes of energy harvesting and conversion via active topological deformations and orientations (dilation, distortions, stretching, expansion, contraction, etc.).

4.1.3 Miniaturization Then Multiplication of Mainstream WEC Systems To Create DEECs

Another method for discovering successful DEEC-Tec-based WEC topologies is to miniaturize existing WEC technologies (and/or characteristics) and then multiply them for the development of DEECs and corresponding DEEC-Tec metamaterials. Some existing non-DEEC-Tec-based WEC technologies available for miniaturization and multiplication could include general power take-off units (e.g., rotary generators) and/or prime movers (e.g., drive shafts, gear boxes).

In a broader sense, this approach has been widely successful in other major industries. In particular, the large tech and semiconductor industries have used and are largely based upon the miniaturization, multiplication, and corresponding integration of components that initially were rather large and discrete but are now microscopic, embedded, and integrated into entire devices. MEMS are examples of miniaturization.

With respect to DEEC-Tec-based WEC topology research, such miniaturization could allow for the creation of topologies with multiple types of energy conversion systems, or the development of DEEC-Tec metamaterials involving multiple types of DEECs, each using its own means of energy conversion, thereby enabling the broadest possible range of available transducer mechanisms to convert marine energy into usable forms, all from one DEEC-Tec-based WEC topology.

4.1.4 Flexible Undulating Surfaces and Strings

Flexible, undulating surfaces and strings could be possible DEEC-Tec-based WEC topologies used to harness, capture, and convert marine renewable energy. The oscillatory nature of such topologies could be effective mechanisms to capture and convert the wide range of frequencies often found in marine energy resources. Thus, a DEEC-Tec-based WEC design could directly and easily be stimulated or resonated via corresponding marine energy frequencies (e.g., ocean wave frequencies) by deliberately designing it to have a topology that is a thin sheet, fabric, flap, or string.

Oscillating strings are a well-characterized phenomenon that could be readily adapted to marine renewable energy applications. Oscillating flaps have been extensively studied in aerodynamics and oceanography, as the vortex-shedding they produce creates variable loading. Likewise, an undulating surface topology (e.g., a flap or thin sheet of DEECs) is directly linked to its characteristic frequency, and these flaps may be rigid or compliant and flexible. Like their string counterparts, the undulating surfaces, as a DEEC-Tec-based WEC topology, could also be readily applied to the conversion of marine energy resources by application of DEEC-Tec.

4.1.5 Bio-Inspired Design

Nature has evolved and optimized topologies of aquatic and marine life over the last several hundred million years. How creatures use their shape and form to create efficient movement through water has been the subject of much study. In general, most aquatic and amphibious adaptations fall into eight broad categories (Zack et al. 2009; Kaji et al. 2017; Koh et al. 2013, Koehl 1982; Koehl 1984; Passino 2004):

- Rigid and flexible fins (vertical and horizontal): most fish, dolphins, whales, manatees, pinnipeds, turtles, tortoises, seahorses, etc.
- Undulating surfaces: stingrays, manta rays, otters, eels, etc.
- Expanding and contracting surfaces or controlled jet propulsion: jelly fish, octopuses, squids, cephalopods, arthropods, etc.
- Long, flexible appendages: jelly fish, octopuses, etc.
- Webbed appendages: frogs, toads, newts, amphibians, otters, etc.
- Anisotropic bone and shell structures: e.g., crustaceans
- Elastic energy storage and latching mechanisms that enable powerful fast snapping or jumping movements: mantis shrimp, pistol shrimp, fleas
- Varying material elasticities and stiffnesses in different parts of the organism that enable them to withstand and dissipate forces from waves and tidal flow: aquatic sessile or anchored organisms, such as sea grass, kelp, sea anemones, and corals.

These fundamental topologies could be implemented for DEEC-Tec-based WECs, especially with the bio-topologies viewed from the perspective of reverse power flows. In other words, instead of using energy to create motion in marine environments (as what some biological archetypes implement via their topologies), bioinspired topologies (and/or their general insights) for DEEC-Tec-based WECs could operate in reverse to harvest and convert marine energy.

For example, rigid and flexible fins effectively act as hinged flaps and oscillating flaps. In this regard, there are many different fin topologies across the animal kingdom—each being optimized for a different function or type of movement—that a DEEC-Tec-based WEC topology could leverage for marine energy harvesting and conversion. Indeed, undulating surfaces could be considered as large fins, due to both the flapping and oscillatory motions they employ. Likewise, the controlled jet propulsion and contracting surfaces used by octopuses and squids are most like microfluidics (micropneumatic and microhydraulic) that DEECs and corresponding DEEC-Tec metamaterials could leverage. Moreover, long, flexible appendages could be particularly well-suited to piezoelectric power generation by way of high-frequency flutter (piezoelectrics tend to be most suitable for high-frequency oscillations). Finally, it has been claimed that there are current examples of potential WEC designs that have used inspiration from flexible organisms such as seaweed and sea snakes in combination with TENGs to generate power (Zhang et al. 2018; Wang et al. 2021).

4.2 DEEC-Tec-Based WEC Morphology Discovery, Design, and Innovation

This section discusses advantageous research methods for the conceptualization and development of DEEC-Tec-based WEC morphologies. To reiterate, a DEEC-Tec-based WEC's morphology describes the converter's flexible and compliant characteristics, which are features such as stretchability, foldability, twistability, inflatability, and/or other features describing a DEEC-Tec-based WEC's ability to deform.

While multiple research methods were found to be useful for the conceptualization and development of DEEC-Tec-based WEC morphologies, most methods center on the specific design and development of DEEC-Tec metamaterials. In this regard, the metamaterials from which DEEC-Tec-based WECs are constructed enable the morphological characteristics of DEEC-Tec-based WECs. What follows, therefore, are the DEEC interconnection types found useful for the research and development of DEEC-Tec-based WEC morphologies.

4.2.1 General Mechanical Joints and Connectors

One of the simplest to understand and most implementable methods for DEEC-Tec-based WEC morphological design is the use of tiny mechanical joints and connectors. These connection types might directly enable highly constrained motion between DEECs, constraining them to only have relative linear motion, relative rotational motion, or relative radial motion. However, such mechanical joints and connectors could also be deliberately employed to enable incredibly large ranges of motion between interconnected DEECs (e.g., the use of ball-and-socket joints, simple hooped links, or elastic connectors between DEECs) and multiple degrees of freedom.

Some common examples of mechanical joints include hinges, ball-and-socket joints, pivots, and sliding/gliding joints. There are also many types of mechanical and electrical connectors, such as hooks, adapters, converters, bearings, threaded bolts/screws, and others. Linkages, such as chains, are a common type for marine applications. Links must be able to durably transfer power, loads, motion, and deformation. Such joints and connectors are necessary in several aspects of DEEC-Tec-based WEC design, such as interfacing components, interconnecting individual DEECs, and connections to foundation and mooring systems.

4.2.2 Chemical Bonds

Another method for connecting individual DEECs to design a desirable DEEC-Tec-based WEC morphology is chemically bonding or adhering the various DEECs to each other, especially if the DEEC materials or components being adhered are inherently flexible. In this regard, flexible adhesives must be durable (not brittle), have excellent fatigue strength, and demonstrate good resistance to degradation in harsh marine environments. A few examples of chemical bonds are adhesives, soldering, and welding.

4.2.3 Fabrics and Textiles

Fabrics and textiles offer another means for interconnecting DEECs to form metamaterials that result in desirable DEEC-Tec-based WEC morphologies. Strands or sheets of DEECs are interwoven or layered into 2D or 3D metamaterials (e.g., column latices), each having different desirable mechanical and structural properties.

The fundamental unit is the strand or filament. Its stiffness properties are a function of its length and material. Strands and filaments may be bundled, braided, and/or twisted into strings or wires. For most DEEC-Tec applications, strings, strands, and filaments provide incredible flexibility and low resistance to motion or deformation. Synthetic strands (such as elastomers and polymers) and natural fibers can provide varied functionality and versatile properties, depending on their use in the DEEC metamaterial. Strands and filaments may be used to produce electricity (e.g., piezoelectric strands or oscillating filaments) or transport electricity (e.g., copper wiring), and to interconnect components (mooring, connecting the foundation to a floating component with surface expression).

Strings, strands, and filaments may also be woven together to form a fabric or textile. Weaving, braiding, or twisting strings together reduces the loads on each strand or filament and causes the loading to be distributed among them. Different braiding, bundling, and twisting strategies can have different effects on the structural and mechanical properties and can also be optimized for a particular application, such as a DEEC-Tec-based WEC.

Likewise, different weave patterns can have significant effects on the structural and mechanical properties of the resultant material. Drapability is the ability of the fabric to conform into shapes with complex curvature (curvature in multiple axes) without buckling (wrinkling). Different weave patterns have different structural implications (some are more rigid than others) and different drapability characteristics, which can be optimized for certain structural properties.

Fabrics need not be homogenous; in other words, weaving dissimilar materials together can have desirable properties for DEEC-Tec-based WECs. For example, materials that generate a changing electromagnetic field could be woven together with electrically conducting materials to reduce losses associated with energy transfer. In addition, there are also homogenous nonwoven fabrics that are both compliant and deformable (tension, transverse loading, etc.), such as elastomers and polymers, that are useful as DEEC-Tec materials.

Strings, filaments, fibers, and fabrics may also be chemically treated and/or coated to provide additional benefits. Soaking them in a chemical bath, coating them using roll-to-roll processing techniques, and steam-treating them are just a few examples of methods for enhancing physical properties.

4.2.4 Layering

Layering of woven and nonwoven DEEC-Tec metamaterials with interstitial materials of different properties can also be beneficial for DEEC-Tec morphological designs. For example, layering electrically conducting and nonconducting materials could allow more electricity to be generated in a smaller volume of DEEC-Tec-based WEC structure. Likewise, another option is to layer materials that are resistant to the ocean/marine environment over and around DEECs to better protect their longevity in such a harsh environment. The strategic layering of DEECs and corresponding DEEC-Tec metamaterials could prove to be a useful DEEC-Tec-based WEC morphological feature for enhancing overall energy conversion and general device performance.

4.2.5 Foldable Structures: Origami

Rather than using mechanical joints or chemical adhesives, DEEC-Tec metamaterials could also be folded into origami patterns and DEEC-Tec-based

WEC structures can arise from such origami. A variety of possible configurations exist that can enable the DEEC-Tec-based WEC to compress and extend, deform, and then return to its initial shape when needed. One such configuration is the Kresling pattern, which is a cylindrical spiral structure with identical triangular panels and cyclical symmetry that has been investigated as a potential configuration for a dielectric elastomer actuator using numerical modeling methods such as finite-element analysis (Park et al. 2019). As the angle of the folds increases or decreases, so does the length of the origami cylinder. In these configurations, the bending and resulting compression and tension at the creases of the metamaterial would be the key areas for mechanical energy harvesting (Park et al. 2019).

5 Innovation Methodologies for the DEEC-Tec Domain

There are multiple research approaches that can be applied for the innovation and conceptualization of DEEC-Tec at any of its hierarchy levels.

For innovation of individual DEECs, a core requirement would be a DEEC's ability to harvest localized external sources of energy (e.g., mechanical dynamic deformations) and convert them into more usable and/or desirable intermediary forms of energy (e.g., electricity or fluidic pressure). Nonetheless, there are many possible ways in which an individual DEEC can be innovated—all of which are dependent upon its energy conversion pathways as governed by its corresponding energy transducer and structural mechanism designs.

Likewise, the innovation requirements for DEEC-Tec metamaterials would have to include (but are not limited to) the ability to integrate many individual DEECs together with all their corresponding "input-output" considerations (e.g., electrical signaling, actuator/generator controls, distribution of captured and converted energy). Moreover, DEEC-Tec metamaterial innovations would also have to account for the fact that DEEC-Tec metamaterials are, by their very nature, construction materials—used to construct larger overall energy conversion structures such as DEEC-Tec-based WECs. To that end, methodologies for the innovation of DEEC-Tec metamaterials shall also include considerations for construction material requirements such as stiffness, ability to be assembled with other types of DEEC-Tec metamaterials and other subsystems, and framework of implementation (a structural fabric, a structural column, a structural plate, an outer cover, an inner conduit, an inflatable, etc.).

Lastly, innovation methodologies associated with DEEC-Tec-based WECs should primarily be innovating within a given DEEC-Tec-based WEC's topological and morphological design requirements. Meaning, innovation methodologies at this hierarchy level should account for the desired shape, general geometry, etc. of a DEEC-Tec-based WEC and, likewise, innovation methodologies should also account for the desired stretchability, deformability, etc. of a DEEC-Tec-based WEC.

This section presents various innovation methodologies identified as promising avenues that DEEC-Tec researchers and developers could utilize for their efforts in effectuating DEEC-Tec designs/conceptualizations at any hierarchy level.

5.1 Design Thinking

A widely used innovation methodology is design thinking (Curedale 2019). The design thinking approach represents a set of cognitive, strategic, and practical processes by which design concepts are developed. It has three main components: inspiration, ideation, and implementation. The design thinking process begins with understanding and appropriately defining the problem or opportunity, which can include benchmarks, metrics, goals, and objectives. For innovations that interface with people, an empathetic technique might be used to better understand the user's, customer's, and/or client's needs—an overarching effort to see their involvement into the design process. Ideation is the generation of ideas and can involve both convergent thinking and divergent thinking:

- Convergent thinking: Giving focus to the discovery and/or development of one well-defined solution to a problem.
- Divergent thinking: Giving focus to the exploration of many, often initially vague, solutions.

Moving on from ideation, the implementation component is the act of turning those fleshed-out ideas into reality and requiring conformance to fundamental physical laws (thermodynamics, Newtonian mechanics, etc.). Prototyping different ideas, testing, evaluating, and iterating are key techniques utilized in the implementation phase. The progression from design thinking to implementation is a highly iterative process and is often circuitous and nonlinear—the practitioner(s) may need to loop back and forth between the phases of ideation and implementation. For example, if an acceptable solution cannot be found with the problem as stated, a common regression is to reframe the problem with different constraints or boundaries. Along these lines, a key component for DEEC innovation would be to gather and address user/customer/client requirements, especially for the design and 21deationn phase, but also during the implementation/prototype phase.

With regard to those users/customers/clients, it should be noted that WECs have a wide variety of stakeholders, and no single stakeholder or stakeholder group clearly dominates the rest. To that end, stakeholder requirements can play both an implicit and an explicit role in the DEEC innovation and implementation phases. Nonetheless, in most cases, the stakeholder(s) are not directly involved in the design and ideation process, though they could be (Curedale 2019).

5.2 Lean Startup

The lean start-up method (The Lean Startup undated) is a principled approach to new product development and is based on three core elements that reside within a feedback loop: learn, build, and measure. As with design thinking, the learning and measuring phases within the Lean Startup methodology can incorporate customer or user feedback to improve the end product/result. While the Lean Startup method is generally geared toward the generation of a minimum viable product quickly, the methodology incorporates an element of short design cycles and iterations that could be useful for individual DEEC design/development.

5.3 The Blue Ocean Method

The Blue Ocean method (Blue Ocean undated) is an exploratory method to identify gaps and areas of need that are not currently being satisfied by existing solutions and may not already have an established market or demand. The name is derived from using a metaphor of red oceans and blue oceans to describe the various markets. Red oceans are activities, technologies, and companies that currently exist with an established and known market space—also known as the competitive market. Blue oceans are filled with activities, technologies, and customers that do not presently exist and represent the vastness of unexplored potential. Thus, the blue ocean market is unknown, but there is also no competition. Some of the Powering the Blue Economy^{TM} markets (LiVecchi et al. 2019) could fall into the blue ocean category—markets where DEEC-Tec could significantly add value. Likewise, with the newness of the DEEC-Tec paradigm, DEECs could open and operate within new markets that have not yet been considered.

5.4 Concept-Knowledge Method

The concept-knowledge method is an exploratory methodology (Arnoux 2021) within which the process of conceiving ideas is formalized through the synthesis of creativity and knowledge from analogous/applicable experience. The “concepts” space represents novelty, imagination, ideas, and the “impossible.” The “knowledge” space concerns the “possible” and allows these concepts to be represented in reality, usually incorporating a multidisciplinary or interdisciplinary knowledge base. The concept-knowledge method allows the practitioner to explore the customer value, business model, functions, and technologies of the idea.

5.5 TRIZ

There are also more structured and logical innovation methodologies such as TRIZ (Haines-Gadd 2016). TRIZ, the theory of inventive problem solving, is an organized and systematic approach to problem solving that is guided by the laws of systems engineering. It is derived from an analysis of repetitions and patterns of problems and solutions across industries and throughout history. TRIZ includes a practical methodology, tool sets, and knowledge base. It can be used for problem formulation (understanding and defining challenging problems), system analysis, failure analysis, pattern identification, and conflict/contradiction resolution. Two areas where the TRIZ methodology could be useful at the DEEC innovation stage, corresponding to the design process, are problem abstraction (to find a more general solution) and contradiction resolution (when competing design goals might be conflicting).

6 Research Methodologies for DEEC-Tec Manufacturing and Fabrication

Manufacturing and fabrication play an important role in the overall techno-economic feasibility of DEEC-Tec-based ocean wave energy converters. Some examples are the determination of estimated recurring and nonrecurring engineering cost drivers, identification of plausible failure modes, consideration of environmental and social factors, and further determination of those overarching benefits associated with the use of DEEC-Tec to harvest and convert ocean wave energy into more useful forms like electricity. Manufacturing and fabrication can also have a significant impact on the ability (or inability) to develop desirable topological and morphological characteristics for any of the three hierarchy levels of DEEC-Tec (individual DEECs, DEEC-Tec metamaterials, and DEEC-Tec-based WECs). In other words, manufacturing, and fabrication techniques impact both the innovation and implementation of the shape/geometry, mechanics, and compliant characteristics of DEECs, DEEC-Tec metamaterials, and DEEC-Tec-based WECs. Thus, different manufacturing and fabrication methods can introduce intrinsic risks and challenges for the procurement of desirable DEEC-Tec characteristics. To that end, the following are research considerations and design concepts cogent to DEEC-Tec manufacturing and fabrication:

- Ability to create or generate various structural geometries, forms, and shapes (topologies)
- Ability to create flexible and/or compliant structures (morphologies)
- Ability to house/co-locate/dual-purpose both transducer and structural mechanisms
- Ability to interconnect the individual DEECs and DEEC-Tec metamaterials in a synergistic way that transfers loads, deformation/displacement, and energy among the DEECs
- Ability to ensure robustness and durability of the three DEEC-Tec hierarchy levels.

Moreover, there is considerable promise in using novel manufacturing and fabrication approaches for the development of DEEC-Tec; for example, nanotechnology (nanomachining, nanocomposites, etc.), emerging forms of additive manufacturing (binder and material jetting, powder bed fusion, directed energy deposition, electron beam melting, etc.), virtual reality (using virtual reality to inform the actual fabrication process in terms of both training technicians and validating part design), and others. DEEC-Tec can immediately take advantage of the multi-material/component-integration capabilities of these relatively new forms of manufacturing and fabrication methods. Indeed, they can be valuable and viable pathways toward achieving DEEC-Tec objectives such as multi-material deposition and/or multi-headed deposition techniques (where multiple heads with different materials can move in tandem in 2D or 3D to create woven or overlapping shapes, materials, metamaterials, and more). Ultimately, other novel manufacturing methods could be discovered and developed explicitly for the manufacturing and fabrication of novel DEECs, DEEC-Tec metamaterial, and complete DEEC-Tec structures such as DEEC-Tec-based WECs.

In fleshing out the yet-to-be-determined methods for DEEC-Tec manufacturing and fabrication, the following research approaches should be considered:

- Conduct a literature review/survey of existing and emerging techniques, particularly those currently employed for energy transducers and fundamental energy conversion processes, including physical phenomena that enable energy conversion such as variable capacitance, Faraday's law of induction, thermodynamic phase changes, solid-state thermoelectrics, redox electrochemical flows, etc.
- Analyze the advantages and disadvantages of current techniques to determine suitability for

DEEC-Tec and identify where beneficial modifications can be made.

- Use TRIZ structured innovation techniques (see page 21 for greater details regarding TRIZ).
- Apply a technique from one research field to a completely different one (cross-pollination), which may require varying levels of abstraction to interrelate the various research fields to DEEC-Tec fabrication and manufacture.

Likewise, the manufacturing and fabrication challenges and obstacles specific to the DEEC-Tec domain are likely due to the following aspects:

- **Tolerances**: As the length scales for individual DEECs decrease, machining and manufacturing tolerances play an increasingly important role by imposing design limitations and constraints. Different manufacturing and fabrication processes will have different tolerances and precision that must be accounted for when deciding which process to use for the given type of DEEC. Similarly, the degree of miniaturization may be limited by available manufacturing and fabrication methods.
- **Relative motion and/or deformation**: DEEC-Tec is a technology domain centered around structures that actively and elastically deform; hence, manufacturing and fabrication techniques are required that permit relative motion and/or deformation between adjacent materials and components. While any sort of joint will have its associated failure modes, those that do not allow relative motion and deformation are significantly more likely to fail.
- **Redundancy**: When manufacturing joints, links, adapters, and connectors, it can be beneficial to build in redundancy through multiple connectors on each DEEC. In addition, the stiffness and strength of these connectors must be accounted for during DEEC-Tec-based WEC design.

Some additional considerations to account for when deciding an appropriate manufacturing and fabrication approach to use for DEEC-Tec research and development are:

- **Waste and byproducts**: Different manufacturing and fabrication methods generate different amounts and types of manufacturing waste, such as waste materials (waste fraction), solid waste (that goes into the landfill), liquid waste (that goes into the local water table), gaseous waste (that goes into the atmosphere), and toxic/hazardous waste (that must be specially handled and disposed of). Each type of waste has different impacts on the surrounding communities and environment that must be considered.
- **Manufacturing impacts and benefits**: Different types of manufacturing and fabrication methods require different skill sets and levels of expertise, create a varying number of different types of jobs, are resource-intensive (energy, water, etc.), have varying costs, and require certain levels of available infrastructure—all of which must be considered when selecting which method to employ.

The following sections dive deeper into selected concepts relating to DEEC-Tec manufacturing and fabrication.

6.1 Deposition Techniques

Deposition, in its most general form as it relates to manufacturing, refers to the precise and controlled creation, synthesis, application, or transfer of a material onto the surface of a substrate material. There are hundreds of types of deposition techniques in combination with thousands of materials across many industries that are all intended to improve some element of performance. Deposition methods are useful to DEEC-Tec in multiple areas: coatings for protection, electroplating for electronics and/or corrosion resistance, additive manufacturing for flexible and compliant structures, and so on. This field can generally be broken into two main categories: thin film deposition techniques and additive manufacturing techniques.

6.1.1 *Thin Film Deposition Techniques*

Thin film deposition techniques focus specifically on depositing a very thin layer (nanometers to micrometers thick) onto a substrate surface. There are many different types: some are based on the phase of the material being deposited (e.g., gas, liquid, or solution). Others are based on the material being deposited, such as chemicals, metals, ceramics, and more. Still others are based on the deposition method (mechanical, chemical, physical, advanced, or interfacial). Note that there may be some overlap in some of the categories (in other words, they might not be mutually exclusive).

6.1.2 *Additive Manufacturing Techniques*

Additive manufacturing, also known as rapid prototyping or 3D printing, has been established for decades as a substantial alternative to traditional subtractive manufacturing with significant benefits. The ability to build or construct a structure layer by layer offers advantages uniquely beneficial for DEEC-Tec, particularly for flexible and compliant structures.

6.2 Filament Processing

Filament (textile) processing is one of the oldest and largest manufacturing methods in the world. Many products and industries employ filament processing daily, such as clothing and fashion, shipping and boating, fishing, recreational sports, aerospace and defense, composite manufacturing (automotive, wind energy), and many more. It offers many advantages to the DEEC-Tec domain, such as flexible and compliant (yet strong) structures, customizable properties and characteristics, varying levels of complexity and performance, and different geometries with different frequency and physical properties.

6.2.1 *Filament Treatments*

This subsection focuses primarily on methods for transforming the physical, mechanical, chemical, and visual properties of a filament, string, strand, or sheet. There are numerous ways to discuss and present these methods. A filament, string, or strand may be created from a raw material by either spinning or extruding it.

Once the filament, string, or strand is created, it can be treated or modified to have the desirable properties. Some examples of modifications and treatments are:

- Steam: subjecting the filament to steam causes shrinkage, which can improve strength and durability
- Dyes: the filament may be exposed to a (usually chemical) dye to change its visual properties
- Coatings: there are many different types of coatings that provide a wide variety of performance enhancements and improvements to the filament, such as lamination, plating, galvanization, and much more.

There are many ways a filament can be modified, including bathing it and roll-to-roll processing. Bathing is described as fully immersing the filament into a chemical or dye bath for a period of time. Roll-to-roll processing begins with a supply roll that is being drawn from, and the filament is wound from the supply roll to a second finished roll while passing through various treatments (such as those listed above) in between. Note that roll-to-roll processing can also be employed with sheets of material, and variants of roll-to-roll processing may be termed cylinder or spool processing. Filaments can be treated or modified before, during, or after combining them into larger structures and components.

6.2.2 *Filament Twisting, Braiding, Weaving, and Knitting*

There are multiple methods for combining filaments into larger structures:

- Twisting: an individual strand may be twisted, or multiple strands may be twisted together

- Braiding: multiple strands may be braided together using a prescribed braiding or interweaving pattern
- Plaiting: when twisted strands are braided together.

Braiding and plaiting may occur with strands of different materials, sizes, and properties. This is commonly used in making ropes, where a core is braided differently using different materials than the outermost layer. Filament winding is typically utilized as a type of composite manufacturing, where a tensioned filament on a roll or spool is fed through a resin bath and then is wound upon a mandrel of the desired shape and size of the end product. As with other types of manufacturing, there are a number of variants on the filament winding process:

- Stationary or mobile/rotating mold
- Dry, wet, or semidry filament being wound
- The filaments may be continuous or discontinuous
- The winding pattern and angle are design variables. Types of winding include helical, polar, circumferential, and longitudinal.

In addition to filament winding, weaving and knitting filaments have been implemented over centuries, with machines performing much of the work now. It is worth noting that most of the above processes are heavily automated, which drastically reduces or eliminates the need for manual labor. There are many weave patterns, each with different advantages and disadvantages. Some are more porous or dense; others improve the ability of the fabric to conform to geometries with complex curvature (e.g., curvature in multiple directions), also called drapability. The various weaves will also dictate the tensile strength along different orientations, and some can even affect the fabric properties when subjected to out-of-plane loading. Careful selection of weave pattern can provide significant advantages.

Finally, nonwoven fabrics may also be created from filaments. The nonwoven fabric industry is driven by technology developments in machinery, process control, and materials (New Cloth Market undated). Nonwoven fabrics are broadly defined as sheet, web, or mat structures of natural and/or synthetic fibers bonded together by entangling the fibers mechanically (tangling or stitching), thermally fusing the fibers, or chemically bonding the fibers (adhesive or dissolving). First the web is formed, then bonded. The final steps are to finish and convert (cutting and shaping) the nonwoven fabric for transport and sale. Nonwoven fabrics are particularly useful for DEEC-Tec due to their lack of porosity, durability, and attractive chemical and mechanical properties.

6.3 Molding

Molding is a manufacturing process involving shaping a liquid or pliable raw material using a fixed hollow frame called a mold. The mold is usually the negative shape of the object, such that the injected raw material forms the positive shape. Molds may have as many pieces as desired and must be manufactured separately. Once the injected material hardens into its final shape, the molds are reused to create thousands of the same shape or geometry. Molding may involve one or more raw materials—when it involves two dissimilar materials (such as fibers and resin), it is termed composite molding process. There are three main types of molding processes: open molding, closed molding, and cast polymer molding (hybrid approach) (Composites Lab 2022).

6.3.1 Open Molding

Open molding allows the material to cure while exposed to air, which has both advantages and disadvantages. This technique is advantageous since no additional resource-intensive processing is needed to cure, reducing costs, materials, and labor. Although, some chemical systems may require elevated temperatures to fully cure. The trade-off for this technique is that is it dependent on curing times, and the exposed surface of the component is not controlled or constrained. Some examples of common open-mold processes are:

- Hand lay-up
- Spray-up

- Casting
- Filament winding.

6.3.2 Closed Molding

Closed molding techniques are used when the raw material is not exposed to the atmosphere to cure and must instead be cured through an additional process step. These are very common in composite manufacturing, and include such processes as:

- Vacuum-bag molding
- Vacuum-infusion processing
- Transfer molding
- Resin transfer molding (including vacuum-assisted resin transfer molding)
- Compression molding
- Pultrusion
- Injection molding
- Reinforced reaction injection molding
- Centrifugal casting
- Continuous lamination.

In fact, vacuum-infusion processing is presently being used to manufacture the HexDEEC concept. Note, also, that closed molding has the benefit that all surfaces of a component are being constrained, thereby ensuring the mold is as near-seamless as possible and has good surface finishes and tolerances all round.

Injection molding is a class of molding with many variations and subcategories. Moreover, it is particularly useful for producing identical parts in large volumes. Some methods may be classified as single-cavity, multicavity, and family molds. Other types include cube molding, die casting (when the raw material is a metal), glass-assisted, micro, reaction, and thin-wall (TWI Ltd. Undated). Injection molding may be used with plastics, polymers, elastomers, glasses, rubber, metals, and other materials. Separate materials may be combined into one part using a two-shot mold. Its advantages include minimal waste production, ability to scale up, and part reliability and consistency. Some disadvantages are the cost of the molds, size limitations (with larger, not smaller, parts), and manufacturing complex parts (TWI Ltd. Undated).

6.3.3 Cast Polymer Molding

Cast polymer molding techniques are unique in that they do not usually contain reinforcing fibers and are designed to meet specific strength requirements of an application. Two common types of cast polymer molding are gel-coated cultured stone molding and solid surface molding.

6.4 Miniaturization Methods

One of the major technological breakthroughs of the 20th century was the miniaturization of mechanical, optical, and electronic components, products, and devices. Miniaturization has been a key enabler for a wide variety of industries, especially in electronics and power systems. Miniaturization and manufacturing are inherently intertwined: miniaturization both demands and is driven by innovative manufacturing techniques. It allows for precision manipulation of ever smaller components/scales and requires increasingly sophisticated manufacturing equipment and facilities.

The benefits of miniaturization in the DEEC-Tec domain are increased performance, decreased cost, and the ability to construct devices and technologies that would be impossible to make otherwise. Miniaturization can also enable the use of existing rigid-body devices as individual DEECs, thus leveraging existing resources, best practices, and scalable devices. It is possible that a DEEC-Tec-based WEC could be constructed of thousands of miniaturized rigid-body devices.

Some challenges and opportunities associated with miniaturization are:

- As the length scales for the individual DEECs decrease, machining and manufacturing tolerances and precision play an increasingly important role through imposing design limitations and constraints. Different manufacturing and fabrication processes will have different tolerances and precision that must be accounted for when deciding which process to use for the given type of individual DEEC. The degree of miniaturization may be limited by available manufacturing and fabrication methods.

- Miniaturization can require different, specialized equipment than for larger scales, which can in turn impose additional requirements on materials and/or require different material properties.
- Structural properties of mechanical devices change as the characteristic length is reduced (Van Riper 2002).
- Some key nondimensional physical quantities that depend on and/or incorporate a length scale can change, which represents changing physics as components are miniaturized. For example, smaller devices can suffer from increased frictional losses (e.g., low Reynolds number) and/or changing frequency response characteristics (e.g., Strouhal number).
- Some physics phenomena can also change when going from very large to very small scales, such as discretization of homogeneity or continuity, assumptions of Newtonian physics, mass transport limitations (Dahlin 2012), etc.
- As scales are reduced, overall magnitudes of signals (forces, moments, strains, stresses, deformations, deflections, etc.) all decrease. Thus, ratio of the signal magnitude to background noise levels increases and has historically caused issues for scaled model testing.
- Some technologies become more efficient with miniaturization, and others become less efficient—it is important to recognize this distinction and make decisions appropriately.
- The cost and hardware required to integrate individual DEECs together could increase with increasing levels of miniaturization, which could impose a constraint in the form of a size limit (could become too small).

Miniaturization can offer significant advantages, but care/caution should be exercised when selecting the characteristic lengths of the individual DEECs and DEEC-Tec metamaterials in order to maximize the gains and minimize the trade-offs (as described above).

7 Conclusions and Future Work

The domain of distributed embedded energy converter technologies (DEEC-Tec) is a new paradigm for the harvesting and converting of marine renewable energies. This new paradigm is based upon the implementation of many, relatively small, distributed embedded energy converters (DEECs)—a distribution of energy transducers that are assembled together to form DEEC-Tec metamaterials. Subsequently, DEEC-Tec metamaterials are used to construct overall larger marine renewable energy harvesting and converting structures. Of particular note, such a structure could be an ocean wave energy converter. In this way, DEEC-Tec has three different hierarchy levels: (1) individual distributed embedded energy converters, also known as DEECs; (2) DEEC-Tec metamaterials—these being, essentially, pseudo-materials made from the interconnection of many DEECs; and (3) overall larger marine renewable energy harvesting-converting structures assembled from DEEC-Tec metamaterials.

The DEEC-Tec domain offers multiple inherent benefits when employed for ocean wave energy conversion: (1) broad-banded energy conversion, (2) inherent redundancy, and (3) lack of force/load concentrations into singular components and/or subsystems—thereby reducing structural and maintenance costs. Considering the full range of cost and performance drivers, it is important to note that the application of DEEC-Tec to ocean wave energy conversion has the potential to bring about multiple and significant advances in all four cost and performance driver categories, namely power absorption and conversion, availability, capital expenditures, and operational expenditures. DEEC-Tec thus represents a promising, high-potential research effort.

Descriptions at all three levels of the DEEC-Tec hierarchy were given: (1) individual DEECs, (2) DEEC-Tec metamaterials, and (3) DEEC-Tec-based WECs. In addition, topologies (shapes, geometries, forms) and morphologies (deformability and compliant design characteristics) that are advantageous for DEEC-Tec-based WECs were highlighted, along with various manufacturing and fabrication techniques deemed most appropriate for DEEC-Tec. Note, there are numerous opportunities for applied innovation techniques within the vast domain of DEEC-Tec and, correspondingly, there are many new materials and manufacturing methods that have not yet been invented or sufficiently developed to capture the full potential of DEEC-Tec.

Being such a large domain, DEEC-Tec covers a multitude of disciplines, materials, manufacturing and fabrication methods, and technologies. Future work will include continuing the exploration of the design space to identify those areas most promising for high-potential solutions at all hierarchy levels: for individual DEECs, for DEEC-Tec metamaterials, and for DEEC-Tec-based WECs. Future work will also create a design guide for technology developers interested in this space, which will explain how to design, develop, manufacture, build, and test a DEEC-Tec technology and/or DEEC-Tec-based WEC.

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