DIRECT GENERATION REPORT

PROGRAMME SUMMARY

Wave Energy Scotland

31st March 2026

1 Executive Summary

1.1 Purpose of the Programme

The Direct Generation (DG) programme was established to explore a radical innovation pathway for wave energy. It investigated fully flexible, distributed generation technologies with the potential to deliver a step-change in cost reduction beyond what conventional Power Take-Off (PTO) systems can achieve currently. This programme builds on two decades of international research and investigative studies performed by WES in the area. The programme supports both concept development and the enabling R&D required to assess technical feasibility, manufacturability, and long-term commercial potential.

1.2 What is Direct Generation?

Direct Generation refers to a class of soft electrostatic generators that convert mechanical deformation directly into electrical energy using variable capacitance mechanisms. They achieve this through exploiting the stretchable and flexible properties of electroactive polymers under wave loading. Two variable capacitance technologies were investigated in the DG programme:

- **Dielectric Elastomer Generator (DEG):** A DEG consists of a dielectric elastomer membrane coated with two **stretchable** electrodes. When the membrane stretches or relaxes, the electrode separation and surface area change, producing a variation in capacitance that can be exploited to generate electrical energy.
- **Dielectric Fluid Generator (DFG**): A DFG uses a dielectric fluid enclosed by a flexible dielectric film and **flexible** electrodes to form a variable-geometry capacitive cell. During operation, fluid motion causes the cell to *"zip"* and *"unzip,"* altering the electrode contact area and capacitance in a rhythmic cycle that enables electrical energy generation.

These technologies enable a new class architecture for wave energy converters (WEC) that are lightweight, modular, and potentially free from complex steel structures.

1.3 Programme Approach

The programme followed a three-strand innovation model:

1. **Design Competition** to generate, down-select and iterate DG-enabled WEC concepts while identifying key technical risks and research priorities, broken down into two rounds:
    - **Round 1:** Five teams participated in an intensive 14-week concept development phase, producing system architectures, identifying systematic benefits, and mapping fundamental R&D needs.
    - **Round 2:** Two teams – 4c Engineering and TTI Marine Renewables – were selected for Round 2. This second round took place over a longer period of 9 months which involved a series of enabling R&D work packages performed for different subsystems to progress their technologies to later stages, e.g., power electronics, electrode-film manufacturing.
2. **Research Projects** to deliver fundamental advances in materials, structures and electro-mechanical fatigue, these projects included:
    - **University of Oxford & Plymouth (FlexFund):** Design and testing of origami-inspired structures for DFGs.
    - **University of Manchester: (FlexFund)** Design and synthesis of stretchable nanocomposite electrodes for DEGs.

- **Swansea University (EPSRC-PhD):** Electro-mechanical fatigue characterisation of DEG/DFG systems.

3. **External Stakeholder Engagement** to meet with leaders in the field such as SBM Offshore and Wacker Chemie AG for technology transfer and knowledge exchange activities.

1.4 Technical Assessment

The outcomes of the programmes allowed for a comparison and assessment of DEGs and DFGs. DEGs are more developed, with clearer performance limits and a simpler deformation-based integration into WECs. But they face fatigue challenges due to the high-strain operation of elastomers. DFGs are at earlier-stage in maturity but offers benefits such as the potential for longer fatigue life from near-zero strain operation and inherent fluid self-healing. The natural end-stop of zipping and unzipping cells could potentially offer more controllable behaviour, albeit with added fluid handling complexity. Together, the concept designs showed systematic-level benefits, including lightweight and morphable structures, distributed energy extraction solutions, modularity with failure redundancy, scalable manufacturing, and advanced functionality such as variable stiffness and self-sensing.

These technologies were assessed against performance metrics including power density, longevity, manufacturability, sustainability, and cost of energy. The analysis also highlights a strong interdependence between power density and longevity, suggesting that future DG devices may require a different economic model, which accepts more frequent replacement of low-cost modules within a larger wave energy converter through a *“use-and-replace”* strategy. On the manufacturing side, DG technologies show promise, with several scalable processes identified that could support commercialisation. However, designing for circularity will be essential to avoid excessive material wastage. While the current cost-performance ratio sits at the lower end of the state-of-the-art and remains subject to several unknowns, the programme revealed substantial innovation opportunities across materials, cell architecture, and power electronics. To simplify the innovation landscape, three areas were prioritised as the primary drivers of levelised cost of energy: power density, longevity, and metamaterial cost. Guidance targets were developed accordingly, including increasing power density to at least 40 W/kg, extending module lifetimes to a minimum of seven years, and reducing metamaterial costs below £50/kg. Despite the challenges, Direct Generation remains a credible and innovative pathway for future wave energy systems, provided that sustained R&D efforts continue across materials development, device design, manufacturing methods, and system integration. The programme has mapped the research themes, associated subtasks, and the stakeholder groups best positioned to deliver them.

1.5 Recommendations

Progressing Direct Generation will require coordinated international collaboration and strong cross-sector engagement. Many of the core research challenges — materials development, stretchable electrodes, metamaterial architecture, scalable manufacturing, and electromechanical characterisation — are shared with adjacent fields such as soft robotics, flexible electronics, biomedical devices, and advanced sensing. Leveraging these overlaps expands the funding base, reduces early-stage risk, and accelerates technology maturation. A staged development pathway is recommended: first advancing materials and prototypes through cross-sector R&D, then demonstrating DG in stepping-stone applications such as sensors, actuators, and small-scale generators, before progressing to larger marine demonstrators and ultimately utility scale WECs.

Contents

Acronyms and terms

Abbreviations	**Definitions**
CAPEX	Capital Expenditure
CWR	Capture Width Ratio
DG	Direct Generation
DEG	Dielectric Elastomer Generator
DFG	Dielectric Fluid Generator
HASEL	Hydraulically Amplified Self-healing ELectrostatic
IEA-OES	International Energy Agency – Ocean Energy Systems
LCOE	Levelised Cost of Energy
OPEX	Operational Expenditure
PCP	Pre-Commercial Procurement
PTO	Power Take-Off
TRL	Technology Readiness Level
WEC	Wave Energy Converter

2 Introduction

2.1 Wave Energy Opportunity

Meeting the UK's decarbonisation targets will require substantial renewable energy deployment and a balanced mixture of generation technologies that supports system stability. Wind and solar dominate new renewable capacity, but alongside these pathways, ocean energy offers a significant contribution and unique complementary characteristics to enhance grid system reliability by reducing variability and overall grid storage requirements[1]. The UK has an estimated 69 TWh/year (27 GW) of theoretical wave energy resource, with Scottish waters holding the largest share[2].

In the period of 2000s to early 2010s, several large-scale prototypes demonstrated the feasibility of extracting electricity from ocean waves at meaningful power levels. Pelamis remains one of the most ambitious Wave Energy Converters (WECs) deployed to date[3], alongside other technologies such as Aquamarine Power[4]. While these early prototypes showed strong performance potential, many relied on intricate electro-mechanical or hydraulic PTO systems with numerous moving parts, which needed further systematic investigation before integration into large WEC systems. The eventual collapse of these companies highlighted the need for sustained, structured, and collaborative funding to tackle shared technical challenges and create a credible pathway toward commercial viability. This recognition led to the development of dedicated innovation programmes, notably those delivered by Wave Energy Scotland, which has been instrumental in advancing the next generation of wave energy technologies.

2.2 Wave Energy Scotland Programme

Wave Energy Scotland (WES) was established by the Scottish Government in 2015 as a technology development body dedicated to advancing wave energy. Since its inception, WES has invested over £70 million to accelerate innovation in this sector. Central to its approach is the use of the Pre-Commercial Procurement (PCP) model — a structured, stage-gate framework that supports technologies as they progress from early-stage concepts to higher levels of maturity, combining competitive down-selection with continuity of support.

WES applied this model across five key technology areas that represent critical challenges and opportunities for the wave energy sector:

- Power Take-Off
- Structural Materials
- Control Systems
- Quick Connection Systems
- Novel Wave Energy Converters

In addition to these programmes, WES is the lead partner in the EuropeWave program, collaborating with the Basque Energy Agency to apply the PCP model at a European scale, enabling large-scale wave energy converter development. Beyond its direct funding activities, WES has also played an influential role in shaping the IEA-OES framework — an internationally recognised roadmap for the development of marine energy technologies, helping to guide global strategic direction in the sector.

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[1] Noble DR, Pennock S, Coles D, Delahaye T, Jeffrey H. Quantifying the System Benefits of Ocean Energy in the Context of Variability: A UK Example. Energies. 2025 Jul 14;18(14):3717.

[2] https://www.marineenergycouncil.co.uk/news/wave-energy-to-have-a-key-role-in-realising-the-uk-s-net-zero-ambitions-according-to-new-report

[3] https://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/

[4] https://www.emec.org.uk/about-us/wave-clients/aquamarine-power/

The ongoing work and outcomes from the WES programme show the latest generation of wave energy devices and subsystems are approaching commercial readiness. This is supported by growing recognition of their value in high-renewable energy systems and their potential to share ocean space, infrastructure, and supply chains with the offshore wind sector. This has been evidenced by the success of companies, such as Mocean and CorPower, now seeking commercial deployment opportunities. In addition, there are other companies, e.g., BlackFish and Apollo, that are applying their Quick Connection Systems to adjacent floating wind sectors.

Alongside this pathway, there is the need to seek innovations that could lead to radical improvements in cost, performance and reliability, beyond possible with the current technology systems.

2.3 Radical Innovation in Wave Energy

Wave energy converters span a wide range of archetypes and configurations, but their functional architecture can be decomposed into three subsystems:

- Primary mover: The hydrodynamic interface that extracts wave induced forces and motions to deliver mechanical power at the device boundary.
- Power take-off: The conversion chain that transforms the mechanical input, e.g., force-velocity, into electrical output, typically through hydraulic or electro-mechanical transduction.
- Non-harvesting subsystems: The structural and enabling systems which make up the remainder of the device. These include the hull/structure, moorings, control, and power electronics.

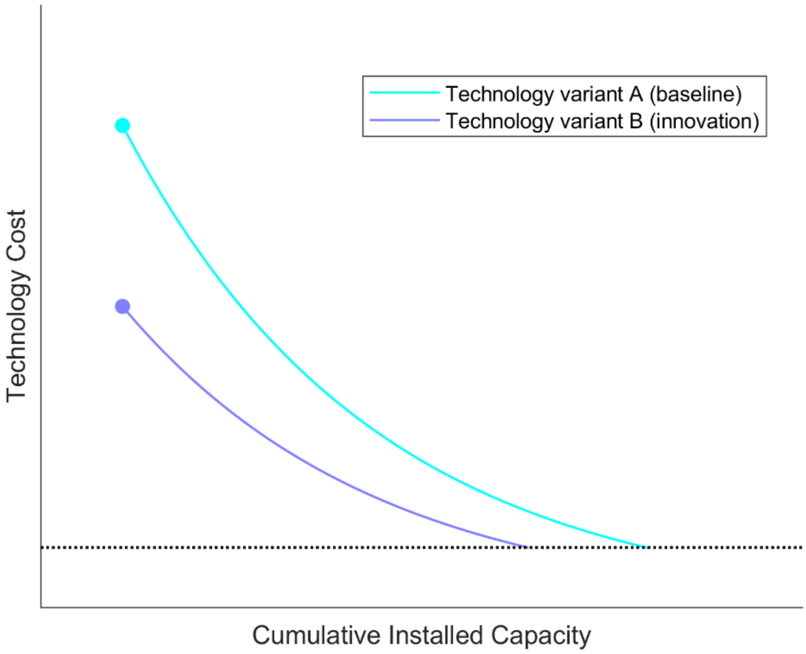

Figure 1: Illustration of baseline experience curve (technology variant A) and a lower cost experience curve representing a technology innovation (technology variant B) (Paul Kerr, 2024).

The majority of WECs utilise permanent-magnet electromechanical or hydraulic PTOs due to their maturity and proven success for other applications. The trend of lowering technology cost with increasing capacity over time is widely observed in many sectors, such as computer processors and solar photovoltaic panels. There may also be opportunities for disruptive innovation to introduce a significantly lower cost (or better performing) variant of a technology. Analogies from adjacent renewables illustrate how architecture-level simplification can unlock step-changes in cost and reliability. In wind energy, the adoption of direct-drive permanent-magnet generators removed multi-stage gearboxes from the drivetrain, reducing mechanical failure modes and maintenance exposure while enabling new scaling pathways. Likewise, in solar, the use of photovoltaic wafers offered a modular, highly scalable route compared to thermal solar. As illustrated in Figure 1, a similar innovation in wave energy could result in a technology reaching its desired economic potential sooner, as well as being cheaper on the pathway to that target. Direct Generation (DG) is a promising vehicle for those future step-change improvements.

2.4 Direct Generation

Direct Generation is the application of novel electrostatic generation technologies. This uses the flexible properties of elastomers and polymers to drive variable capacitance, a characteristic that can be used to directly transform movement (stretching, twisting, bending) of a material, into electrical energy. Two examples of these technologies are Dielectric Elastomer Generators (DEGs) and Dielectric Fluid Generators (DFGs). These technologies have potential to bring many benefits when applied in wave energy:

- Enables a new class of flexible architectures, without reliance on high-cost steel structures.
- Simplified power conversion process relative to conventional wave energy architectures.
- Greater percentage of the wave energy converter's (WEC) mass and cost directly involved in energy generation, reducing the share of mass and cost in other areas.
- Distributed generation throughout the body of the wave energy converter.
- Adaptable, tuneable, and survivable in varying wave energy resources.

2.5 Aims and Scope of this Report and the Wider WES DG Programme

This document is a summary of the outcomes from the Direct Generation programme and provides suggestions on a future pathway to commercialisation. Section 4 introduces the state-of-the-art in DG, explaining how these technologies operate and how they can be integrated into WEC architectures. Section 5 provides an overview of the DG programme itself, detailing its three key strands: the design competition, the supporting research projects, and the external stakeholder engagement activities. This section also outlines how the programme was structured and delivered. Section 6 presents the programme outcomes, including the high-level benefits identified, the performance assessment of DG technologies against key metrics, and the resulting research tasks. Finally, Section 7 offers recommendations for advancing DG through future technology stage-gates and includes a stakeholder map that identifies the organisations best placed to support progression.

3 Background on Direct Generation

The motivation behind Direct Generation is to pursue a radical innovation pathway that can deliver significant cost savings by reducing the overall number of components and enabling greater modularity. This idea builds on two previous strands of research: **electroactive polymers** and **large-scale flexible marine structures**.

Variable capacitance electroactive polymers have been investigated for several decades. These technologies operate on the principle of Maxwell stress, a long-established physical phenomenon in which an applied electric field generates an electrostatic pressure across a dielectric material. Depending on how this effect is used, the same material system can function in two modes: actuator or generator. In actuator mode, the electric field actively deforms the material by compressing it through Maxwell stress. In generator mode, external mechanical forces deform the material, and the resulting change in Maxwell stress and capacitance is used to harvest electrical energy. These technologies have broad cross-sector applications, including actuators for soft robotics and medical devices, active motion and vibration control in acoustic systems, variable stiffness suspension and tyre concepts in the automotive sector, generators for wearable electronics, and power generation components within renewable energy systems.

Large-scale flexible marine structures have already been investigated extensively for wave energy, beginning with devices such as the Lancaster Bag and Sea Clam in the 1980s, and later evolving through prototypes developed by Checkmate and Bombora in the 2010s[5]. These devices use the deformation of the structure to drive motion of an internal working fluid through turbomachinery, with the flexible structure typically made of an elastomeric composite.

Direct Generation builds on both approaches and is the idea of not only using a flexible WEC structure but also embedding and distributing the electroactive material throughout the entire device. This represents a fundamental paradigm shift: rather than concentrating energy capture at a single mechanical interface, power is harvested across the full structural area. As a result, the energy harvesting process becomes more comparable to solar energy extraction, where energy is captured and converted over a large surface area, instead of focused on a localised concentrated point. Two of the most promising variable capacitance technologies are Dielectric Elastomer and Dielectric Fluid Generators which work on the same principle, but use a different mechanism to achieve capacitance change, these are outlined in Section 2.1 and 2.2.

3.1 Dielectric Elastomer Generator (DEG)

Dielectric elastomer actuators have been researched since the 1990s[6], but their use as energy generators was first reported in 2001 by Ron Pelrine et al[7]. This landmark paper spurred significant interest from academia and industry, leading to extensive research into harvesting energy from various sources like wind, waves, vibrations, and human motion. Several WEC implementations utilising DEGs have been explored. Notably, SRI International developed a heaving buoy WEC that replaced the traditional hydraulic PTO system with a cylindrical stack of

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[5] Collins I, Hossain M, Dettmer W, Masters I. Flexible membrane structures for wave energy harvesting: A review of the developments, materials and computational modelling approaches. Renewable and Sustainable Energy Reviews. 2021 Nov 1;151:111478.

[6] Pelrine, Ronald E., Roy D. Kornbluh, and Jose P. Joseph. "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation." *Sensors and Actuators A: Physical* 64.1 (1998): 77-85.

[7] Pelrine, Ron, et al. "Dielectric elastomers: generator mode fundamentals and applications." Smart Structures and Materials 2001: Electroactive Polymer Actuators and Devices. Vol. 4329. SPIE, 2001.

DEG material[8], and with similar concepts patented by Bosch[9]. SBM Offshore developed a bulge-wave WEC since the early 2010s, incorporating DEG rings along the length of a tubular structure[10], with a similar concept described in an AWS Ocean Energy Limited patent[11]. The PolyWEC project, a collaboration between the Universities of Trento, Bologna, SSSUP (Pisa), and Edinburgh, investigated DEG integration into various WEC types, including oscillating water columns, surge devices, and pressure-differential devices. Scaled testing of the oscillating water column and submerged pressure-differential device was conducted at the FloWave facility[12].

Fundamentally, the operation of a DEG relies on charging and discharging a variable capacitor. In an idealised configuration, consider an elastomer sandwiched between two stretchable electrodes. The capacitance of a stacked electrode-dielectric system is governed by:

$$C = \frac{\varepsilon A}{d} \tag{1}$$

where C is the capacitance, ε is the permittivity of the dielectric material, A is the surface area of the electrodes and d is the distance between the electrodes. The permittivity of dielectric material is amount of charge that can be stored at the electrodes, with values differing across material systems. Elastomers are approximately incompressible, so when stretched their surface area increases while thickness decreases; applying a charge at points in this cycle can lead to a net-gain in electricity. The constant charge energy harvesting cycle is one of the most common and is shown in Figure 3, with the process of energy harvesting can be explained in four distinct stages, relating to Figure 2:

- **A-B:** The elastomer is stretched by external loading, increasing the surface area and reducing its thickness. This increases the overall capacitance.
- **B-C:** At the maximum stretch, the electrodes are charged.
- **C-D:** As the external load is removed, the elastomer relaxes. The electrodes move further apart, causing the capacitance to decrease. Since charge is held constant, voltage rises as the membrane relaxes.
- **D-A:** Once the membrane has returned to its relaxed state, the stored charge is released. Because the discharge occurs at a higher voltage than the charging event, net electrical energy is harvested.

In Figure 3, the constant charge cycle is illustrated with the blue bounds of maximum and minimum capacitance (C_{max} and C_{min}). The maximum electrical field limit is illustrated with E_{max}. The energy amount of harvested from a cycle depends on the capacitance change and the corresponding charge or voltage applied, for a constant charge energy cycle this can be expressed as:

$$\Delta E = E_2 - E_1 = \frac{1}{2}(C_2 V_2^2 - C_1 V_1^2) \tag{2}$$

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[8] Kornbluh, Roy D., et al. "From boots to buoys: promises and challenges of dielectric elastomer energy harvesting." *Electroactivity in polymeric materials* (2012): 67-93.

[9] Scherber, Benedikt, Matthias Grauer, and Andreas Köllnberger. "Electroactive polymers for gaining sea power." *Electroactive Polymer Actuators and Devices (EAPAD) 2013*. Vol. 8687. SPIE, 2013.

[10] Jean, Philippe, et al. "Standing wave tube electro active polymer wave energy converter." *Electroactive Polymer Actuators and Devices (EAPAD) 2012*. Vol. 8340. SPIE, 2012.

[11] Grey, Simon, and Andrew Borthwick. "Apparatus and method for extracting energy from fluid motion." U.S. Patent No. 8,633,608. 21 Jan. 2014.

[12] European Commision CORDIS EU research results, New mechanisms and concepts for exploiting electroactive Polymers for Wave Energy Conversion, https://cordis.europa.eu/project/id/309139/reporting. 2020

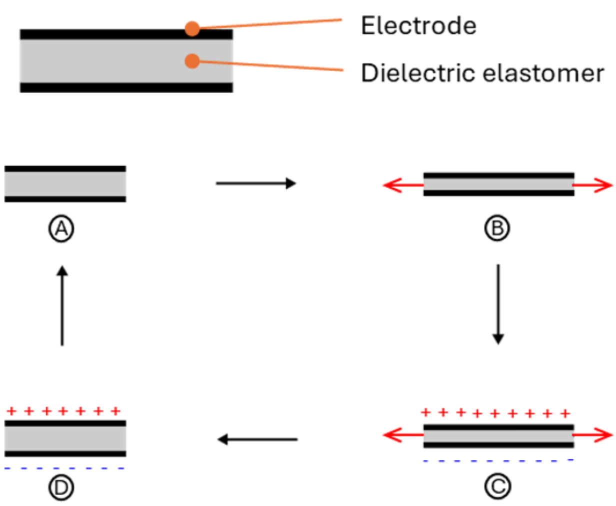

Figure 2: Dielectric Elastomer Generator harvesting cycle

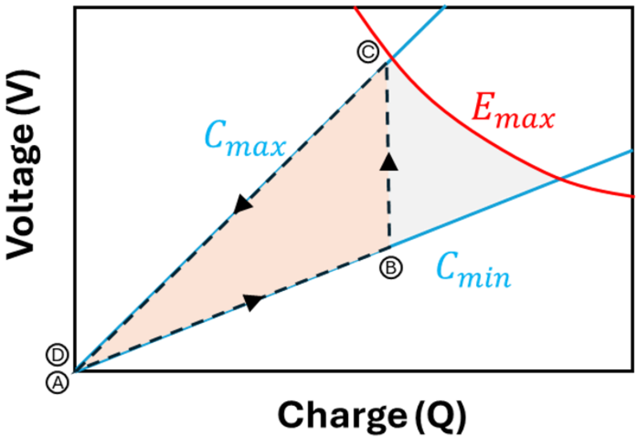

Figure 3: Dielectric Elastomer Generator harvesting cycle (a) Elastomer schematic (b) Constant-charge cycle

As harvested energy depends quadratically on voltage, operating at higher voltages can significantly increase harvested energy. However, dielectric breakdown imposes a strict upper bound on operational voltage, particularly as films become thinner. Furthermore, maximising the area under E_{max} becomes important for improving the energy density, which is detailed extensively in Section 4.3.1.2.2.

3.2 Dielectric Fluid Generator (DFG)

In contrast to DEGs, Dielectric Fluid Generators (DFGs) are a relatively nascent technology with limited research to date[13, 14]. While less extensively studied, DFGs have shown promise in actuator form, particularly as Hydrostatic Actuators with Sealed Elastomeric Layers (HASELs) for soft robotics applications[15].

The operational principle of a DFG is analogous to that of a DEG with the key difference being that the primary deformable medium is a dielectric fluid rather than a solid elastomer. The fluid is typically contained within a series of interconnected cells or chambers. When external mechanical loading is applied, the fluid is

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[13] Duranti, Mattia, et al. "A new class of variable capacitance generators based on the dielectric fluid transducer." *Smart Materials and Structures* 26.11 (2017): 115014.

[14] Yang, Ruisen, et al. "A new flexible electrostatic generator using dielectric fluid." *Journal of Applied Physics* 134.10 (2023).

[15] Kellaris, Nicholas, et al. "Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation." *Science Robotics* 3.14 (2018): eaar3276.

redistributed between these cells, producing variations in electrode separation and effective capacitance, thereby enabling electrostatic energy harvesting.

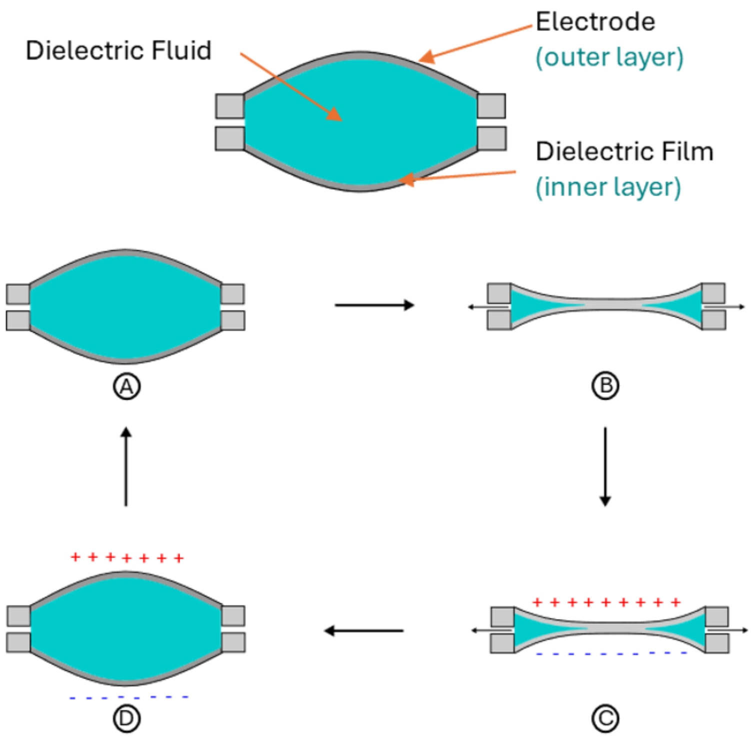


Figure 4: Dielectric Fluid Generator harvesting cycle

A typical DFG layout differs from a DEG, requiring flexible electrodes which are bonded to a flexible dielectric film which encapsulates a dielectric fluid, thereby having both solid and fluid dielectrics. The dielectric film isolates the opposing electrodes to prevent short-circuiting when all the fluid is evacuated from a cell. Taking a similar constant charge harvesting method, the process can broadly be categorised into four distinct stages:

- **A-B:** The cell has the maximum amount of fluid and electrode separation is at a maximum, this is referred to as the **unzipped state**.
- **B-C:** An external load causes the cell to compress resulting in negative fluid pressure and fluid to leave the cell, until the electrodes reach their closest distance. Then a charge is placed on the electrodes. This referred to as the **zipped state**.
- **C-D:** As the cell is unloaded, the positive fluid pressures cause the cell to refill, causing the capacitance to decrease. The charge is held constant and the voltage increases.
- **D-A:** Once the cell has refilled returning to an **unzipped state**; the stored charge is released. Because the discharge occurs at a higher voltage than the charging event, net electrical energy is harvested.

3.3 DG WEC Archetypes

Wave energy can be extracted in various locations: nearshore, far offshore, on the surface, or submerged near the seabed. This diversity has led to numerous archetypes of WECs, each tailored to exploit different forms of wave-induced motion. As a fundamentally different approach to power take-off, DG was expected to benefit from a similar breadth of conceptual possibilities.

To explore this design space, WES held a workshop in 2022 to identify potential DG WEC archetypes. The workshop centred on architectures that maximise the proportion of electroactive material within the load path while minimising dependence on metallic structural components. This exercise resulted in the four archetypes illustrated in Figure 5. These designs show how the hydrodynamic interaction of the waves can lead to strain/fluid excitation and to direct generation:

- **Point Absorber:** Experiences heave motion (vertical oscillation) as it rides wave peaks and troughs, generating power through its interaction with the seabed.
- **Bulge Wave:** A pressure differential across the length of a tubular structure causes a propagating bulge, capturing wave energy.
- **Surge Converter:** Undergoes horizontal surge motion (back and forth) driven by wave forces, converting this motion into power.
- **Mattress Converter:** Experiences varying pressure distributions across its surface, leading to compression and extension in different areas, capturing wave energy through these deformations.

The electroactive polymer integration of cells is shown in Figure 6. Each cell consists of an individual DEG/DFG unit; multiple cells combine to form a metamaterial, which in turn forms modular units. The overall WEC architecture is then constructed from these interconnected modules.

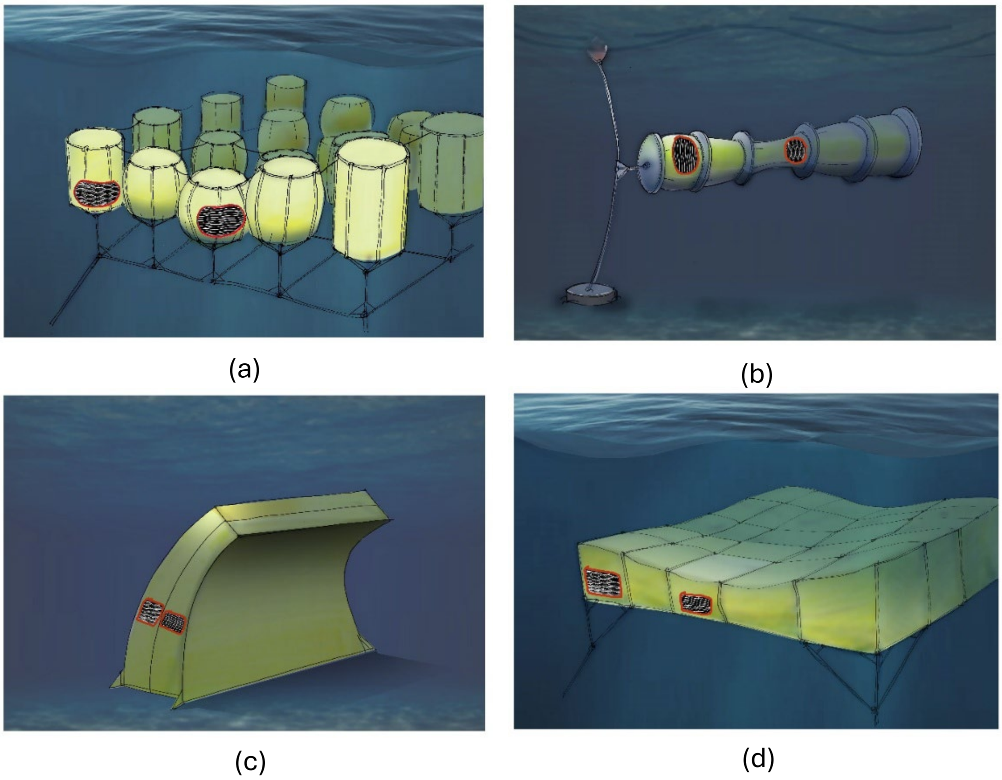
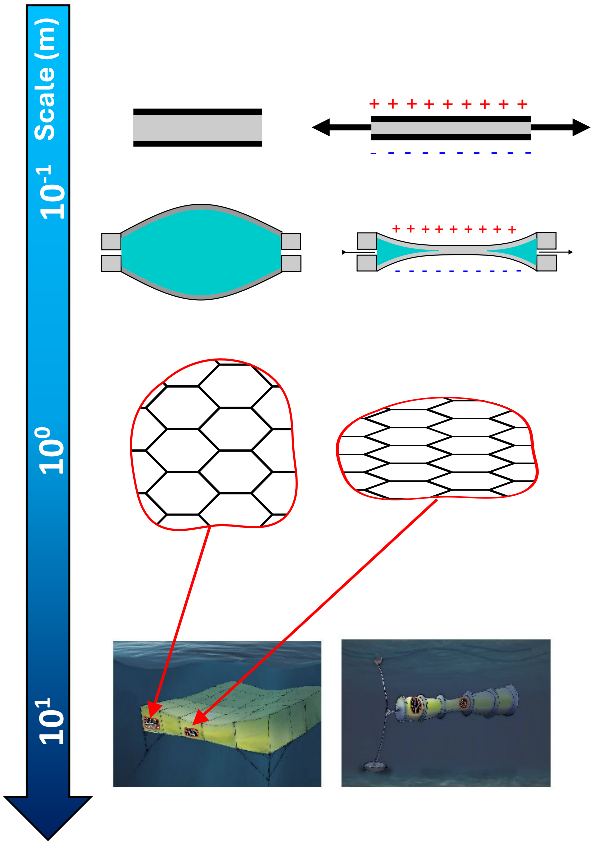


Figure 5: Possible Direct Generation WEC archetypes, starting from top left: point absorber, bulge wave, surge flap and mattress



Level 1: Individual Cell

Electroactive DEG/DFG Cell which generates electricity from stretching and deformation.

Level 2: Module

Cells aggregate (e.g., Honeycomb) to from a metamaterial where tens to hundreds of cells form a module.

Level 3: Wave Energy Converter

A WEC is discretized into modules.

Figure 6: Hierarchy of Direct Generation WEC, starting from individual cells through to metamaterials to WEC devices.

4 Direct Generation Programme

Wave Energy Scotland has monitored developments in electroactive technologies by reviewing external programme results, commissioning internal studies, and subsequently establishing its own feasibility and R&D programme. This staged process has steadily expanded the knowledge base and informed strategic decision making.

4.1 External Programmes

During the 2010s, two major development programmes played an important role in shaping the DG landscape:

- **PolyWEC (FP7, 2012–2017):** Funding by the European Commission's Seventh Framework Programme (FP7). The PolyWEC project carried out a comprehensive investigation into DEGs, including materials research, numerical modelling, and wave-tank testing of several small-scale prototypes, as well as techno-economic and environmental assessment[16]. An example prototype was a 1:30th scale floating Oscillating Water Column device built and tested at FloWave, with a diameter of 0.4m and length of 1.6m, equating to 2–3 W power output which is estimated to be 300–440 kW at full-scale.
- **SBM Offshore S3 Programme (ADEME-supported):** Single Buoy Mooring (SBM) were supported through the French government's ADEME-managed innovation funding to develop the SBM S3 WEC. The S3 is a fully flexible submerged tube made from electroactive polymer, functioning similarly to a DG device by directly converting wave-induced deformation into electricity. The programme has involved extensive prototype development, including large-scale tank (35m length) testing at l'École Centrale de Nantes for hydrodynamic validation, as well as significant R&D development for manufacturing of large-scale DEGs. The latest prototype device has a diameter of 1.2m and length of 10m and length, comprising of multilayer DEG tubes. Despite this progress, the team identified significant physical challenges related to scale-up of DEGs which have added uncertainty to achieving foreseeable techno-economic viability[17], noted extensively in Section 3.9.1.
- **DEEC-Tec & InDEEP (Supported by US Department of Energy and National Laboratory of the Rockies):** The NLR have investigated Distributed Embedded Energy Converters technologies (DEEC-Tec). These are akin to Direct Generation technologies with a similar philosophy to design, compromising of differing hierarchy levels. The NLR have patented devices, performed research investigations with the University of Florida, and most notably run an innovation prize. The Innovating Distributed Embedded Energy Prize (InDEEP) prize started in March 2023 and finished in February 2025. The two year prize had a $2.3 million purse, and was launched by the US DoE Water Power Technologies Office (WPTO) in partnership with NLR and Sandia National Laboratories. The competition had the aim of advancing distributed embedded energy converter technologies (DEEC-Tec) for wave energy applications and comprised of three stages:
    - Phase 1: Concept Creation. Focussed on team building and developing initial DEEC-Tec concepts with up to 20 winners at $15,000 each.
    - Phase 2: Prototype Proof-of-concept. Development of bench-top prototype where up to 15 teams could win $80,000 each. This was open to new and returning competitors.
    - Phase 3: Complex Prototype. The development of integrated multiple DEECs into a metamaterial with techno-economic analysis. Up to 4 teams could with $200,000 each.

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[16] Moretti G, Herran MS, Forehand D, Alves M, Jeffrey H, Vertechy R, Fontana M. Advances in the development of dielectric elastomer generators for wave energy conversion. Renewable and Sustainable Energy Reviews. 2020 Jan 1;117:109430.

[17] Taine E, Claverie A, Caille F, Seima S, Fourdilis N, Hendrikse JM, Boulard R. The S3 wave energy converter story. In Electroactive Polymer Actuators, Sensors, and Devices (EAPAD) 2025 2025 May 12 (Vol. 13431, pp. 119-129). SPIE.

4.2 WES Prior Investigations

WES has supported research into DG technologies through multiple avenues, including its PCP programme, an externally commissioned landscape review, and PhD-level research. These are outlined below:

- **Power Take-Off (PCP):** In 2017, WES investigated DEGs through a project funded through WES' PTO programme: *the Direct Contact Dielectric Elastomer PTO for Submerged Wave Energy Converters*, which expanded on concepts emerging from PolyWEC. This project further developed DEG-based submerged WEC concepts, assessed technical feasibility, and documented lessons learned from prototype development and testing, reaching Stage 2 within the call. However, due to its low Technology Readiness Level (TRL) at the time, it did not progress to Stage 3, despite demonstrating promising techno-economic potential for future development[18].
- **Frazer-Nash Study:** In 2020, WES commissioned Frazer-Nash to perform an extensive review of *'Alternative Generation'* technologies. Using a stage-gate down-selection process, four technologies were down-selected for the final economic analysis stage: Triboelectric, Dielectric Elastomers, Piezoelectric and Magnetostrictive technologies. One key conclusion was that *'Alternative Generation technologies (at least over the next 25 years) will not deliver a step change reduction in the cost of energy when used as a direct replacement of the Electrical Generation Subsystem alone, with the potential exception of DEG.'* The study also highlighted that substantial LCOE improvements could be achieved if alternative generation technologies replace other subsystems within the WEC, such as the mechanical conversion stage or major structural elements. DEGs were identified as a potential enabling technology in this regard. Despite this potential, DEGs were observed to suffer from poor overall economic performance at scale, driven predominantly by low power density and the resulting requirement for large volumes of electroactive material.
- **Direct Generation PhD:** In a similar vein, WES funded a PhD to investigate DG technologies, titled: *'Radical innovation for the wave energy sector, an investigation of the potential of direct conversion as an enabling technology.'* This research conducted a detailed literature review on the state-of-the-art alternative generation technologies found in the prior Frazer-Nash study, developing metrics relating to cost, energy output, lifetime, durability, and embodied carbon of the direct conversion technologies. Minimum performance thresholds were identified for these parameters and embedded into a two-stage process where technologies were accepted or rejected at each gate. The project evaluated six technologies with DEGs and DFGs showing the most promise by passing both stage-gates, but partly due to a lack of evidence to rule them out.

4.3 Innovation and Strategy of DG Programme

Building on this trajectory, WES sought to investigate DG technologies using a multifaceted approach. This included fostering innovation and design via a design competition and advancing research through the funding of postdoctoral and doctoral research projects. WES's earlier assessments of alternative generation technologies identified two promising candidates for further exploration: DEGs and DFGs which would be the technologies investigated in the next stages. The goal of the design competition was to stimulate fundamentally new DG concepts. Whereas earlier work often explored electroactive polymers as drop-in replacements for conventional PTO systems, the DG programme aimed to transform this approach, seeking architectures where electrostatic generation is directly and integrally coupled to the primary wave-driven motion. The innovation programme consisted of three-strands:

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[18] Wave Energy Scotland. Direct Contact Dielectric Elastomer PTO For Submerged Wave Energy Conversion. Stage 2 Report. Available: https://www.waveenergyscotland.co.uk/wave-technology/power-take-off/direct-contact-dielectric-elastomer-pto-for-submerged-wave-energy-converters/

- **Design Competition:** A two-phase design competition was launched to stimulate innovative concepts. The first phase involved five teams and began in September 2023, running for 14 weeks. Its purpose was to generate a broad range of concepts that demonstrate initial feasibility and offer systematic benefits, as well as identify the key R&D requirements needed for further progression. The second phase, launched in March 2024, involved a down-selection to two teams and ran for nine months. This phase focused on a more detailed analysis of the selected concepts, enabling further refinement, providing targeted insights to inform future R&D priorities, and assessing each concept against a series of performance metrics.
- **Fundamental Research:** Concurrent with the second round of the competition, WES funded fundamental research in key areas to support the development of these promising technologies. WES built a suite of enabling R&D projects which focused on addressing these needs, starting with two 12-month Supergen ORE Impact Hub FlexFund projects and one 4-year PhD, covering material, metamaterial and module development.
- **Knowledge exchange, collaboration and outreach:** During the competition stages, WES held two workshops with the Direct Generation project teams and engaged stakeholders from outside the programme for knowledge exchange. WES has presented project and research findings at leading conferences in the field such as All Energy, IOM3 events and EuroEAP.

Figure 7 illustrates a strategic roadmap where the design competition generates a series of design vehicles for vision and to generate the R&D requirements to inform the enabling R&D. From the outcomes of the programme, the research may find its way into other stepping-stone applications before making their way into wave energy.

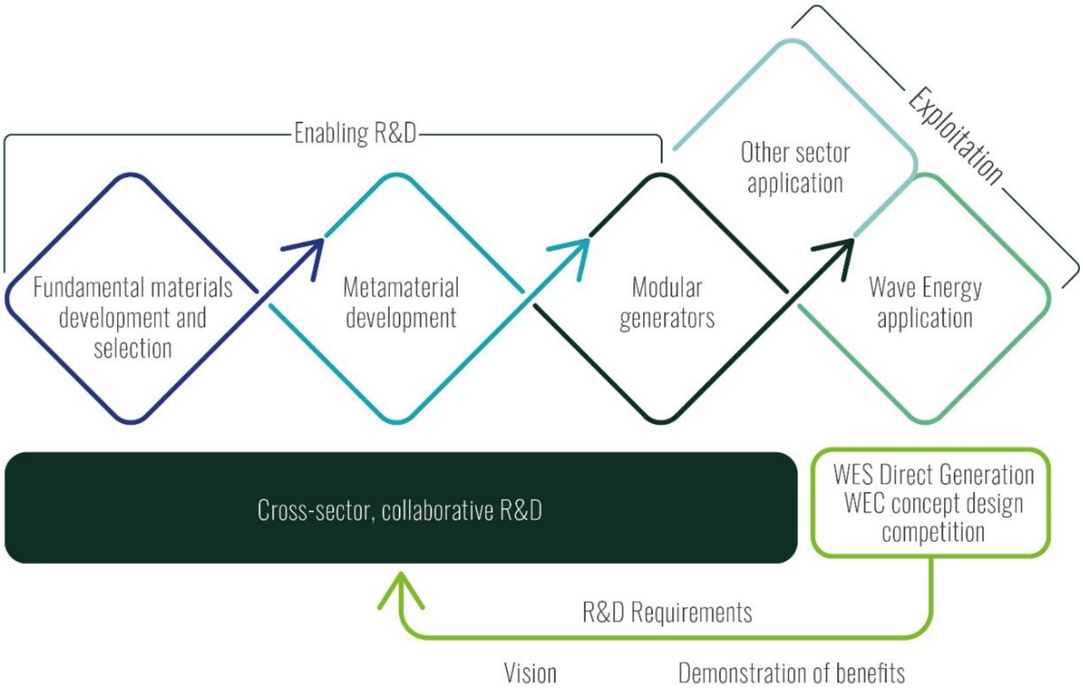

Figure 7: WES Strategy for Direct Generation

4.4 Design Competition: Round 1

The first round of the competition was used as means to garner interest in DG, produce a series of design vehicles and act as a springboard into later stages. This started with a brokerage event which enabled interested stakeholders to find out more about the competition. Following this, teams were invited to apply for the first round through a proposal and evaluation process, where five teams were selected to be taken forward. The process is illustrated in Figure 8.

1. Invitation and Evaluation:
Brokerage event to kick-off programme and share the plan for DG programme. Teams were invitied to apply with 17 proposals reviewed and 5 teams taken forward to design competition.

2. Concept Generation and Down-Selection:
Methodology for creating DG design concepts and down-selection of most promising concept to use as design vehicle

3. Understanding of Feasiblity:
High-level understanding of techno-ecnomic potential, technical risks, manufacturing and sustainability to justify further research

4. Identification of Research Tasks:
Identified list of resarch tasks required to make DG a reality for the next stages of development

Figure 8: Workflow for Direct Generation Round 1

4.4.1 Project Teams, Approach and Outcomes

4.4.1.1 4c Engineering (DFG) 'Ebb-Flow'

Team: 4c Engineering was project lead and worked with Cheros Srl on a DFG-based Direct Generation concept.

- **4c Engineering (4cE):** Engineering consultancy firm with experience in structured innovation, project management and technology development. 4cE has both led and participated in numerous wave energy related R&D funded by Wave Energy Scotland, EuropeWave, the US Department of Energy, and Innovate UK. This includes contributing to the development of the Sea Power platform within WES' Novel Wave Energy Converter programme, where the project progressed to Stage 2, as well as supporting the Quick Connection programme in a subcontractor role.
- **Cheros Srl:** Spin-out company of Scuola Sant'Anna, Pisa (Italy), established in 2016 as an outcome of pioneer projects on wave energy harvesting with DEGs, namely EU projects PolyWEC and WetFeet. Cheros has been involved in several projects, including WES projects in the framework of the PTO and Control calls and collaborations with other partners in the ocean engineering sector (e.g., Bombora Wave Power). Cheros core expertise is in the field of electroactive polymer devices and transducers in general, with a portfolio of activities that range from numerical modelling to experimental demonstration. In this project, they provide expertise in DFG systems including experimental and modelling work.

Approach: A methodological approach was applied in which designs are evaluated against a set of qualitative metrics, each weighted according to its level of importance. Two design streams are explored: (1) cellular DFG metamaterial configurations and (2) wave energy hydrodynamic interfaces. After identifying the optimal solutions within each stream, these were integrated into a single combined design.

Outcome: They converged on single design solution with a detailed technical feasibility assessment. The identified tasks for further development were material testing, scalability assessments, numerical modelling and turning the theory of Round 1 into a testable prototype where the performance and power electronics theory could be tested.

4.4.1.2 *AWS Ocean Energy (DEG)*

Team: AWS Ocean Energy partnered with several companies on this project with significant expertise in DEGs.

- **AWS Ocean Energy:** AWS is a wave energy technology developer with two decades of experience of conventional and flexible WEC structures. They were part of the Novel Wave Energy Converter programme reaching Stage 3 with their WaveSwing device. They have also investigated DEGs prior to this competition through the development of the patented Electric Eel DEG-based WEC concept.
- **4c Engineering & Cheros Srl:** See above. In this project they worked as design consultants.
- **SRI International:** SRI International is an independent nonprofit research institute headquartered in Menlo Park, California. SRI pioneered the invention of dielectric elastomers and created the spinoff company Artificial Muscle Inc. The technology has been licensed to several companies for a variety of applications including harvesting energy from ocean waves. They played an advisory role in this project.
- **Pelrine Innovations:** Led by Ron Pelrine who was principal inventor of dielectric elastomers in the early 1990’s. Ron Pelrine has led many of seminal advances in this field including identification of the DE mechanism, failure modes including electromechanical instabilities, development of a wide range of carbon and metal electrode materials, and discovery of the transducer DE properties of many of the leading DE materials including silicones and acrylics. They played an advisory role in this project.

Approach: This project had a basis of design which involved setting out the commercial requirements for a real world site location at Costa Head, whilst ensuring external practicalities were realistic for the expected lifetime. The team performed a thorough literature review along with knowledge capture sessions to identify the necessary input information for concept design generation and subsequent down-selection.

Outcomes: The down-selected design was modular, scalable, and optimised for regular DEG replacement throughout operational life. The design has been visualised with the creation of a 3D CAD model and high-level system breakdown which informed estimates on the annual energy production and bill of materials. This information allowed for a high-level techno-economic analysis to take place suggesting competitive levels of performance after scale-up and with learning rates applied. The team identified a series of critical R&D requirements relating to DEG fatigue and methods to optimise the lifetime energy of the design.

4.4.1.3 *TTI Marine Renewables (DEG)*

Team: TTI Marine Renewables partnered with the University of Manchester combining knowledge of marine energy systems, flexible structures and electrical engineering to work on this DEG project.

- **TTI Marine Renewables Ltd (TTI-MR):** The TTI team has prior experience with elastomeric materials offshore through the development of the Netbuoy as part of the Structural Materials program at WES. Throughout the three Stages of the NetBuoy project they developed significant hands-on experience in the design of marine structures using reinforced elastomer laminates and the behaviour and characteristics of elastomers in general. This included designing and conducting large-scale fatigue characterisation testing, net-on-membrane abrasion testing and a large-scale field trial demonstration. They also have a long established track record of advanced synthetic mooring systems for the marine renewables sector.
- **University of Manchester (UoM):** The Electrical Engineering and Materials departments brought both specialised material development and electrical testing expertise to the project. The university has the high voltage laboratory for the electrical utility sector alongside

elastomeric expertise in processing and characterisation from the world-renowned Graphene Institute. In this project, they delivered material development and testing of dielectric elastomer material systems.

Approach: The team engaged in various activities, including defining requirements, analysing prior art, creating and ranking concepts, and studying the governing physics. A technical risk-based approach was taken to qualify concepts and inform R&D priorities for the future. The concept identification process involved a formal brainstorming workshop facilitated by TRIZ (Theory of Inventive Problem Solving) experts at Oxford Creativity Ltd. TRIZ was used to rank concepts before conducting quantitative engineering analyses (time-domain models) for the shortlisted concepts.

Outcome: The team utilised their knowledge of the governing physics to develop an initial time domain model, which was used to build a power density matrix of the selected concept and calculate energy yield for the chosen wave environment. The concept was chosen because it maximises the use of DEG material in the device while minimising the need for relatively expensive rigid structures and mechanical elements. Cost and energy yield analysis demonstrated significant headroom in the levelised cost of energy when compared with published targets for wave power. The concept was designed to have good survivability and performance potential under average wave conditions with scalability in mind, making it applicable to different markets and sites. Some of the challenges identified included the durability and power density of the candidate DEG materials, but these were not considered insurmountable with ongoing research targeting these areas.

4.4.1.4 WaveX (DEG/DFG)

Team: The WaveX team collaborated with experts in DEGs and a major elastomer manufacture for their project.

- **WaveX:** A French tech start-up company with expertise in flexible structures. They were part of the Climate Launchpad competition and in the grand final of the Venture Catalyst Challenge. They successfully tested a fully flexible WEC prototype in the coastal flume tank at Imperial College, generating 0.4W of power with flexible bags anchored in sediments under 12cm waves for a small-scale prototype.
- **Cheros Srl:** See above. They worked as subcontractors, providing DEG and DFG expertise and undertaking modelling work.
- **Michelin/Aircaptif:** Michelin is a multinational French manufacturer of tyres and other elastomeric components established in 1889. They have a track record of groundbreaking R&D and have provided tyres for motorsports such as Formula 1 and Le Mans. Within this project they played an advisory role, suggesting potential manufacturing and design methods.

Approach: The team's core requirements included high wave energy capture and the ability to use both DEGs and DFGs effectively. Owing to these characteristics, the team initially took an agnostic approach to DEGs and DFGs, instead prioritising a design which provides good power capture and replaces expensive rigid materials with a full elastomeric structure using rigidification techniques developed by Michelin. Eventually they settled on a DEG design due to the easier implementation and possible improvements in the power density. The design was iterated using time-domain numerical models that were able to effectively calculate the required dimensions to meet the target power requirements. Within this modelling work, a sensitivity analysis was performed with parameters such as the material stretch and the applied electrical field modified. These allowed for an understanding the trade-off between size and amount of DEG material required. The preliminary Front End Engineering Design (FEED) study investigated the choice of materials and their corresponding assembly method, whilst understanding the sustainability of the selected materials. To understand the competitiveness, the team performed a techno-economic analysis with different materials and device configurations.

Outcomes: The outcomes of the project suggest the potential of DEGs to reduce cost centres as well as performance from a high degree of operational bandwidth and improvements in practical aspects such as deployment and survivability during storms. The identified challenges related to availability of materials which were affordable and offer an adequate lifetime, the manufacturing of large DEG modules, and having a power electronics system capable of performing the energy harvesting requirements.

4.4.1.5 University of Southampton (DEG/DFG)

Team: The University of Southampton collaborated with the University of Nottingham to combine expertise in numerical modelling, control systems and materials science.

- **University of Southampton (UoS):** UoS has a strong track record in wave energy, particularly in hydrodynamics and control of WECs. This team had expertise in parameter identification, frequency domain analysis, and state-space representation. Within this project, UoS were responsible for leading the design activities and conducting numerical modelling investigations.
- **University of Nottingham (UoN**): UoN contains the University Technology Centre (UTC) that is home to Rolls-Royce’s Manufacturing and On-Wing Technology. The UTC team has previously developed several soft robotics prototypes based on DEA using silicone elastomers. In this project, UTC performed a material investigation based on experiments utilising their prior experience with DEAs.

Approach: The team took an agnostic approach to design by considering both DEGs and DFGs, initially performing benchtop experiments to compare the performance of both. Later, Computational Fluid Dynamics (CFD) simulations were used for load predictions on cells under wave loading. This informed them on possible design options, where a structured decision matrix was used to down-select and prioritise the most promising designs.

Outcomes: The outcomes included a detailed analysis into appropriate materials, detailing the pros and cons for different DEGs and DFG configurations, this underpinned the work for a future technology review study, see Section 3.9.4. Furthermore, the team produced converged on two design solutions for both DEGs and DFGs after down-selection, alongside with suggestions for WEC control and manufacturing methods.

4.4.2 Round 1 Outcomes and Influence on Strategy

Round 1 of the DG design competition concluded with a workshop event where all the teams gave a presentation on their findings, including concept design outcomes and demonstration of benefits. There was a knowledge gathering session for collating all the future R&D requirements and a presentation given by WES on potential methods of evaluation for DG. Further details are provided in Section 3.11.

Based on the outcomes from Round 1, WES produced two documents: a *Research Agenda* and an *Evaluation and Guidance framework*. The research agenda was broken down into four themes:

- **Material/Metamaterial Selection, Characterisation and Development:**
    - Understanding the optimum materials and characterising their electro-mechanical performance in terms of energy harvesting and fatigue, as well as consideration of innovative methods such as self-healing.
- **Generating Module Design and Development:**
    - Understanding design solutions for modules with consideration given to flexibility of the architecture, reliability, control and load transfer between cells.
- **Manufacture and Integration Process Development:**

  - Understanding the manufacturing processes applicable, tolerances and quality control.
- **WEC Architecture Development:**
  - Ensuring designs are maximising the benefits of DG materials, scale-demonstration and a mixture of computational modelling processes for evaluating performance.

For more information on these areas with a detailed breakdown of subtasks, refer to the *DG Research Agenda*[19] document and Section 4.4.

The evaluation framework was broken down into five themes which were inspired by IEA-OES[20] and Technology Performance Level (TPL)[21] frameworks, as well as Paul Kerr's PhD thesis[22]. These areas are:

- **Power density:** The rated power per unit mass (W/kg), and the rated power per surface area (W/m^2).
- **Cost of energy:** A structural cost per unit energy (£/kg) based on the metamaterial manufacturing and assembly. Other high-level costs centres, i.e., CAPEX, OPEX and DECOM, form part of a qualitative discussion.
- **Longevity:** Longevity of the system encompassing failure modes at varying scales: material fatigue (cell), electronic unreliability (metamaterial/module), and survivability challenges (device). A combined qualitative and quantitative approach is proposed for assessment. This approach considers metrics such as through-life energy density (measured in J/kg), the number of potential fault locations, and the effectiveness of load shedding capabilities.
- **Practicalities:** Practical considerations include manufacturability, deployability, and operation and maintenance, assessed through qualitative methods. Key factors within these areas include transportation costs, ease of mooring and integration with existing infrastructure, and the inclusion of an onboard equipment room.
- **Sustainability:** Sustainability is assessed by evaluating the device's carbon footprint across its lifecycle, encompassing construction, operation, and decommissioning phases. This quantitative assessment considers metrics such as total lifetime carbon emissions per unit of energy output. Furthermore, it examines the use of critical materials, potential leaching of harmful substances, and adherence to a '*leave no trace*' decommissioning philosophy.

For more information on these evaluation areas with a discussion surrounding the metrics for each, refer to the *DG Evaluation and Guidance*[23] document and Section 4.3 where the outcomes are benchmarked against these metrics.

Round 1 suggested there was significant potential for DG technologies requiring further investigation through more detailed design and research investigations. Following this, WES started the process of co-funding research projects in crucial areas of R&D as well as inviting the participants from Round 1 to apply to the Round 2 stage of the DG design competition.

4.5 Round 2

To build on the success and outcomes of Round 1, the second round of the DG design competition aimed to further study the proposed concepts by performing the enabling R&D activities necessary to take them to the next stages of development. This involved identifying technology collaborators and working out a pathway to short and medium-term market access. An overview of the workflow for Round 2 is given in Figure 9.

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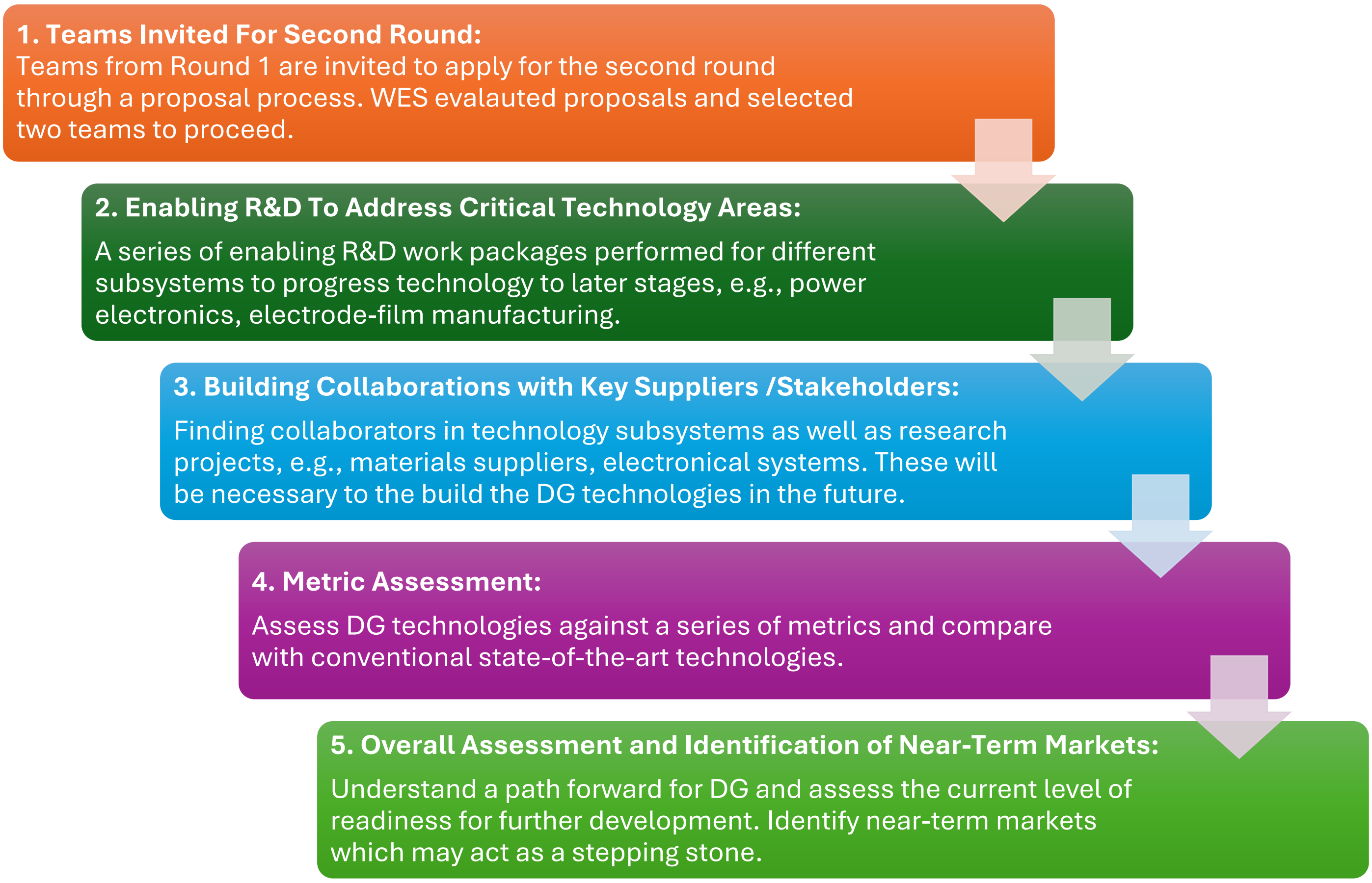
[19] Collins I, Hodges J. Direct Generation Research Agenda. Wave Energy Scotland; 2024.

[20] Hodges J, et al. "An international evaluation and guidance framework for ocean energy technology." IEA-OES: Lisbon, Portugal (2021).

[21] Mendoza N, Mathai T, Forbush D, Boren B, Weber J, Roberts J, Chartrand C, Fingersh L, Gunawan B, Peplinski W, Preus R. Developing technology performance level assessments for early-stage wave energy converter technologies. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2021 Oct 8.

[22] Kerr, P. (2024). Radical innovation for the wave energy sector: An investigation of the potential of direct conversion as an enabling technology.

[23] Collins I, Hodges J. Direct Generation Evaluation and Guidance. Wave Energy Scotland; 2026.



1. Teams Invited For Second Round:
Teams from Round 1 are invited to apply for the second round through a proposal process. WES evalauted proposals and selected two teams to proceed.

2. Enabling R&D To Address Critical Technology Areas:
A series of enabling R&D work packages performed for different subsystems to progress technology to later stages, e.g., power electronics, electrode-film manufacturing.

3. Building Collaborations with Key Suppliers /Stakeholders:
Finding collaborators in technology subsystems as well as research projects, e.g., materials suppliers, electronical systems. These will be necessary to the build the DG technologies in the future.

4. Metric Assessment:
Assess DG technologies against a series of metrics and compare with conventional state-of-the-art technologies.

5. Overall Assessment and Identification of Near-Term Markets:
Understand a path forward for DG and assess the current level of readiness for further development. Identify near-term markets which may act as a stepping stone.

Figure 9: Workflow for Direct Generation Round 2

The proposal stage application form had questions relating to:

- A summary of the first project conclusions relating to the benefits of Direct Generation and the strength of the case for further R&D and technology development.
- The team's approach to evaluating attractiveness of Direct Generation in wave energy and discussion of the suitability of that process to drive future R&D and technology development.
- Description of the enabling R&D activities recommended to push Direct Generation to readiness for full WEC technology development. The project approach, structure and strategy for securing future funding. The detailing of three mandatory work packages relating to WEC and DG module concept design, approach to delivery of enabling R&D and the specific and detailed plan for tangible and measurable activity relating to building partnerships.

4.5.1 Project Teams, Collaborations, Work Packages

4.5.1.1 4c Engineering (DFG) 'Ebb-Flow'

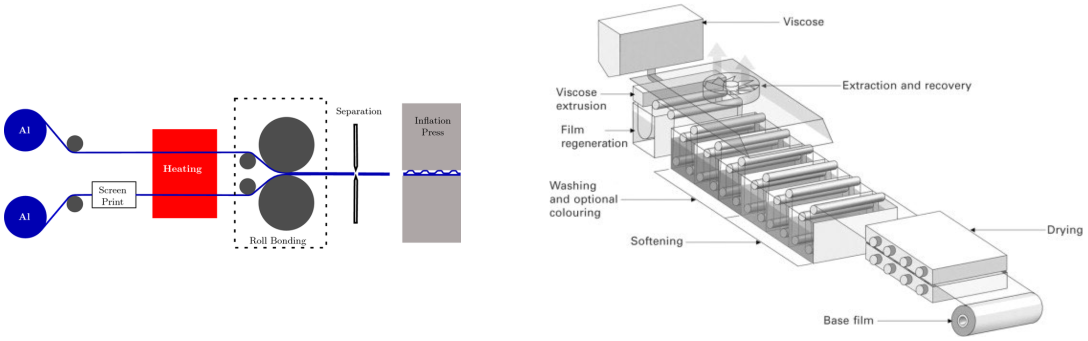
4c Engineering continued their collaboration with Cheros Srl for Round 2, but also engaged with a variety of other stakeholders for completing their enabling R&D tasks. There were a series of work packages to address critical technology areas such as manufacturing of DFG cells and building a proof-of-concept demonstrator. Ultimately progressing to a position to apply for follow-on innovation funding.

Building Collaborations: Throughout the concept generation stage and enabling R&D, 4c Engineering engaged with a range of different stakeholders in the manufacturing domain, as well as materials suppliers and universities. These included:

- **Cheros Srl:** Expertise in dielectric fluids/films for prototype development.
- **Emerson and Renwick (E&R):** Manufacturer specialising in custom roll-to-roll production machinery for coating, laminating, vacuum deposition, and printing.
- **Fraunhofer FEP:** One of 76 Fraunhofer research institutes focusing on vacuum coating, surface treatment, and organic semiconductors.
- **Supply Design (SD):** Electronics specialist design consultancy.

These collaborations led to a series of work packages, which included:

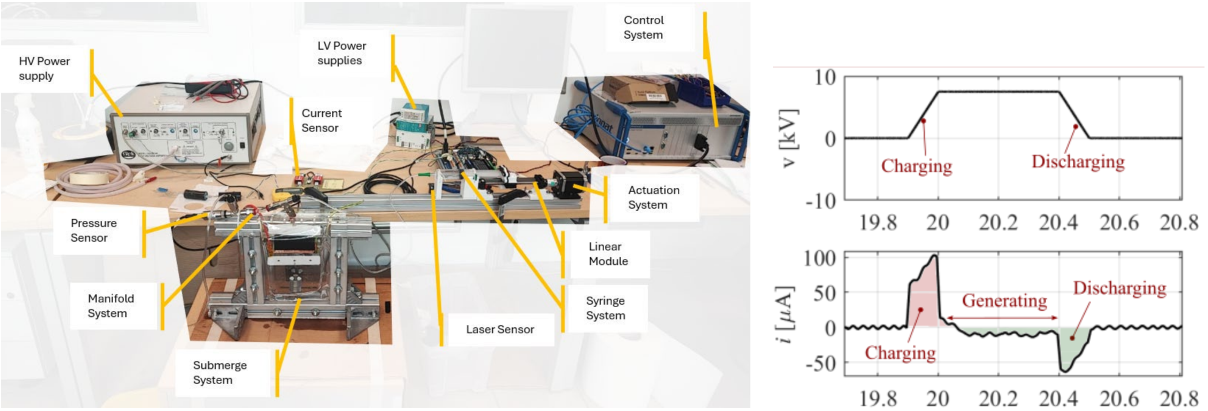
- **Materials Investigation:** 4cE worked with Fraunhofer and Cheros to investigate material systems for DFGs, including the film, electrode and encapsulation layers. Fraunhofer performed a materials landscaping review of dielectric films, electrodes and encapsulations layers, while Cheros provided a technical narrative on the operational characteristics of these materials. This identified suitable materials from both a performance and manufacturing point of view.
- **Manufacturing:** 4cE engaged with E&R to identify manufacturing techniques that would be applicable for cell manufacture and identify potential constraints. They wanted to understand if new technology needs to be developed for mass manufacture of cell material. They found that it is possible to repurpose existing equipment and use the same processes and techniques. They considered roll-to-roll manufacturing techniques (analogous to other film industries) and pouch filling and sealing (with reference to the food industry), see Figure 10 for example production lines.



(a) (b)

Figure 10: Manufacturing Process (a) Schematic of roll-to-roll process (b) Design of production line in a factory setting

- **Power Electronics:** 4cE identified power electronics as a risk due to the potential lack of component systems to work at high voltage/ low current in a cost-effective way. They worked with SD through a feasibility study looking into different power electronics solutions. Fortunately, they were able to identify topologies with commonly available components suitable for the WEC performance characteristics.
- **Testing:** Due to the absence of prior DFG proof-of-concept devices, 4cE needed to demonstrate a complete generation cycle. This effort built on their experience from their desktop demonstrator which was constructed for the US DoE InDEEP prize Phase II. For Phase III, a larger multi-cell variant of this technology needed to be demonstrated (discussed in more detail in Section 3.9.3). Cheros aided 4cE in building this demonstrator which was tested at the University of Trento. Cells were hand-manufactured in the 4cE lab and then transported to Italy for assembly. In total, approximately 35 cells were produced in a repeatable manner, with capacitance and resistance measured. These tests proved that energy could be generated though the pouch-filled cell DFG method as shown in Figure 11(b), an overview of the setup is Figure 11(a).



(a) (b)

Figure 11: Proof-of-concept desktop demonstrator (a) Layout of test-bench (b) Generation cycle showing charging and discharging

Metric assessment: Using the WES metrics outlined in Round 1, 4cE evaluated their technology to assess feasibility and identify key innovation areas for further development. Metrics included estimates on power density, manufacturing readiness and embodied carbon, while acknowledging the difficulty in assessing cost performance ratios at this stage.

Outcomes: This project led to the formation of Ebb-Flow Ltd which received TechX funding to advance their technology further. Looking ahead, they are actively testing and refining their concept while pursuing new funding opportunities and exploring interim markets to advance and demonstrate their technology.

4.5.1.2 TTI Marine Renewables

TTI Marine Renewables initially collaborated with Manchester University on early enabling R&D activities focused on DEG material development, while continuing detailed numerical analysis of their design. This work led to the identification of key material requirements that required further investigation, particularly around fatigue and manufacturability. To address this, in the second half of Round 2, TTI-MR engaged a new suite of stakeholders in large-scale manufacturing and durability testing.

Building Collaborations: TTI-MR engaged with leading silicone suppliers and testing expertise, these included:

- **University of Manchester:** Expertise in nanocomposites and flexible electrodes.
- **Wacker Chemie AG:** Silicone supplier and manufacturer of NEXIPAL dielectric material.
- **Endurica/ACE Laboratories:** Test laboratories with fatigue and ageing expertise for polymeric materials, including a framework for life predictions.

These collaborations led to several work packages, which include:

- **Time Domain Modelling:** TTI-MR conducted a parametric study to simulate a range of design configurations and loading scenarios. This analysis produced a spectrum of strain conditions, from lower strains in low intensity sea states to higher strains under survivability loads. Strain and damping data were then converted into power matrix estimates. An example of the power density vs maximum strain is given in Figure 12, where different strain ranges and material stiffnesses are ranked against a corresponding power density. This was followed up with subsequent research into fatigue testing, based on the rainflow counting spectra derived from this study.
- **Material Selection and Metamaterial Development:** TTI-MR engaged with Wacker Chemie AG on material selection and chose silicone due to its good ageing properties in air, seawater and UV resistance, as well as its high dielectric breakdown strength. Through a collaboration with ACE Laboratories and Endurica, TTI-MR were able to investigate fatigue, ageing and the microplastic loss rate

in seawater. The fatigue methodology was based on intrinsic strength testing which provides the minimum energy release rate below which a crack will not grow. This methodology can be used for early fatigue life predictions through strain history and energy balance. The initial results proved long lifetimes could be possible for a conservative strain level. Additionally, the microplastic loss rate was minimal, indicating good environmental performance offshore. While both these results were promising, further investigations are required to build confidence in these findings.

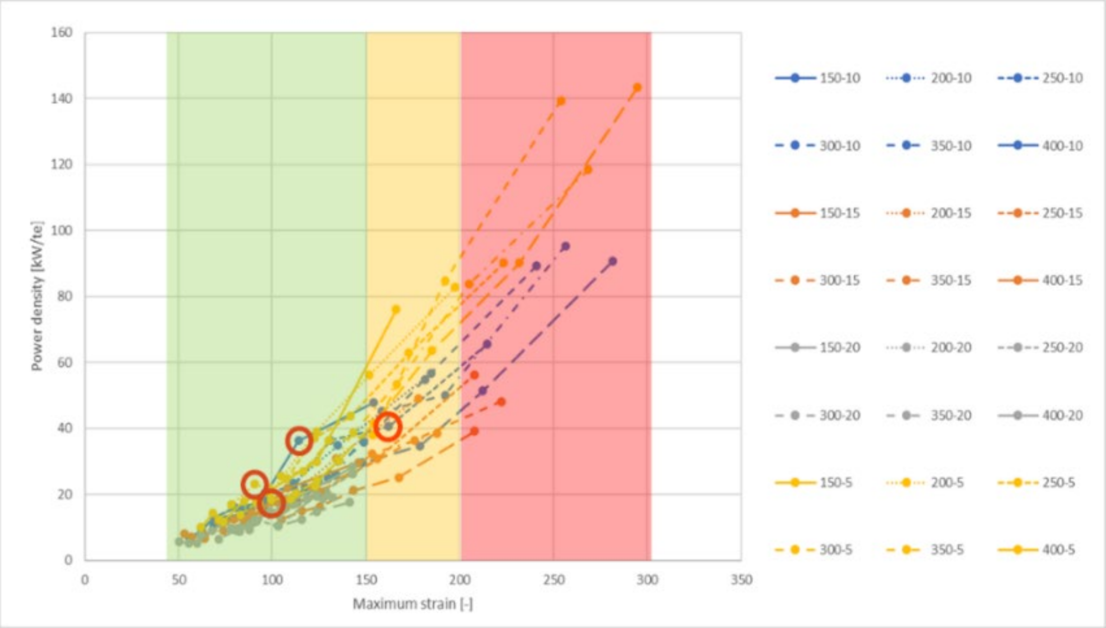
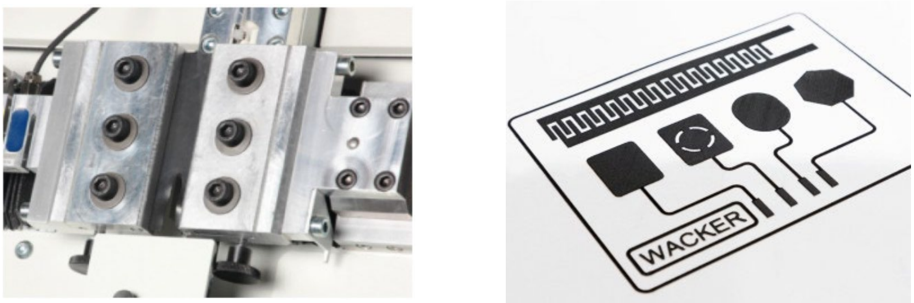


Figure 12: Outputs from time-domain modelling parametric study showing strain vs power density.

- **Techno and Socio-Economic Considerations:** TTI-MR performed predictions on the cost of energy for a range of scenarios, resulting in a required device capacity and material cost to give estimates on LCOE. A review of the socio-economic benefits suggested the large potential feedstock for the manufacturing of silicone materials and initially good environmental performance in seawater.



(a)

(b)

Figure 13: Material Investigation (a) Intrinsic strength test used for fatigue predictions (b) Wacker silicone coated electrodes in NEXIPAL

Metric assessment: TTI-MR were able to provide high level cost estimates for materials and an overall annual performance for a selected sea-state. This led to enabling R&D activities and details surrounding innovation areas for the next stages.

Outcomes: The learnings from the DEG project led to the identification of intermediate markets in the offshore renewable sector and other marine and industrial sectors. TTI-MR acquired follow-on funding in the Scottish Enterprise CanDo project to investigate integrated strain measurement for mooring (and other) synthetic fibre ropes. They are now looking at taking that technology to commercial markets, making it the perfect stepping stone for energy harvesters.

4.6 Research Projects

In parallel with the Design Competition, WES has co-funded several targeted academic initiatives to accelerate foundational research in direct generation technologies. These include two 12-month Supergen ORE Impact Hub FlexFund projects led by Oxford University and Manchester University respectively. Alongside this, a jointly funded four-year PhD programme with EPSRC, is being delivered through Swansea University.

4.6.1 FlexFund Projects

4.6.1.1 Origami DFGs (Oxford & Plymouth)

The University of Oxford and Plymouth have combined expertise in origami structures and wave energy converters. In the past they have considered the implementation of origami structures to wave energy converters in the *'Sea-Clam'* WEC concept, where the device's volume dynamically collapses under wave loading, displacing a working fluid or activating a mechanical PTO system between two interacting bodies[24]. In this FlexFund project, however, the focus shifted to evaluating how origami-inspired architectures could enhance DFG cells within a larger modular structure. This work combined experimental and numerical studies to design and develop an individual cell capable of forming a scalable modular metamaterial.

Approach: The project was broken down into three core work packages:

- **Origami cell-based design:** Development of desktop-scale models to demonstrate deformation modes, shown in Figure 14(a). Key design requirements included *'stackability'* for scalable architectures, stress isolation to flexible joints (ensuring pure rigid-body motion with minimal strain), and controlled electrode displacement to enhance energy conversion efficiency.
- **Multiphysics modelling:** Advanced simulations were conducted to analyse electro-structure-fluid interactions for selected origami geometries. A comparative study between air and oil as dielectric fluids revealed that oil significantly outperformed air, increasing energy output by 86%.
- **Experimental testing:** A test-rig was built to validate the DFG cell harvesting theory and compare with numerical models, see Figure 14(b). Experimental testing pointed to materials recommendations for the dielectric fluid and dielectric film with higher permittivities. The team encountered challenges at low frequency cycling as a result of charge leakage.

Outcomes: The project concluded that modular architectures using origami-based DFGs are feasible and offer the advantage of minimising material strain, which could significantly enhance fatigue life. Power density was found to be highly sensitive to material selection, with high-permittivity materials such as **polyamide** and **PVDF** showing the greatest potential.

However, despite these promising results, questions remained on how achievable competitive levels of power density would be, especially in terms of cost. Preliminary estimates suggest large amounts of material, e.g., for a 500 kW device, up to 124 m^3 of active material was required when using a polyimide coating operating between 2 kV (priming) and 8 kV (working). The priming voltage is the input necessary to harvest energy during a constant charge cycle.

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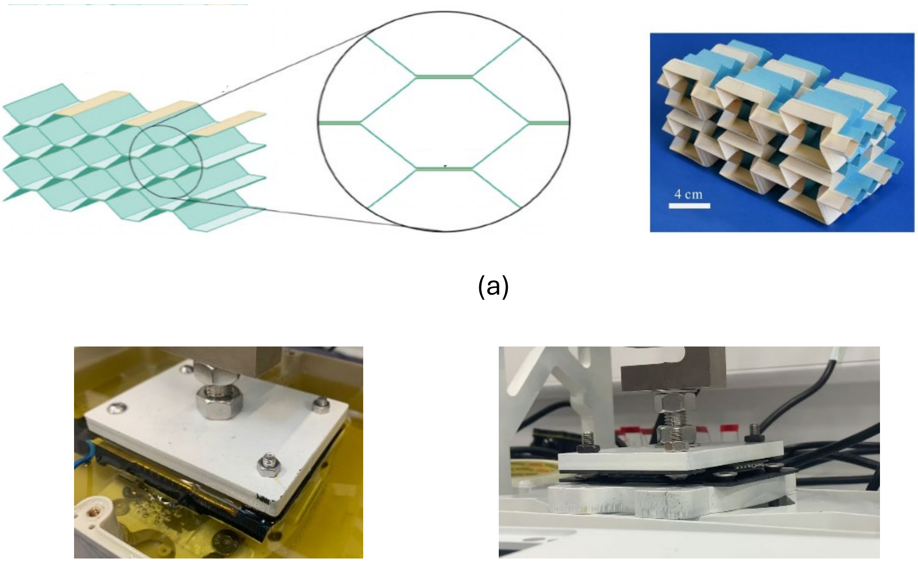
[24] Yang J, You Z, Cheng S, Wang X, Puzhukkil K, Cox M et al. Origami-adapted clam design for wave energy conversion. Proceedings of the European Wave and Tidal Energy Conference. 2023 Sept 2;15(0). Epub 2023 Sept 2. doi: 10.36688/ewtec-2023-329



(a)

(b)

Figure 14: (a) Cellular design, (b) Experimental testing of DFG cell

4.6.1.2 Flexible Electrodes for DEGs (University of Manchester)

The University of Manchester (UoM) has been exploring conductive elastomeric nanocomposites as a promising solution for DEG design. One of the key challenges in DEG development is achieving a reliable interface between the electrode and the elastomeric dielectric. While the elastomer undergoes significant deformation under mechanical loading, the electrode must maintain conductivity while accommodating this deformation. Conventional electrodes are rigid and bonded to the dielectric which creates stiffening and shearing forces between the layers, which is unacceptable from a fatigue perspective.

To address this, the UoM project has been investigating conductive nanocomposites that are uniformly embedded throughout the elastomeric matrix as layers of conductive material. This approach enables the formation of fully integrated electrodes within the bulk material, potentially eliminating interface issues and enhancing mechanical and electrical compatibility.

Approach: The project took place over three work packages:

- **Stretchable electrode integration:** Two fabrication methods were investigated for integrating the electrodes with the dielectric elastomer. The first was the conventional doctor-blade technique, in which a thin blade is used to spread a semi-liquid dielectric mixture across a substrate before curing. Repeating this process enables the creation of multilayer DEG stacks with controlled film thickness. This approach was compared with spray-coating, where a conductive silicone ink is atomised and deposited onto the dielectric surface, forming a nanocomposite electrode layer embedded within the elastomer. In this study, the sprayed conductive silicone ink was applied to Elastosil 2030 membranes, producing films approximately 30 μm thick per layer across a stack of five layers. These coated films were subsequently assembled in a layer-by-layer configuration, with thin copper tapes applied to selected electrode surfaces to provide electrical connections for testing.
- **Microstructure analysis:** To assess the interface between the electrode and dielectric layers, scanning electron microscopy (SEM) was performed. The SEM images (see Figure 15) revealed a homogeneous dispersion of carbon black (CB) and carbon nanotube (CNT) fillers within the elastomer matrix, confirming effective distribution of conductive particles and supporting the integrity of the embedded electrode structure.

- **Electro-mechanical characterisation:** Quasi-static mechanical properties were evaluated through tensile and cyclic loading experiments on the stacked DEG structures and compared against virgin elastomer films as observed in Figure 16(a).

Outcomes: The nanocomposite DEGs demonstrated strong potential for energy harvesting applications. Their stress-strain response closely matched that of the single-layer elastomer, showing excellent overlap up to strains of 300%. Beyond this point, the stacked elastomer shows a stiffening behaviour, indicating the influence of the embedded electrodes, shown in Figure 16(a). Furthermore, the materials demonstrated robust tear resistance, with tearing forces measured around 10 kN/m and exhibiting a knotty tearing behaviour which is characteristic of tough elastomeric systems, see Figure 16(b). The capacitance swing was shown to increase by 40% between rest and 200% strain, highlighting its promise as a high-energy generator. But also, the system proved to be an excellent high-resolution sensor capturing changes to capacitance and voltage in-situ. Looking ahead, this process is planned to be applied with higher permittivity dielectric elastomers for improvements in power density.

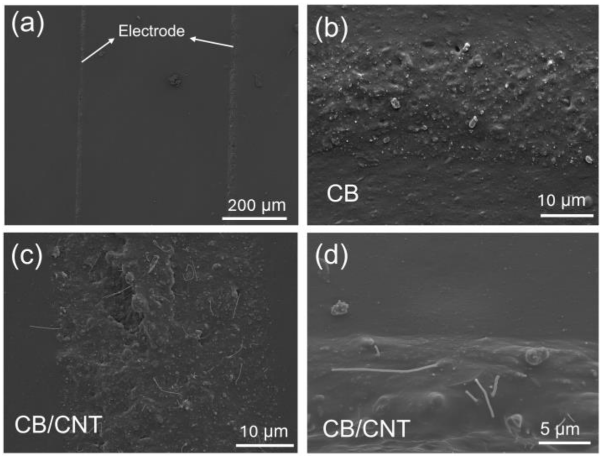


Figure 15: SEM micrographs for cross-section of nanocomposite DEG

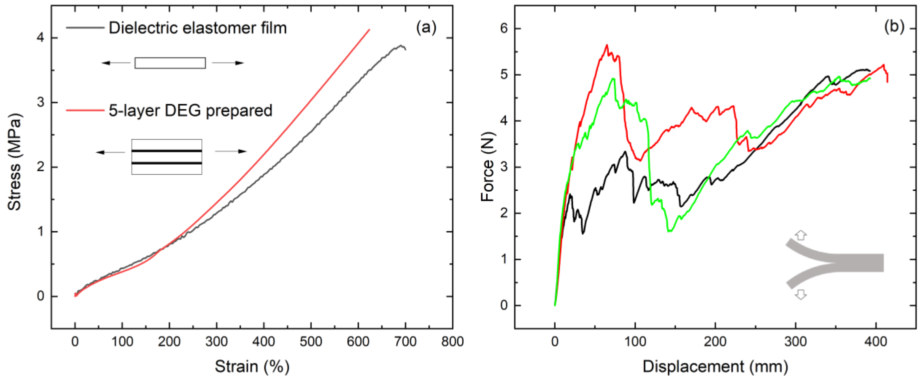


Figure 16: Stress-strain of virgin materials and force displacement curves obtained from T-peel test.

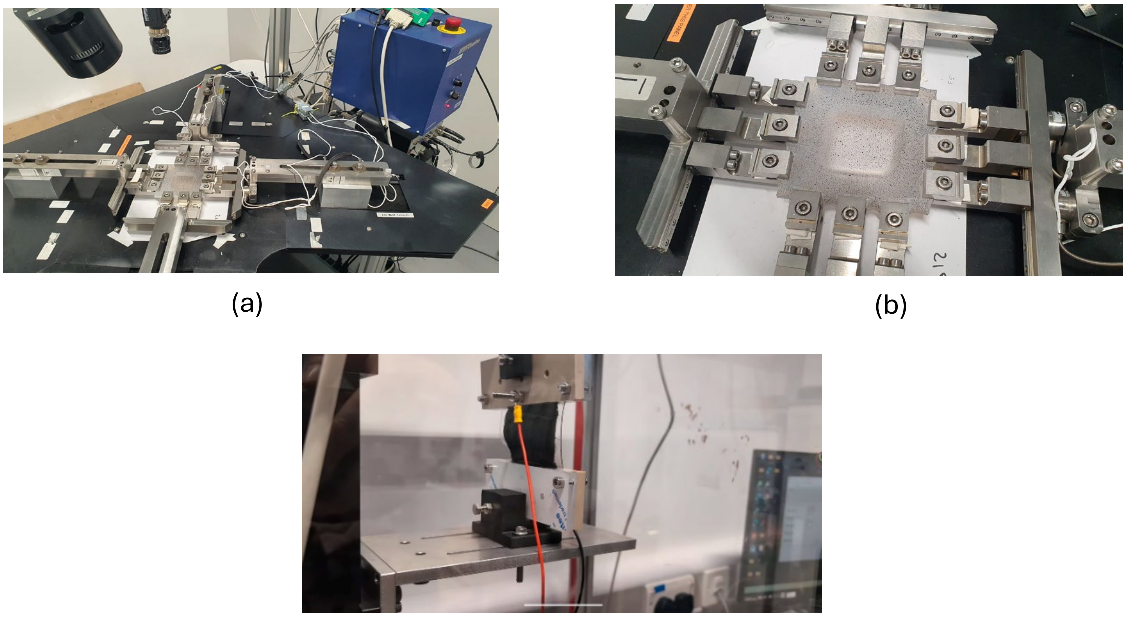
4.7 EPSRC-Funded PhD

4.7.1 Electro-mechanical fatigue characterisation of DEG and DFG systems

WES is co-funding an EPSRC PhD which is performing extensive fatigue investigations on DG material systems. Energy absorption by WEC system using DEGs or DFGs is limited by the lifetime of DEG or DFG materials. Therefore, understanding the material limitations is crucial when designing a WEC, as the straining excitation mechanism is closely tied to the overall system architecture.

Approach: To support future design decisions, it is essential to build a comprehensive database of material properties and performance metrics. WES is supporting this project, led by Swansea University, that will focus on:

- **Material synthesis:** Development of in-house dielectric elastomers through synthesis of novel material systems. This will be performed using 2D conductive fillers (e.g. MXene) which enable integrated electrodes within the elastomer matrix alleviating the debonding risks of sandwich-based elastomer-electrode solutions.
- **Experimental campaign:** Uniaxial and biaxial testing of dielectric elastomers to develop a database of long-term fatigue data (as expected in operation). This will start off with uniaxial and biaxial tests (see Figure 17(a-b)) on material dielectric elastomers with the electro-mechanical properties tested at intervals to understand degradation, see Figure 17(c). The programme will progress to electro-mechanical fatigue testing, where electrical performance will be measured in-situ during cyclic loading. The data generated from this work will be used to inform material selection and support the development of fatigue modelling frameworks.


(a)

(b)

(c)

Figure 17: (a) Biaxial testing machine (b) Biaxial sample and (c) electro-mechanical test bench

Outcomes: After one year of project activity, the focus has been on understanding the degradation of the dielectric elastomer, irrespective of the electrodes. To do this, Ecoflex samples have undergone testing for several hundred thousand ($10^5 - 10^6$) cycles under uniaxial loading conditions. At predetermined cycle counts, carbon-grease electrodes were applied to the fatigued samples to assess how electro-mechanical performance evolved as the underlying dielectric material aged. The results indicate a clear reduction in harvested energy, consistent with degradation in the material's permittivity and energy density, which aligns with findings reported elsewhere in the literature.

Looking ahead, the project will extend testing to higher cycle counts and develop more durable stretchable electrode systems to enable true in-situ electro-mechanical fatigue characterisation. This will provide a more complete picture of the degradation mechanisms affecting both the dielectric and electrode layers. Finally, the testing protocol will be expanded to biaxial loading configurations to assess how different loading regimes influence the fatigue behaviour of the system.

4.8 External Stakeholder Engagement

In addition to the design competition and co-funded research projects, WES has actively engaged with external stakeholders and participated in key industry conferences. These efforts have enabled knowledge transfer, strategic R&D roadmap development, and supported the dissemination of programme outcomes to encourage wider sector involvement in the development of DG technologies.

4.8.1 SBM Offshore

In April 2025, WES visited SBM Offshore's offices in Carros, France for a dedicated knowledge exchange day focused on DEG wave energy. The visit included a series of presentations, technical discussions, and a laboratory tour, offering a comprehensive overview of SBM's S3 wave energy device.

The SBM S3 project, which began in 2009, has undergone multiple design iterations. A standout feature of the S3 is its deployment simplicity, with an inflatable structure that can be assembled directly on-site. Early proof-of-concept testing was conducted in a flume in Monaco, followed by larger-scale (35m long tube) hydrodynamic testing in Nantes, France, to validate performance and calibrate numerical models.

Figure 18: SBM Offshore scaled prototype in Carros, France

The most recent phase of development involved a large-scale silicone DEG tube, measuring 10 metres in length and 1.2 metres in diameter, aimed at addressing challenges in scalable manufacturing and power electronics integration, see Figure 18. Developing this technology resulted in several notable innovations:

- **Large-scale roll-to-roll fabrication:** Employed a roll-to-roll fabrication process, where two opposing layers of dielectric film and electrodes of alternating polarity are axially wound (Figure 19(c)) to form a cylindrical structure which resulted in over 145 layers of DEG material (Figure 19(b)).
- **Quality control methods:** Implemented a dielectric breakdown scanning system capable of identifying defects in silicone sheets. For ad-hoc repairs on large-sheets, SBM patented a custom-designed insulating plugs[25], which acts as a *‘repair-kit’* on parts of the membrane.
- **Module joining methods:** Created specialised moulds and tools to join silicone rings, using UV curing to form robust seals between each ring.
- **Electrical terminations:** Developed liquid (Gallium) metal-based electrical terminations to accommodate for large strain of DEG rings.
- **Self-sensing power electronics:** Developed power electronics solutions to monitor capacitance change in-situ and map voltage to maximise energy harvesting potential.

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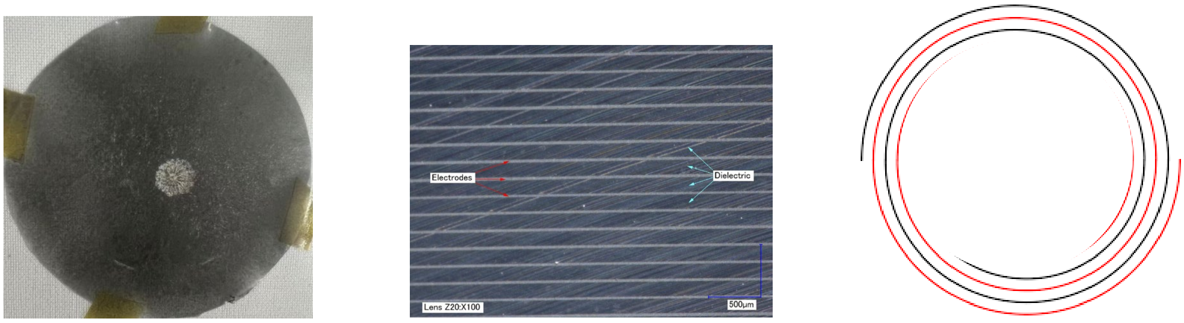
[25] Taine E, Jean P, Boulard R, inventors; Single Buoy Moorings Inc, assignee. Electroactive polymer device and method for manufacturing such an electroactive polymer device. United States patent application US 17/279,970. 2021 Dec 16.

- **Self-clearing electrodes:** Developed electrodes which oxidise and isolate the flaw to avoid dielectric breakdown, see Figure 19(a).[26]



(a) (b) (c)

Figure 19: Electrode-electrode innovations (a) Self-clearing electrode, (b) 145 stacked layers of dielectric-electrode material, (c) Axially wound layers of material

Despite these innovations, SBM ultimately chose not to progress further with the S3 device due to several critical technological challenges. These challenges were discussed during the site visit and are documented in multiple research publications, these include:

- Mechanical fatigue, which proved to be the dominant failure mode, making lifespans beyond 10 years difficult to achieve[27, 28].
- Low power density at scale, driven by material flaws and scaling effects. These flaws increased the likelihood of failure when scaled up, forcing the device to operate within narrow constraints, detailed in Taine et al[29].
- Thermal instability, where the hysteresis from mechanical loading and electrical cycling led to heating between layers with no way of dissipating the energy to air/water which led to in some cases, thermal runaway of the composite material.

While these challenges are significant, they are not insurmountable. Overcoming them will require breakthroughs in material science to enable the step-change improvements necessary for future DEG-based wave energy systems, which are discussed in Section 4.3. This knowledge has guided WES' thinking and strategy for Direct Generation. For more information on the SBM S3 story, refer to the SPIE conference proceedings[30] and the PhD thesis titled: "*Reliability of dielectric elastomer generators for wave energy converters*"[31].

4.8.2 Wacker Chemie AG

One of the key collaborators in the TTI Marine Renewables project was Wacker Chemie AG, which are a global leader in silicone materials. Their product Elastosil 2030 has been extensively studied over the past decade for use in DEG development. Building on this foundation, Wacker has recently introduced a new dielectric material

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[26] Taine, E., Electro-active polymer device and method for manufacturing such a device, patent wo/2019/072922. 2019.

[27] Taine E, Andritsch T, Saeedi IA, Morshuis PH. Dielectric breakdown strength of PDMS elastomers after mechanical cycling. Energies. 2023 Nov 3;16(21):7424.

[28] Taine E, Andritsch T, Saeedi IA, Morshuis PH. Optimizing energy density in dielectric elastomer generators: a reliability-dependent metric. Smart Materials and Structures. 2024 Oct 17;33(11):115030.

[29] Taine E, Andritsch T, Saeedi IA, Morshuis PH. Size effect and electrical ageing of PDMS dielectric elastomer with competing failure modes. Smart Materials and Structures. 2023 Sep 11;32(10):105021.

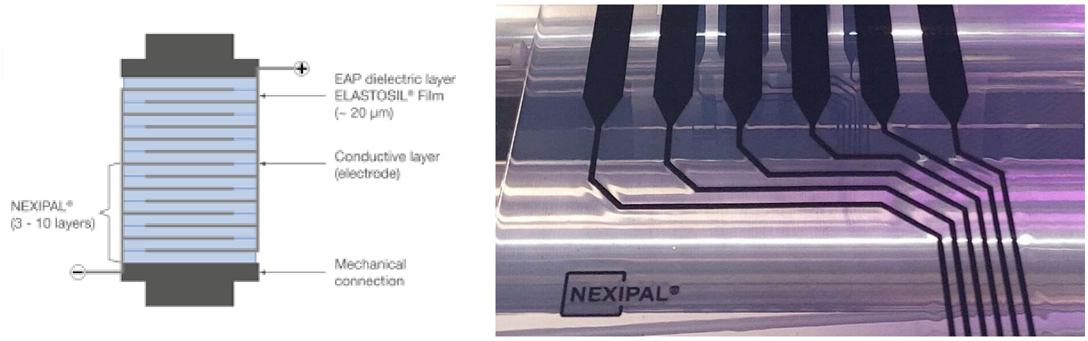
[30] Taine E, Claverie A, Caille F, Seima S, Fourdilis N, Hendrikse JM, Boulard R. The S3 wave energy converter story. InElectroactive Polymer Actuators, Sensors, and Devices (EAPAD) 2025 2025 May 12 (Vol. 13431, pp. 119-129). SPIE.

[31] Taine E. Reliability of dielectric elastomer generators for wave energy converters (Doctoral dissertation, University of Southampton).

called NEXIPAL. Shown in Figure 18(a), it is a multi-layer silicone system coated with electrodes[32,33], which can be mass produced, see Figure 19(b).

While NEXIPAL is primarily targeted at the sensor and actuator market, with a sensor products already commercially available, it has the potential to be adapted for generator applications as demand grows. Alongside the TTI Marine Renewable project, WES conducted a tour of Wacker's facilities and held detailed discussions on the feasibility of using DEG technology for WECs. This included:

- Challenges of increasing permittivity: Increasing permittivity results in more polarisation pathways for dielectric breakdowns to occur meaning there is inverse correlation when increasing permittivity.
- Challenges of self-healing within DEG materials: Incorporating fillers, additives, or self-healing agents into dielectric elastomers often compromises their mechanical compliance, increases stiffness, and introduces interfaces that decrease breakdown strength. These drawbacks generally outweigh the potential benefits, making effective self-healing difficult to achieve without major performance trade-offs.



(a)

(b)

Figure 20: Wacker Nexipal material, (a) Layered schematic, (b) Roll-to-roll manufacturing of Nexipal sheets

4.8.3 Collaboration with US Department of Energy and National Laboratory of the Rockies

WES has a longstanding collaborative arrangement with the US Department of Energy and NLR. Throughout the Direct Generation programme, WES and NLR have had regular meetings to discuss strategy and technical aspects of Direct Generation and DEEC-Tec. NLR ran InDEEP, for more information, see Section 3.1 and the final report: *Innovating Distributed Embedded Energy Prize (InDEEP): A lessons learned report.*[34]

Notably, 4c Engineering participated in both the Direct Generation and InDEEP programmes, benefiting from cross-programme insights. The knowledge gained from InDEEP complemented the Direct Generation approach: InDEEP followed a bottom-up design methodology (starting with material development), while Direct Generation adopted a top-down strategy (starting with device development), offering a well-rounded perspective on innovation in wave energy technologies. Regular discussions have pointed to learnings at both ends of the innovation cycle.

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[32] https://www.wacker.com/cms/en-us/products/brands/nexipal/nexipal.html

[33] Neuwirth J, Köllnberger A. NEXIPAL®: industrial manufacturing of EAP transducers. InElectroactive Polymer Actuators, Sensors, and Devices (EAPAD) 2025 2025 May 12 (p. PC134310L). SPIE.

[34] Boren B, et al. Innovating Distributed Embedded Energy Prize (InDEEP): A lessons learned report. National Laboratory of the Rockies.

4.8.4 Collaboration with University College London (Direct Generation Research Paper)

In a rapidly evolving landscape, understanding what research has already been conducted and identifying the next steps remains a key challenge. WES has supported Yao Yang at University College London in developing a research paper that compares DEG and DFG technologies, titled: *"Assessment for Direct Generation of Ocean Wave Energy: Dielectric Elastomer Generator and Dielectric Fluid Generator."* [35]

4.9 Conferences

Throughout the Direct Generation programme, WES has participated and disseminated Direct Generation in several conferences both domestic and international, these included:

- **All Energy:** The largest UK conference in renewable and low-carbon energy. Direct Generation was presented within WES' programme update slot. Furthermore, 4c Engineering had their desktop demonstrator at the WES stand.
- **FlexWave:** The FlexWave project has been running to improve the design, manufacture and survivability of flexible WECs. WES has attended the workshops, presenting the latest findings from within the DG programme.
- **IOM3:** The Institute of Materials, Manufacturing and Mining has held regular events on elastomeric materials and their use in industry. WES has presented at these events and networked with key stakeholders.
- **EuroEAP:** The largest conference for electroactive polymers in Europe which is an annual conference. WES has participated in these conferences with presentations and engagement of key academic and industry stakeholders.

4.10 Programme Review Events

There were two programme review events that took place during the DG competition, the first one in February 2024 and the second in April 2025. These were used at each juncture in the programme to share the findings and collaborate in preparation for the next stage.

Round 1

For Round 1, an event was held on 22nd February 2024 at the Edinburgh Climate Change Institute which brought together all the teams from the programme including design competition and research projects. It had three key sessions:

- Concept design outcomes and demonstration of benefits and opportunities: individual team presentations
- Technology challenges and R&D requirements: knowledge exchange
- Knowledge gathering and consensus building: facilitated workshop session

This event was used to kick-start the next stage of the DG Design Competition.

Round 2

For Round 2, an event was held at the Radison Blu Hotel on 29th April 2025. This event invited stakeholders external from the programme to participate including SBM and Max Planck. The day was structured into three main sessions, followed by a closing segment.

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[35] Zhang Y, Song Y, Gao T, Zeng T, Dong X, Wang X, Meng M, Bucknall R, Greaves D. Assessment for Direct Generation of Ocean Wave Energy: Dielectric Elastomer Generator and Dielectric Fluid Generator. Research. 2026 Feb 10;9:1127.

The opening session featured introductions from WES and NREL, outlining the objectives of the DG programme and DEEC-Tec initiative, respectively. This was followed by:

- Programme updates from the DG Design Competition teams.
- Presentations from FlexFund projects, highlighting recent developments and milestones.

The second session showcased a range of different perspectives from industry and academia:

- Prof. Deborah Greaves: Update on FlexFund project progress.
- Dr. Qing Xiao: Insights into fluid-structure interaction and its integration with electro-mechanical modelling for DEG WECs.
- Andreas Koellnberger: Manufacturing processes for Nexipal and Elastosil materials.
- Dr. Marco Fontana: Transitioning from DEG to DFG: experimental work on electroactive polymers.
- Emmanuel Taine: The SBM journey: current progress and future plans.
- Sophie Kirkman & Lawrence Smith: HASEL DFG experimentation at the Max Planck Institute.

The third session was an interactive round-table workshop which aimed to explore the key challenges of DG. Topics included:

- Cross-sector collaboration
- Techno-economics
- Research priorities

The event closed with two talks:

- A presentation from NLR on the InDEEP programme.
- A forward looking talk from WES on the future direction of Direct Generation.

5 Programme Outcomes

The final stage of the programme was to review the outcomes and to understand what needs to happen next. As outlined earlier, the DG programme adopted a multi-faceted approach to explore the potential for radically different WEC designs. It delivered several key achievements, including the creation of new IP, identification of emerging markets, and addressed fundamental research questions. The design competition and enabling R&D activities provided evidence-based insights into the opportunities and challenges for DG technology. These findings ultimately led to two core areas of discussion: performance benchmarking against defined metrics and the fundamental research tasks required to advance the technology. Since these areas are closely interlinked, as performance limitations in DG could be mitigated through targeted research innovations. The following section explores these aspects, notably:

- **Key differences between DEGs and DFGs:** What are the strengths and weaknesses of DEGs vs DFGs?
- **High-level understanding of systematic benefits:** What are the main design benefits identified for selecting DG, and correspondingly, what are the main challenges?
- **Evaluation of DG through metrics:** How do these technologies compare to conventional technologies currently and potentially in the future? What are the physical limitations for these technologies? What are the target thresholds?
- **Prioritised research tasks:** How do you meet the target thresholds identified by the metrics? What are the main tasks of interest for DG?
- **Progressing DG through consortia building and collaboration:** Which research and technology developer stakeholders should be targeted for future developments? What are overlapping requirements and tasks with these sectors?

5.1 Key Differences between DEG and DFGs

Both the design competition and the research projects included DEGs and DFGs, providing a strong foundation for comparing the two technologies. This allowed us to identify their respective strengths and weaknesses and assess where each might perform better. The following subsections compare DEGs and DFGs across maturity, WEC integration, capacitance swing, electrical behaviour, dissipation, failure modes, manufacturability, and environmental risk.

5.1.1 Maturity

A primary distinction between DEGs and DFGs is their relative maturity. DEGs have been explored for longer, resulting in more prototype variants and a broader academic and industrial evidence base. This maturity provides both advantages and caveats: there is more performance data and clearer understanding of failure modes, but also more known constraints (particularly related to long-term durability).

DEG theory dates back to the 1990s, with laboratory testing starting in the 2000s, and numerous resulting prototypes from SRI International, SBM Offshore and the PolyWEC programme tested in wave tanks and offshore during the late 2000s and 2010s. This puts the TRL of DEGs at **TRL 5-6**, but with the caveat of key technological challenges required to overcome to progress to higher levels.

DFGs remain comparatively underexplored, with fewer published prototypes and less validated performance data. There are a handful of papers dated back to 2017 on theory and prototyping of these technologies. As a result, additional work is required to reach the same level of confidence in performance, reliability, and scaling behaviour. But currently, the TRL of DFG is at **TRL 3-4.**

The recent programme activities have helped reduce this gap. For example, DFG research within the programme has demonstrated that protagonist/agonist cells can be excited and electrically cycled (charged/discharged) to produce electricity, while DEG research in the programme has expanded further beyond *"PTO-only thinking"* and explored more fully flexible DG architectures integrated into deformable WEC concepts. Together, these developments have pushed understanding further; however, given the unequal maturity and evidence base, it remains premature to conclude *"which is better"* in absolute terms and much of the following discussion points reflect this.

Summary: DEGs are better understood with more data and clearer limitations, while DFGs are earlier stage and likely to evolve rapidly as evidence grows.

5.1.2 WEC Architecture Implementation

Although DEGs and DFGs both operate as variable capacitance generators, they require different excitation mechanisms, which in turn drives differences in WEC architecture and system complexity. In both cases, the hydrodynamic interaction matters, i.e., how the WEC radiates waves and whether this radiation interacts constructively or destructively with the incident wave. But broader WEC design hydrodynamics is beyond the scope of the present discussion. Instead, the focus here is on the cell-level activation mechanisms that distinguish DEG and DFG operation.

5.1.2.1 DFG integration (pressure-driven, working fluid excitation)

DFGs generate electrical work by moving a working fluid to activate the cell (often through zipping/unzipping), as explained in Section 2.2. This introduces a central design challenge: controlling fluid displacement under wave loading. As DFG cells have a finite volume over which capacitance changes (via zipped vs unzipped states), the system must manage pressure differentials, flow paths, and potential head losses. Two architectures emerged in the competition:

- Fluid Reservoir: Fluid transfers between cells and a larger reservoir. While conceptually straightforward, it can involve long transfer distances and therefore higher losses (e.g., head losses, viscous effects).

- Protagonist/Agonist Pairs: Fluid cycles between open and closed states within a pressurised loop. This reduces travel distance and can substantially reduce flow losses compared with a reservoir-based approach. Cell pairing requires careful consideration at the hydrodynamic interface to ensure pressure-differential is moving fluid into another neighbouring cell.

5.1.2.2 DEG integration (strain-driven elastomer excitation)

DEGs are mechanically simpler in the sense that they do not require fluid movement: energy conversion is achieved by stretching and relaxing an elastomeric capacitor throughout the wave cycle. However, the WEC must still incorporate a mechanism capable of imposing controlled strain. Critically, because DEG membranes lack a natural end-stop, designs must include strain-limiting features or supporting structure to avoid overstretching and premature failure.

5.1.2.3 Sea-State Response

The overall stiffness of the WEC is governed by the individual cell response. For DEGs, a large component of the overall stiffness comes from the mechanical properties of the elastomer layer. In DFGs, there is no main straining layer, so the Maxwell stress likely dominates, and is controllable by varying the priming voltage. Therefore, this opens the potential for controllable variable stiffness, which could be useful for overall device tuning.

A useful emerging hypothesis is that DFGs may behave more reliably in low-energy sea states, because zipping/unzipping can provide a more controllable actuation process with an inherent geometric end-stop. By contrast, DEGs tend to benefit from stronger excitation, where larger deformation is available to generate a larger capacitance swing, but at the detriment of overall durability.

Summary: DEGs are conceptually simpler (strain-driven, fewer subsystems). DFGs introduce fluidic complexity but may offer more controllable behaviour and built-in end-stops making it better suited in variable excitation sea states.

5.1.3 Capacitance Swing

Both DEGs and DFGs rely on changing capacitance over a cycle. The capacitance of a stacked electrode-dielectric system is given earlier in Equation 1 in Section 2.1.

5.1.3.1 Electrode Separation and Geometric Changes

For a DEG, both the electrode area and distance between them change during operation. Elastomers are approximately incompressible, so when stretched their surface area increases while thickness decreases, producing a strong geometric amplification of capacitance[36]. The amplification factor depends on the deformation mode:

- Under biaxial stretch λ_{bi}: $A_{\mathrm{bi}} = A_0 . \lambda_{\mathrm{bi}}^2$
- Under uniaxial stretch λ_{uni}: $A_{\mathrm{uni}} = A_0 . \sqrt{\lambda_{\mathrm{uni}}}$.

Biaxial stretching can therefore produce a substantially larger capacitance swing for the same stretch ratio. However, higher strain energy increases fatigue risk, creating an inherent trade-off between maximising capacitance swing and preserving durability. These stretches are achieved through different geometries and their hydrodynamics interaction method, e.g., tubes, membranes, as shown in Figure 22.

In a DFG, capacitance swing is driven primarily by changes in distance between the electrodes, arising from fluid redistribution and the zipped/unzipped geometry. Although changes in gap can be large, the electrode area is typically more fixed because the film and electrodes are not intended to undergo large in-plane stretch. Another

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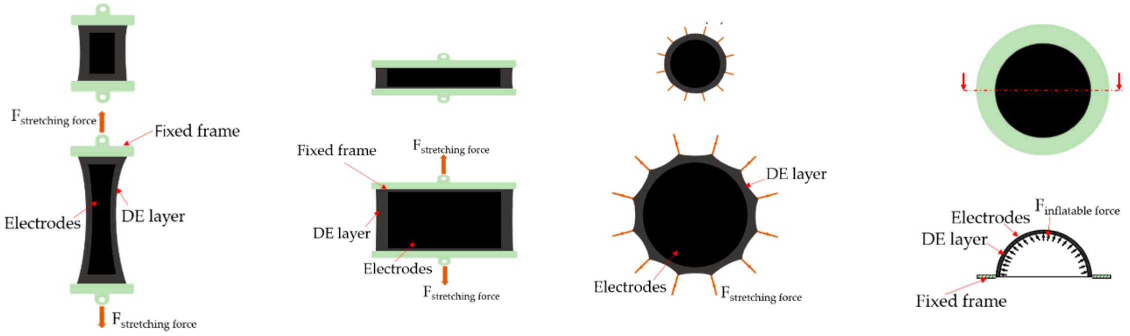
[36] Rosset S, Anderson IA. Squeezing more juice out of dielectric elastomer generators. Frontiers in Robotics and AI. 2022 Feb 11;9:825148.

important design consideration is maintaining the highest possible parallel alignment between the electrodes, as this maximises effective plate area and increases the achievable capacitance swing, which is the motivation behind origami DFGs mentioned in Section 3.6.1.1. At present, there is insufficient experimental evidence to determine whether DFGs can surpass DEGs in terms of capacitance swing, due to the limited number of DFG prototypes and their actuator counterparts reported in the literature.



Uniaxial (a)

Pure Shear (b)

Biaxial (c)

Biaxial (d)

Figure 21: Different excitation modes for DEGs, adapted from Di et al.[37]

Summary: DEG capacitance swing is driven by elastomer area increase and thickness decrease, resulting in large geometric amplification but face a durability trade-off; DFG capacitance swing is drive by large gap changes without tensile strains resulting in a fixed area. Further prototype development is required for better understanding of whether DFGs can surpass DEGs.

5.1.3.2 Material/Fluid Permittivity

Permittivity strongly influences energy density, but higher permittivity often comes with reduced dielectric strength due to charge localisation and increased likelihood of conductive pathway formation. The materials used in DEGs and DFGs have different levels of permittivity (ε_r) and dielectric breakdowns (DB), these are (values from Zhang et al.[38]):

- DEG elastomers (e.g. silicone): $\varepsilon_r \approx 1.5–3$, DB ≈ 70–150 MV/m
- DFG fluids (e.g., silicone, mineral, or ester oils): $\varepsilon_r \approx 2–3.5$, DB ≈ 30–45 MV/m
- DFG films (e.g., Polyimide, PVDF: $\varepsilon_r \approx 3$-10, DB ≈ 700–800 MV/m

Modification of materials through fillers, chemical modification, or polar group addition can increase permittivity, but often at the cost of breakdown strength, fatigue life, manufacturing complexity, and cost, discussed further in Section 4.3.1.2.1.

Dielectric elastomers generally exhibit a much higher breakdown strength than dielectric fluids, since fluids more easily form ionisation pathways and suffer from instabilities than solids. While dielectric films offer the best overall performance. In a DFG architecture where a solid film and a dielectric fluid both contribute, the dielectric stack behaves as a series combination:

$$\frac{1}{C} = \frac{1}{C_{\text{film}}} + \frac{1}{C_{\text{fluid}}} \tag{3}$$

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[37] Di K, Bao K, Chen H, Xie X, Tan J, Shao Y, Li Y, Xia W, Xu Z, E S. Dielectric elastomer generator for electromechanical energy conversion: A mini review. Sustainability. 2021 Sep 2;13(17):9881.

[38] Zhang Y, Song Y, Gao T, Zeng T, Dong X, Wang X, Meng M, Bucknall R, Greaves D. Assessment for Direct Generation of Ocean Wave Energy: Dielectric Elastomer Generator and Dielectric Fluid Generator. Research. 2026 Feb 10;9:1127.

Even if the solid film has excellent breakdown strength, the fluid layer often becomes the limiting factor due to its lower breakdown strength, constraining maximum allowable field and therefore limiting the energy cycle. However, pairing a high-permittivity/high-strength film with a fluid can still be advantageous in increasing overall capacitance, but this introduces an additional challenge: charge accumulation at material interfaces, discussed below.

Summary: DEGs typically exhibit moderate permittivity and dielectric breakdown strength, whereas DFGs combine a high-performance dielectric film with lower performance dielectric fluids. The film can partially compensate for the fluid's weaker electrical properties, but this introduces charge accumulation challenges.

5.1.4 Charge Accumulation

Charge accumulation can occur in both technologies, but it is typically more critical for DFGs due to multilayer interfaces and fluid-film combinations.

In multilayer dielectric assemblies, differences in permittivity and conductivity can distort the electric field and trap charge at interfaces. Real dielectrics have finite resistivity, so charge leaks gradually. Discharge behaviour is characterised by:

$$\tau = \rho\varepsilon \tag{4}$$

where τ is discharge time, ρ is resistivity, and ε is permittivity. When adjacent layers have significantly different discharge times, charge redistribution becomes uneven, leading to interface charge build-up. This can reduce efficiency, cause transient current spikes, and increase the risk of electrode damage or local breakdown. There are mitigation strategies such as matching resistivity and permittivity across layers through material selection, or neutralising charge through reverse polarity cycling.

Summary: Charge accumulation is a primary concern for multilayer DFGs and likely a secondary concern for DEGs (where fatigue usually dominates lifetime).

5.1.5 Hysteresis/Dissipation

Both technologies incur dissipation, but via different physical routes. In DEGs, losses are dominated by viscoelastic dissipation during cyclic loading. In multilayer assemblies, trapped heat and poor thermal paths can risk thermal build-up; thermal management becomes important, particularly for large area or stacked designs to avoid thermal runaway.

Whereas in DFGs, losses are dominated by viscous dissipation during fluid motion through channels and between cell states. Minimising transfer distances and viscous losses (e.g., via protagonist/agonist architectures) as well as optimising flow geometry can reduce these losses. In addition, emerging dual-fluid[39] system designs which have been explored in HASEL-type actuators may offer further opportunities to reduce viscous losses and improve pressure-to-capacitance change coupling if adapted for DFG architectures.

Summary: DEGs require careful material selection to manage viscoelasticity and stack design to manage thermal behaviour; DFG efficiency depends strongly on fluidic path design to minimise viscous losses.

5.1.6 Failure Modes, Fatigue and Self-Healing

In DEGs, the main failure mode is dielectric breakdown likely caused by electro-mechanical fatigue. It is expected strain ranges will be between **5-100% for DEG membranes** when optimised for life. The main degradation mechanisms expected include mechanical softening due to micro-void formation and electrode degradation from crack formation or delamination. Micro-voids within the dielectric weaken the material

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[39] Taghavi M, Helps T, Rossiter J. Electro-ribbon actuators and electro-origami robots. Science Robotics. 2018 Dec 19;3(25):eaau9795.

permittivity reducing operation limits and ultimately dielectric breakdown. Electrodes can de-bond from the base dielectric causing immediate failure. This coupling between high strain and cyclic electrical loading makes fatigue one of the most critical lifetime limits for DEGs. There is also the importance of ensuring non-relaxing conditions within the material which can be severely detrimental to fatigue when materials lose tension. Another area requiring consideration is the transition between flexible electrode and electrical termination which is non-trivial since typical electrical terminations (e.g., copper wires) do not perform well under straining conditions.

In contrast, **DFGs operate under near-zero** tensile strain, because the compliant elastomer composite is replaced by a dielectric fluid contained between the dielectric film and flexible electrodes. As a result, the film and electrodes primarily experience bending rather than extension. This substantially reduces mechanical fatigue and removes many of the degradation pathways associated with elastomeric composites. Nevertheless, delamination of electrodes from the dielectric film is still a risk, but manageable. Dielectric fluids also offer an additional advantage: inherent self-healing behaviour. When localised electrical breakdown occurs, the damaged region can disperse within the fluid and reintegrate into the bulk, rather than forming a permanent defect as in a solid membrane. This reduces irreversible electrical ageing and can significantly extend operational lifetime.

Summary: DFGs have a potential lifetime advantage due to low tensile strain and fluid self-healing but requires further validation; DEGs remain more fatigue limited under high-cycle offshore operation.

5.1.7 Ease of Process, Scale-up and Maintenance

Both DEGs and DFGs are compatible with scalable manufacturing concepts, including roll-to-roll processing. DEGs likely have fewer steps and a simpler *"solid capacitor"* concept which could make them cheaper to manufacture. However, they require a solution for stretchable electrodes with industrial processes still in their infancy. Additionally, damaged elastomeric layers may require removal and replacement which is difficult in multilayer assemblies.

DFGs add the complexity from fluid filling which introduces sealing requirements. That said, filling could potentially be performed in-situ at deployment, reducing transport complexity. The electrodes require to be flexible, not stretchable, with expected technology transfer from the flexible electronics industry. Maintenance may be simpler in some cases: systems could be serviced by draining and refilling fluid rather than replacing full elastomeric assemblies. Though the maintenance requirements of dielectric film/electrode systems need to be better understood.

Both technologies demand high tolerances and likely clean-room fabrication. Scale-up will be challenging for each, but DFGs benefit from natural modularity, while DEGs will require engineered segmentation to isolate failures.

Summary: It is too early to tell which technology will be simpler and cheaper to manufacture at this stage. DEGs likely have fewer manufacturing steps, but require segmentation; DFGs may offer easier servicing via fluid replacement but require robust sealing and fluid handling strategies.

5.1.8 Environmental Risk

From a sustainability perspective, DEGs and DFGs share many material classes and therefore exhibit similar trends in embodied carbon, depending on manufacturing route and lifetime. The more substantial distinction is environmental risk. In DFGs, there is the potential for dielectric fluid leakage requiring mitigation strategies such as containment, monitoring, fluid selection, as well as recovery procedures.

While DEGs avoid fluid leakage presenting a lower risk profile, there is still abrasion of material that may leach microplastics to the surrounding environment, requiring consideration of polymer toxicity, recyclability, and end-of-life disposal.

Summary: DFGs require stronger environmental risk mitigation due to fluid leakage potential; DEGs may be simpler from an environmental containment standpoint.

5.1.9 Conclusion

At present, a definitive performance judgement between DEGs and DFGs is difficult, largely because the technologies sit at different maturity levels and DFG datasets remain limited. However, some conclusions can still be drawn:

- DEGs offer conceptual simplicity and large capacitance swing at high strains, but face an inherent trade-off between high performance and long-term fatigue life.
- DFGs introduce fluidic complexity and interface-charge challenges, but benefit from low tensile strain operation and the potential for fluid self-healing, which may make long-life operation more achievable.

Table 1: Comparison of strengths and weaknesses of DEGs vs DFGs

	DEG	DFG
Maturity	**Higher** DEGs have been studied since the early 2000s as generators with many prototypes and implementation into WECs	**Lower** DFGs have been studied since mid-2010s for generator with limited prototypes and only laboratory studies at small-scale
WEC Architecture Implementation	**Lower** Simpler integration into WEC architectures due to direct strain-based energy conversion	**Higher** Harder to integrate due to the demand of moving fluids through cellular channels.
Capture Width Ratio	**Unknown** Both DEGs and DFGs offer equally promising methods to capture wave energy. Both technologies depend on WEC design rather than generator type, so CWR is not a differentiator.	
Power Density	**Unknown** Difficult to determine at this stage. DEGs limited by available high-permittivity elastomers; DFGs require differing material/fluid combinations to get best performance, but this introduces charge accumulation challenges.	
Longevity	**Shorter** The combined electrode-dielectric straining of DEGs places significant burden on the energy harvesting material. High cyclic strain accelerates mechanical fatigue and electrical aging.	**Longer** DFGs decouple the electrodes and dielectric, where the dielectric is a self-healing fluid and electrode is bonded to a non-straining dielectric film.
Manufacturing Complexity	**Unknown** DEGs have fewer production stages but require stretchable electrodes which are limited in production currently. Furthermore, these materials require specialised handling to maintain pre-strain during assembly and deployment. DFGs potentially use more materials, requiring designing a cell to enclose the fluid, as well as filling the cells with fluid. However, they only require flexible electrodes where the knowledge and processes can be borrowed from the flexible electronics industry.	
Maintenance Cycles	**Harder** Likely involves replacing elastomer layers, requiring module disassembly and offshore handling. This will likely take place at regular service intervals.	**Easier** The fluid dielectric will degrade over time, but there is the opportunity for draining and refilling in-situ. The lower mechanical wear and self-healing properties will likely reduce the frequency of maintenance intervals.
Sustainability	**Neutral** Both use similar materials; recyclability depends on design. Risks include microplastic release from elastomers and fluid leakage from DFGs.	

5.2 Systematic Benefits of Direct Generation

A core objective of the design competition was to identify the potential advantages that DG technologies could offer over conventional wave energy converters. Through the evaluation of DG concepts, several opportunities emerged across five key design aspects: structural integrity, performance, practicality, sustainability, and cost. However, each area also revealed its own set of challenges, highlighting the need for targeted research and development to fully realise the benefits of DG systems.

Round 1 of design competition acted as first-screening for the potential of these technologies. Early work in this round focussed on the potential benefits and challenges of using electroactive materials as part of a WEC design. This led to question on whether this technology could unlock fundamentally new architectures capable of delivering a step-change in performance. From an architectural perspective, many concepts demonstrated that DG could substantially simplify the structural chain of components. This would enhance redundancy, distributed functionality, and overall modularity. However, corresponding challenges were also apparent. Chief among these was ensuring that DG-enabled designs could survive offshore conditions comparable to those faced by established renewable energy systems, and addressing manufacturing complexities, particularly the scale-up and reliable production and termination of electrodes and dielectric materials. The full list of opportunities and challenges identified is given in Table 1 below.

Table 2: Opportunities and challenges for Dielectric Elastomers and Dielectric Fluid Generators

	Opportunity	Challenge
WEC Architecture	**Structural simplification:** Concept designs that use electroactive material have the opportunity to reduce or eliminate the prime mover mechanism, instead wave energy is directly coupled to the energy extraction method. Removes or reduces the need for bearings, seals, hydraulics and rotating equipment. **Lightweight materials:** Structure can be made from lightweight elastomers reducing strain on other component systems such as moorings. **Load distribution:** A fully flexible structure can distribute the forces throughout the structure resulting in lower peak forces. **Structural morphing:** Through differing rigidification methods, the structure can Morph relative to the sea surface to capture more energy in lower energy sea-states and shrink to reduces loads in storms. **Redundancy:** Spreading the energy harvesting material throughout the whole structure can improve the redundancy (if segmented). This can avoid single point failures causing the full structure to fail. Moreover, structural and material degradation is expected to occur gradually over time, i.e., individual cell failure and not overall module failure, meaning a distributed and modular layout can help maintain overall performance even as individual sections age. **Self-healing capability:** DG technologies present the opportunity for the structure to recover from certain failure modes; if an electrical	**Longevity:** The large straining and charging/discharging effect on the material causes significant wear and degradation. This limits the lifetime of DG systems with evidence suggesting this would be difficult in 10^7 cycles range (or similar to 5 years or more of operation in typical sea conditions). This challenge has been identified for DEG systems, while DFGs are expected to fare better due to lower strains. **Electrode design:** Designing an electrode which integrates within an elastomer and can deform/bend alongside that material. **Up-scaling (size effect):** The scaling up of direct generation systems increases the likelihood of dielectric breakdowns. This is due to probabilistic increase in voids from having a greater volume of bulk material between the end terminations. **End-terminations:** Designing a method moving from a straining material and circuit termination to avoid electrical connections being in tension. This is likely more of a challenge in DEGs compared with DFGs. **Hysteresis/Thermal instability:** Energy dissipation occurs within the material during mechanical stretching and relaxation, as well as during electrical charging and discharging. In layered material systems, this can lead to heat generation without an effective means of cooling, e.g., internal layers within a large material system. Since the effect of this is amplified by high strain systems, it is expected to be more of an issue in DEGs. However, the movement of viscous fluids in large systems could pose similar challenges.

	breakdown occurs in a DFG cell, the cyclic flow of the fluid "resets" the damaged area. While DEG systems require further research to understand the feasibility of elastomeric self-healing.	
Power Capture	**Scalable power capture:** Using a modular flexible material allows for easier upscaling per kW through duplication of cells/modules which can be distributed over the entire wave front instead of a single location. **Tuneable through variable stiffness:** Possibility of using the material in actuator mode to change the stiffness to adapt to differing wave energy states. For example, applying a higher voltage increases Maxwell stress, which enhances resistance to deformation and effectively stiffens the system. **Self-sensing capability:** Through measuring changes in capacitance, voltage and charge, it is possible to self-sense for understanding deformation characteristics and adaptive control.	**Power density:** Current material systems exhibit low permittivity and limited dielectric breakdown strength. As a result, achieving significant energy output requires large changes in capacitance, which in turn accelerates material fatigue and reduces overall lifespan. **Charge accumulation:** Using materials/fluids of differing permittivity across layers can result in charge accumulation on charging and discharging. Materials either need to be matched, or a bi-polar electrical power electronics solution is necessary. **Control and power electronics:** Maximising energy harvesting efficiency requires a predictive control mechanism where charging and discharging of the material is matched with the oncoming waves. Self-sensing is required to ensure the material is operating within the dielectric breakdown range. Non-predictive mechanisms do exist and may be easier to implement for lower technology maturity devices, but at significantly lower efficiencies. **Charge leakage:** Charge leakage occurs in a shorter timescale than typical wave periods due to polarisation decaying with time. It is important to maximise the resistivity of the dielectric material to minimise leakage as much as possible.
Practicalities	**Supply chain:** Simple bill of materials for the components that make a metamaterial compared with other renewable energy systems. **Scalable through replication:** Cellular designs can be efficiently produced using roll-to-roll manufacturing techniques combined with spray-coated electrode systems. This approach enables metamaterials to be tailored to the precise amount needed for WEC applications, supporting scalable and cost-effective production. This more closely emulates the scale-up of solar photovoltaics, compared with traditional monolithic PTOs. **Structural health monitoring:** Performance degradation can be tracked by monitoring changes in electro-mechanical properties and detecting individual cell failures. This capability allows for in-situ	**Manufacturing cost:** While the raw material cost of silicones is relatively low per kilogram and comparable to steels, manufacturing a DEG or DFG composite involves additional processing steps and stringent quality assurance to prevent defects. These requirements can significantly increase overall costs through the requirement of clean rooms. However, scaling up production through optimised processes is expected to reduce costs over time. **Electrode and dielectric bonding:** Develop a robust manufacturing process that ensures strong bonding between electrodes and dielectric elastomer films. For DEGs, the electrodes must maintain high electrical conductivity while withstanding large strains without delamination or performance loss. DFGs have lower requirements, but still have the risk of delamination from continuous bending during operation. Spray-coated electrodes seem the most promising options available currently, but remain at low TRL (3-4).

	structural health monitoring, allowing for improved understanding of when to replace material systems. **Packing and deflation:** Depending on the WEC type, structures can use a working fluid or air, allowing for them to be deflated and packed for transportation.	**Tolerances and quality control:** Create materials with high tolerance and minimal voids to prevent weak points that could lead to dielectric breakdown. This requires advanced scanning techniques for defect detection, proactive prevention measures, and retroactive repair methods to maintain reliability. **Design around replacement:** Given the longevity challenges of electromechanical materials, incorporate design strategies that allow for easy replacement of components at scheduled intervals, minimising downtime and extending system life.
Sustainability	**Abundance of raw materials:** DEG and DFG systems are composed of relatively abundant raw materials. Common elastomers/fluids are relatively easily manufactured from raw materials (e.g., silicone, synthetic rubbers), dielectric fluids/oils (e.g., silicone or ester-based), and flexible films (e.g., silicone or polyethylene). This simplifies sourcing, instead of complex composites and alloys. Furthermore, these systems do not typically require rare earth elements, precious metals, or other critical minerals often associated with supply chain risks. **Fewer mechanical parts:** With a lack of mechanical machinery, DG systems can operate quietly and in greater harmony with the marine environment minimising ecological impact. **Biodegradable and biopolymers:** There is the potential for use of fully sustainable polymers that can be recycled or biodegrade at end of life resulting in a closed carbon cycle.	**Carbon intensity:** The carbon required to produce silicone is greater than steel. This is due to the large number of petroleum-based feedstocks used in manufacturing silicone. **Microplastic leakage:** Materials that are strained and relaxed while being subjected to abrasion can undergo leakage of material to the surrounding environment. Although, this can be mitigated through encapsulation layers and non-toxic polymers. **Toxicity of fillers:** Certain fillers (e.g., carbon nanotubes) can be highly toxic, and need be handled with care. This brings in concerns to ecological aspects, especially when it comes to leakage. **Critical materials:** Certain materials (e.g., Fluorides) have been banned by the EU Critical Materials Act. Careful consideration is also needed for selecting new materials mindful of potential future bans.

5.3 Metric Evaluation of Direct Generation

To understand whether DG offers a meaningful step-change for wave energy, it is important to evaluate DEG and DFG concepts against a set of performance metrics. Although direct like-for-like comparison with conventional WECs remains difficult due to low technology maturity, the programme generated enough evidence to build a first-order view of relative performance. This exercise was also useful to understand where performance needs to be for it to deliver on that step-change. Metrics were provided to teams in Round 2 and were used to guide design decisions, highlight trade-offs, and give a comparative means to the state-of-the-art.

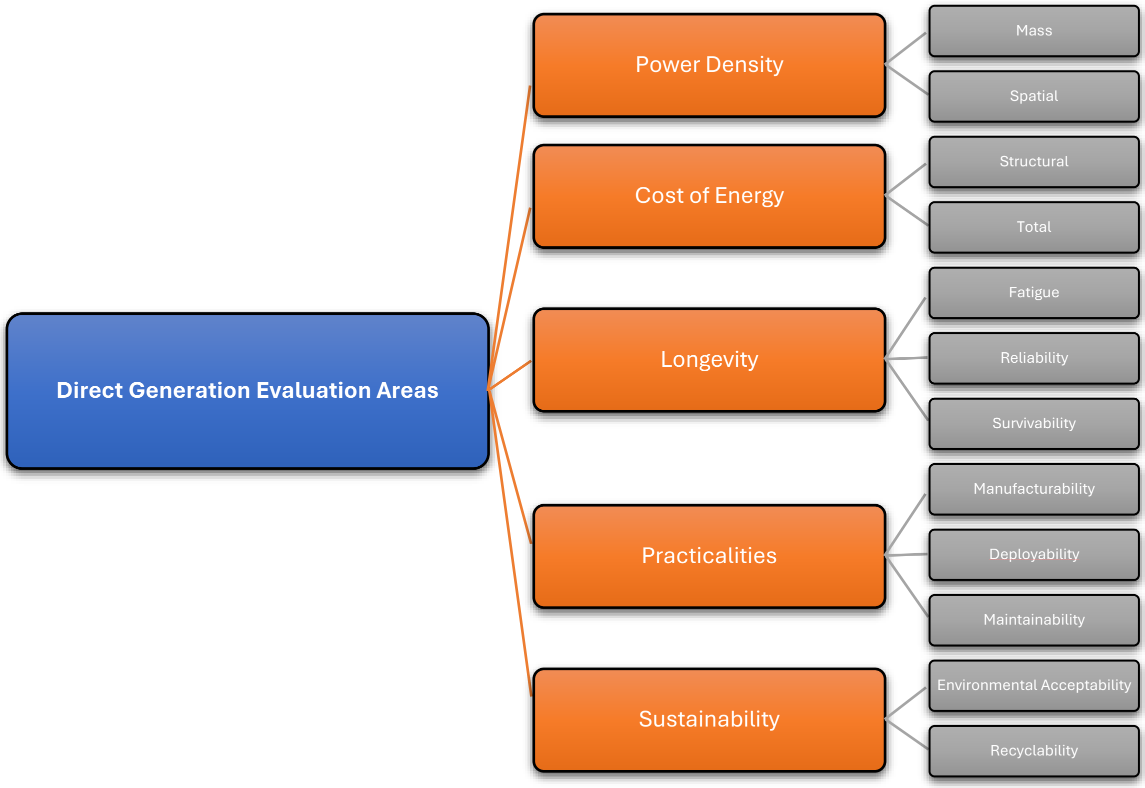

Figure 22: Evaluation areas of Direct Generation (orange) with selected metrics (grey)

5.3.1 Power density

Power density (W/kg) is one of the most influential metrics because it drives device footprint, material usage, and system cost. Across both programme rounds, power density estimates varied widely, reflecting the limited maturity of DG systems and strong sensitivity to input assumptions.

5.3.1.1 Quantitative Assessment

5.3.1.1.1 Conventional wave energy (W/kg)

Conventional WECs typically deliver **1-5 W/kg** based on their rated power and total structural mass. DG concepts fall within the same order of magnitude but face penalties in volume, not mass. This means DG is comparable in principle but needs improvements in power density to realise competitive structural footprints, discussed below.

5.3.1.1.2 DEGs (W/kg)

Theoretical studies indicate that DEGs can reach up to **280 W/kg**[40] under idealised, high-strain conditions. However, when strain limits and fatigue life are accounted for, this theoretical value decreases by one to two orders of magnitude. In practice, most DG projects reported values below **30 W/kg,** and consulted DEG experts suggested the real number to be near **1–3 W/kg** once longevity is accounted for, see Figure 22.

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[40] Huang J, Shian S, Suo Z, Clarke DR. Maximizing the energy density of dielectric elastomer generators using equi-biaxial loading. Advanced Functional Materials. 2013 Oct;23(40):5056-61.

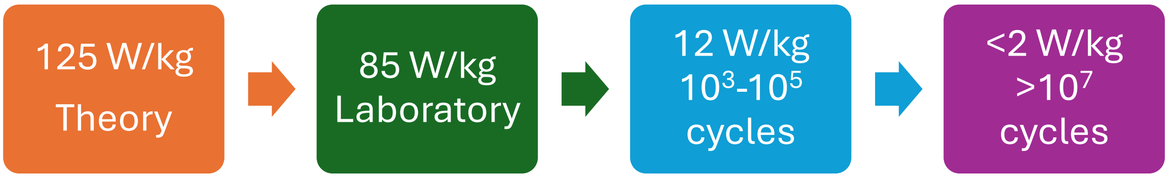

Figure 23: The power density challenge when considering longevity (Adapted from Marco Fontana presentation given at Programme Review Event)

5.3.1.1.3 DFGs (W/kg)

DFG power density evidence is more limited. One published study suggested up to **6 W/kg** (for a single cycle with a 10 second period)[41]. Given the small sample of early prototypes, a definitive value is premature; however, programme estimates suggest DFGs are broadly in the same order of magnitude as DEGs. Notably, the gap between theoretical and practical performance may be smaller for DFGs, because they avoid the large-strain fatigue trade-offs that constrain DEGs.

5.3.1.1.4 Device footprint (W/m^2)

From a volumetric perspective, a lower power density equates to larger devices for equivalent rated power. But ultimately, the size of individual devices will follow the wave capture principles which dictate the sizes of conventional wave energy. Within the programme, estimates for array-level surface area usage reached up to **11 W/m^2** when densely packed, aligning with other studies that report values between **2** and **10 W/m^2** for wave and offshore wind energy arrays[42,43]. This is at the high end of the current-state-of-the-art. But given the nature of density of elastomers/films to steels, the volume trend is expected to be larger based on current power density estimates.

5.3.1.2 Performance Levers

Although current DG power densities are on the lower end, the DG programme identified multiple *"performance levers"* capable of producing large improvements. Since the DG performance is highly sensitive to material parameters, geometry, excitation, and voltage-control strategy, significant gains may be achievable through coordinated R&D.

5.3.1.2.1 Material/Fluid Permittivity

The current ranges of permittivity for DEG and DFG materials are mentioned in Section 6.1.3.2. To push performance further, researchers have explored enhancing permittivity beyond the limits of base elastomers and fluid systems.

Filler Addition: One established strategy for increasing elastomer permittivity is the incorporation of high-dielectric fillers such as Titanium Dioxide (TiO_2) or Barium Titanate ($BaTiO_3$) into the polymer matrix[44,45]. These

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[41] Duranti M, Righi M, Vertechy R, Fontana M. A new class of variable capacitance generators based on the dielectric fluid transducer. Smart Materials and Structures. 2017 Oct 9;26(11):115014.

[42] Enevoldsen P, Jacobson MZ. Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. Energy for Sustainable Development. 2021 Feb 1;60:40-51.

[43] Shadmani A, Nikoo MR, Gandomi AH. Ocean Wave Energy Technology. 2025.

[44] Yin G, Yang Y, Song F, Renard C, Dang ZM, Shi CY, Wang D. Dielectric elastomer generator with improved energy density and conversion efficiency based on polyurethane composites. ACS applied materials & interfaces. 2017 Feb 15;9(6):5237-43.

[45] Gurjar KV, Sadangi AS, Kumar A, Ahmad D, Patra K, Collins I, Hossain M, Ajaj RM, Zweiri Y. Dielectric elastomer generators: recent advances in materials, electronic circuits, and prototype developments. Advanced Energy and Sustainability Research. 2025 Jan;6(1):2400221.

composites can achieve relative permittivities up to $\varepsilon_r \approx 9$ or higher. However, these gains come with important trade-offs:

- Reduced elasticity and flexibility: High-ε fillers are rigid, increasing the stiffness and lowering extensibility.
- Worsened fatigue resistance: Filled elastomers are more prone to crack initiation and accelerated damage under cyclic loading.
- Lower dielectric breakdown strength: As permittivity increases, breakdown strength typically decreases due to increased charge localisation, reducing the safe operating voltage and energy density.

Dipole Modification: An alternative approach involves **chemical modification** of the elastomer backbone by introducing polar functional groups, thereby increasing dipole density without adding rigid particulate fillers. Recent studies have reported permittivity values as high as $\varepsilon_r \approx 23$-34, but still face challenges with increased stiffness due to increased molecular interactions.[46, 47]

High permittivity films/fluids: For DFGs, the use of high permittivity films and fluids needs further exploration. For instance, pure water has a permittivity as high as $\varepsilon_r \approx 80$[48] and a dielectric breakdown of around 70MW/m[49]. In principle, such fluids offer excellent dielectric performance. However, practical implementation is severely constrained by purity requirements due to ionic contamination. DFGs also have access to a wide range of films which have very good permittivity properties but will likely be constrained by cost.

5.3.1.2.2 Cell Design and Power Electronics

Improving the performance of DEG/DFGs relies heavily on optimising both cell design and power electronics. Several design strategies can increase the harvestable energy per cycle, including maximising the effective electrode surface area, reducing voltage requirements through geometric scaling, and improving the efficiency of the charge-discharge cycle.

Film/Electrode Miniaturisation: Miniaturisation of DEGs through thin films and stacking has the potential to increase surface area and reduce the operating voltage requirement for achieving the same electric field. Likewise, making cells smaller in DFGs can have a similar effect to a lesser degree, but both methods approach thresholds:

- **Increased defect probability** and **reduced dielectric breakdown** strength as elastomers/films become very thin.
- **Higher electrode resistivity** when electrodes are made thinner or more compliant, potentially increasing resistive losses.

Power Electronics Innovation: Beyond material and geometric optimisation, a major opportunity for improving performance lies in the power electronics architecture used to harvest energy from capacitance change. Figure 23 illustrates a range of harvesting regimes, progressing from simple to increasingly sophisticated approaches.

- **Resistive Charge (RC)** is the most straightforward and is well suited for early prototypes and laboratory demonstrations. It uses a fixed voltage source and a series resistor, allowing the device to charge and discharge passively as capacitance changes. Since the charge leaks through the resistor, voltage

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[46] Jiang S, Peng J, Wang L, Ma H, Shi Y. Recent progress in the development of dielectric elastomer materials and their multilayer actuators. Journal of Zhejiang University-SCIENCE A. 2024 Mar;25(3):183-205.

[47] Danner PM, Venkatesan TR, von Szczepanski J, Owusu F, Opris DM. Pushing the boundaries of dielectric permittivity in polysiloxanes: polar dipole modifications enable amorphous pyroelectric polymers. Materials Horizons. 2025.

[48] Permittivity of Pure Water, at Standard Atmospheric Pressure, over the Frequency Range and the Temperature Range

[49] Haynes WM. CRC handbook of chemistry and physics. CRC press; 2016 Jun 24.

remains nearly constant, making RC easy to implement but relatively inefficient, as evidenced by the small rectangle.

- **Constant-Charge (CQ)** and **Contant-Voltage (CV)** regimes both offer higher efficiency than RC and yield similar overall energy extraction, but they differ in what electrical quantity is held constant. In CV, voltage is fixed throughout the deformation cycle; in CQ, the generator is electrically isolated to keep charge fixed. Both methods require more active control than RC to ensure stability and to avoid over voltage conditions during relaxation.
- **Optimised Transfer (OT)** cycle uses tailored voltage trajectories that dynamically follow the mechanical deformation of the dielectric. These approaches can significantly increase harvested energy by maximising the enclosed area of the C-V loop, but they require a self-sensing capability, with bidirectional power electronics control to match the voltage profile to changes in thickness and capacitance.

Maximising the energy harvested through power electronics is an engineering challenge, not a physics one. Therefore, this should be studied extensively with the main balance being cost and complexity of the power electronics solution. Advanced methods may be easier to implement in DFG compared to DEG, due to the greater predictability in the end-stop of the cycle.

5.3.1.2.3 Other Options

Outside of material, cell and power electronics design innovations, other opportunities may exist to improve overall power density. These include:

- **Higher frequency excitation:** Operating at higher frequencies improves the power density but methods to do this are not trivial for DEG/DFG systems without introducing significant design complexities. Suggestions for dual-fluid systems with fluidic amplifiers have been suggested in the HASEL-actuator space[50], these solutions could find their way to generators in the future.
- **Hybrid DEG/DFG Systems:** Recognising the benefits of each individual system and applying it to a combined system could hold promise but integration complexity and hydrodynamics need thorough investigation.

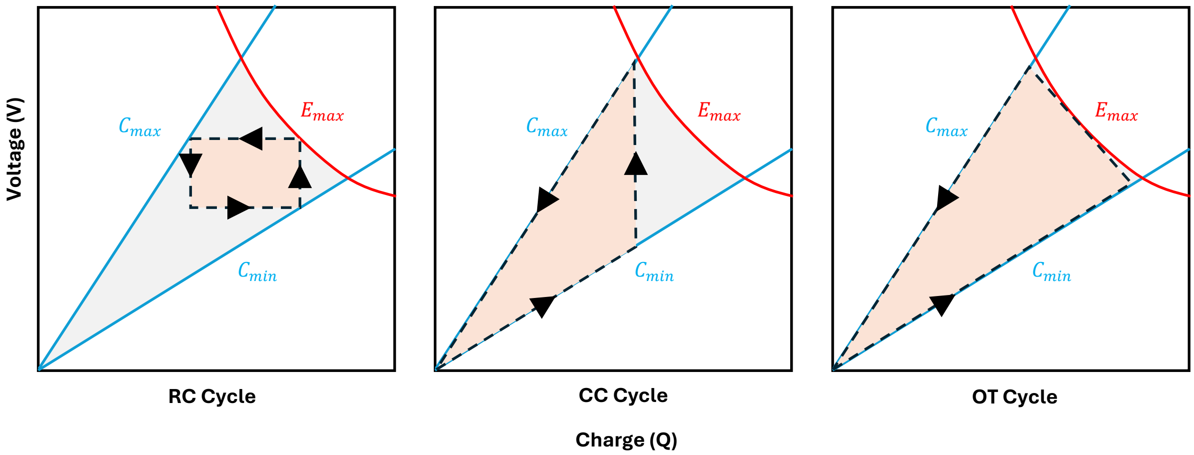

Figure 24: Different energy harvesting cycles - Resistive Charge (RC), Constant Charge (CC), Optimised Transfer (OT) Cycle

Summary: The present power density performance of DEGs and DFGs sits on the lower end compared with other PTO technologies, largely due to their relative immaturity. However, the analysis highlights significant untapped potential for performance gains across materials, mechanics, and power electronics strategies. Among the two, DFGs currently appear to offer the broader innovation space, particularly in their amenability to a greater range

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[50] Diteesawat RS, Helps T, Taghavi M, Rossiter J. Electro-pneumatic pumps for soft robotics. Science robotics. 2021 Feb 17;6(51):eabc3721.

of high permittivity materials, easier implementation of advanced control schemes, and potential solutions to allow for higher frequency operation. A summary of these approaches in given in Table 3.

Table 3: Summary of performance levers for improving power density

Performance Lever	**Options**	**Feasibility**	**Reasoning**
Permittivity	- Fillers (e.g., $BaTiO_3$, TiO_2) - Dipole modification	Moderate	Permittivity can be enhanced using fillers or molecular engineering, but improvements must be balanced against elasticity, fatigue resistance, and dielectric breakdown strength. Current research shows promise but also trade-offs, particularly around dielectric breakdown.
Miniaturisation	- Multi-layer stacking - Novel structures, e.g. origami - Thin films - Segmentation	High	For DEGs, decreasing the thickness of films and the dielectric, increasing electrode area through stacking or innovative geometries is feasible and offers significant potential for performance enhancement. Thinner electrodes allow for higher electrical fields at lower voltages. For DFGs, reducing the pouch size can also lead to an increase in power density, because the capacitance scales with the square of the scale factor, while the liquid volume goes with the cube.
Strain range (capacitance change)	- WEC design - Cell design	Limited	The strain range is strongly coupled with fatigue and therefore the extent in which you can increase this parameter is limited.
Power electronics	- Higher breakdown materials - Adaptive voltage control	High	Advanced control strategies can make the most of the energy available within the strain range. The energy capture through control can be improved significantly if innovations such as adaptive voltage control are realised as well as using high breakdown materials. Furthermore, the squared law between power and voltage encourages maximising the voltage, however this is limited by many subsystems within the WEC (e.g., dielectric breakdown, electrical cables etc.)

5.3.2 Longevity

The next critical metric to evaluate was system longevity, which is strongly coupled to power density. In practice, the two behave as interdependent trade-offs: efforts to increase power density introduce stresses that reduce operational lifetime, while designs optimised for longevity typically limit achievable power density. Whether this energy is consumed rapidly through high-strain high-energy cycles, or distributed over a longer period with lower energy per cycle depends on the system's economic and operational objectives. The stochastic nature of load range, plus the frequency and duration of load cycle are the key parameters that influence the fatigue life in a wave energy application.

5.3.2.1 Quantitative Assessment

5.3.2.1.1 Conventional wave/wind energy and other sectors

Conventional WECs typically follow offshore structural design principles, utilising steel, composites and concrete, targeting 20–25 years of service life (e.g., as reflected in IEC 62600[51] design practice). By comparison, wind turbine blades routinely endure 10^8–10^{10} fatigue cycles over a similar lifespan, a level of durability that DEG/DFG modules are unlikely to reach in the near term. For reference, at typical wave periods, **10^6-10^7** cycles equate to several months to three years of wave energy operation. As outlined below, achieving beyond 10^7 cycles seems challenging. Given this disparity, a more practical strategy may be to adopt a *"use-and-replace"* economic model, similar to the tyre industry. In this approach, the primary offshore structure is designed for a 20–25 year life, while DEG/DFG modules are replaced periodically as part of normal operations. This shifts the value proposition toward modularity and maintainability, which are explored further in the next section.

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[51] IEC TS 62600-2:2019, Marine energy - Wave, tidal and other water current converters - Part 2: Marine energy systems - Design requirements

5.3.2.1.2 DEG Fatigue (No. of Cycles)

To achieve attractive levels of power density, DEGs require large strains of up to 200% in laboratory settings, and likely up to 100% in a wave energy application. There is also a minimum input to achieve meaningful net-positive energy out. Therefore, the longevity is dominated by electro-mechanical fatigue, with mechanical fatigue being the greater challenge compared with electrical ageing. Previous studies are limited to between **10^4-10^7** cycles, operating at a **reduced strain (<50%)** where performance drops dramatically in these cases[52]. Taine et al.[53] showed that optimising for survival of **~10^6** cycles causes a **~50% drop in power density compared with an ideal case**, with even steeper reductions expected for 10^7-10^8 cycles. The best evidence suggests lifetimes beyond a year are possible but there is currently no evidence to suggest that DEGs can reach 10-year lifetimes without major materials innovation or modular replacement architectures.

5.3.2.1.3 DFG Fatigue (No. of Cycles)

DFGs avoid large tensile strain and instead operate under primarily bending or pressure-driven loading. Combined with the self-healing behaviour of dielectric fluids and the possibility of routine fluid replacement, DFGs may have a **higher theoretical ceiling for fatigue life**. However, evidence is limited, with most reported tests below **10^5 cycles**. Expected failure modes shift toward electrical breakdown, charge accumulation, and seal/fluid stability.

5.3.2.2 Performance Levers

Like power density, lifetime can be improved through materials, architecture, and operations enhancements. As longevity is strongly coupled to strain and electric field, the primary optimisation challenge is to find the best compromise that maximises lifetime energy output rather than peak energy density.

5.3.2.2.1 Datasets and Material Economics

To optimise both performance and durability, the key metric becomes Lifetime Energy Density (LED):

$$LED(J/kg) = \frac{E_{cycle}(J) \times N_{cycle}}{Mass(kg)} \tag{5}$$

where $E_{cycle}(J)$ is the total energy captured and N_{cycle} is number of cycles endured, both over the full operational life, which is divided by the $Mass\ (kg)$ of material. This metric clarifies the trade-off between per-cycle energy and survivable cycle count.

The optimal operating point therefore depends on service interval economics rather than per-cycle performance alone. For DEGs, Taine et al.[54] demonstrated this behaviour across a range of cycle counts, i.e., 1, 1000, 1 million cycles (Figure 25), showing a clear *"sweet spot"* where the material delivers maximum lifetime energy output before fatigue or breakdown mechanisms dominate. While this does not represent a material innovation, establishing robust, **long duration experimental datasets** is the essential first step toward designing DEG/DFG systems that align with **realistic O&M strategies** and **lifecycle cost models**.

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[52] Jean-Mistral C, Jacquet-Richardet G, Sylvestre A. Parameters influencing fatigue life prediction of dielectric elastomer generators. Polymer Testing. 2020 Jan 1;81:106198.

[53] Taine E, Andritsch T, Saeedi IA, Morshuis PH. Optimizing energy density in dielectric elastomer generators: a reliability-dependent metric. Smart Materials and Structures. 2024 Oct 17;33(11):115030.

[54] Taine E, Andritsch T, Saeedi IA, Morshuis PH. Optimizing energy density in dielectric elastomer generators: a reliability-dependent metric. Smart Materials and Structures. 2024 Nov 1;33(11):115030.

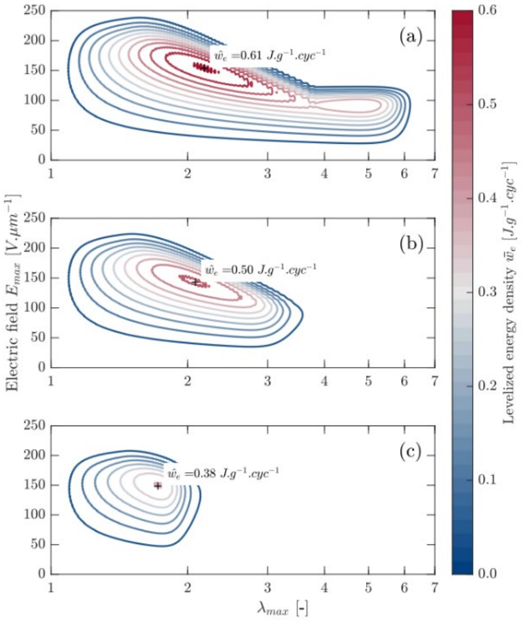

Figure 25: Energy density per cycle when optimised for three different loading scenarios (a) 1 cycle, (b) 1000 cycles, (c) 1 million cycles (Taine et al)

5.3.2.2.2 Material Innovations

The research community is actively investigating methods to improve the performance of dielectric elastomer systems, which include the following:

- **Strengthening fillers (DEGs):** Fillers such as carbon nanotubes (CNTs) and graphene have been shown to improve resistance against crack growth which promotes longer fatigue life.[55] Although these solutions do come at a high cost.
- **Nanocomposite electrode systems (DEGs/DFGs):** Spray coated or printed compliant electrodes can mitigate delamination and improve cycling durability, addressing a historical failure mode for DEGs.
- **Self-clearing electrodes (DEGs/DFGs):** Isolation of defects from the rest of the electrode allowing normal operation to continue after localised failure. Patents currently exist based on work from the SBM programme.
- **Self-healing dielectric capability (DEGs/DFGs):** For DEGs, incorporating self-healing agents within the elastomer matrix offers a potential route to extending operational life by repairing micro-cracks or punctures[56]. However, the commercial feasibility of such approaches remains uncertain. Challenges include potential degradation of baseline material properties, limited healing effectiveness under cyclic loading, and added manufacturing complexity. These may result in increased cost or reduced power density, outweighing the benefits of extended life. In contrast, DFGs are inherently self-healing to some extent, as the dielectric fluid naturally redistributes to fill minor voids or defects.

5.3.2.2.3 Structural health monitoring (SHM)

DG materials allow self-sensing via capacitance or impedance changes. This supports condition monitoring, predictive maintenance, and automated load management. Integrating SHM with adaptive control could extend lifetime and reduce risk of excessive strain or electrical overload.

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[55] Guo H, Ji P, Halász IZ, Pirityi DZ, Bárány T, Xu Z, Zheng L, Zhang L, Liu L, Wen S. Enhanced fatigue and durability properties of natural rubber composites reinforced with carbon nanotubes and graphene oxide. Materials. 2020 Dec 16;13(24):5746.

[56] Madsen FB, Yu L, Skov AL. Self-healing, high-permittivity silicone dielectric elastomer. ACS macro letters. 2016 Nov 15;5(11):1196-200.

Summary: Fatigue remains the primary challenge for the feasibility of DG. There are limited studies to suggest that DEGs and DFGs can achieve moderate lifespans of up to 10 years and look unlikely to surpass conventional structures offshore in terms of life. DFGs seem more attractive overall, though this assessment is still largely speculative due to the immaturity of the field. Given these constraints, it is likely that both technologies will require modular architectures that support a ***"use-and-replace"*** maintenance model, provided the economics are favourable. However, there still remains untapped potential innovation, particularly in materials, fatigue modelling, and system design, but these improvements are expected to be limited. A summary of these options is given in Table 5.

Table 4: Summary of performance levers for improving the longevity.

Performance Lever	Options	Feasibility	Reasoning
Optimising for Lifetime Energy Density	- Metric for balancing life - Benchmarking materials through metric	High	Establishes a consistent basis to balance energy output vs. survivable cycles; guides operating envelopes and O&M intervals.
Structural Health Monitoring	- Self-sensing capability - Operational adjustment	High	Capacitance/impedance monitoring is straightforward; could facilitate predictive maintenance and prevents mechanical/electrical overload.
Material selection and electrode design	- Filler reinforcement - Electrode integration	Moderate	Lifetime extension opportunity but still limited by large-strain marine duty; requires dispersion control and robust adhesion under cyclic loading.
Self-Healing	- Agent dispersed within polymer matrix for in-situ healing - Healing done as part of a maintenance cycle	Unknown	For DEGs, it is conceptually attractive, but unproven at commercial scale; potential penalties in power density and cost. DFG automatically has a self-healing capability.

5.3.3 Practicalities

DG introduces novel material systems which differ significantly from conventional WEC construction materials such as steel, composites and concrete. As a result, this introduces unfamiliar manufacturing routes with different quality control challenges and integration methods. A DG device takes place over seven stages from *'cradle-to-grave'* as indicated in Figure 26. A discussion is made below on each of these areas.

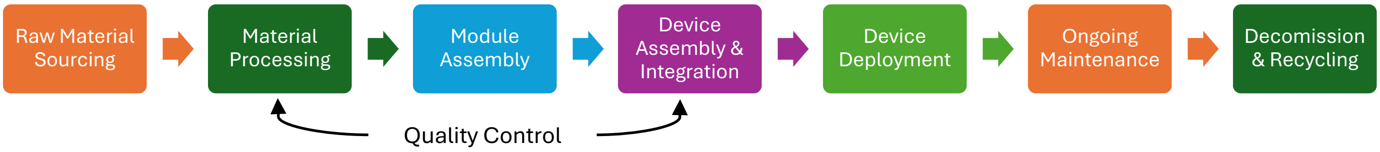


Figure 26: Manufacturing, Deployment and Maintenance Approach for Direct Generation Systems

5.3.3.1 Qualitative Discussion

5.3.3.1.1 Raw Material Sourcing

Materials within DEG/DFG systems include dielectric elastomers/films, conductive metallic/polymeric electrodes, dielectric fluids and specialised filler systems. These materials are generally available with no critical supply shortages. However, their sourcing costs are currently higher than those of conventional metallic structures used in traditional PTOs. This cost difference is largely driven by the high purity requirements for silicon-based components, and limited global manufacturing volume (economies of scale). Another consideration is regulatory restrictions, such as the banning of certain substances (e.g., fluorides previously used in energy harvesting but banned under the Critical Materials Act), which may influence future material choices and design strategies.

5.3.3.1.2 Material Processing

The fabrication of DEG/DFG cells progresses through a sequence of steps, starting with the mixing and curing of the base materials, then advancing to lamination and electrode deposition. Final assembly includes encapsulation, and in the case of DFGs, additional steps such as fluid filling and sealing.

For DEGs, roll-to-roll processing is the most promising pathway and is shown to have high reproducibility. For DFGs, manufacturing remains largely conceptual. Processes are likely to resemble food-packaging or pouch-cell fabrication where cell cavities are formed, filled with dielectric fluid and then sealed at the end. Both approaches require clean room environments, as contaminants (dust, moisture, air bubbles) can trigger dielectric breakdown. Furthermore, manufacturing tolerances are expected to be very high to avoid micro-defects.

DG processing is more similar to electronics manufacturing than to traditional marine engineering, which has clear implications for cost, workforce skills, and quality assurance. Economies of scale can bring these costs down, but learning rates associated with improvements in processing will be necessary to make it competitive relative to conventional PTOs.

5.3.3.1.3 Module Assembly

Turning individual cells into functional DG modules requires mechanically and electrically integrating multiple units, including the transition zones between electroactive regions (strained or fluid-filled) and the surrounding structural supports. These interfaces introduce several challenges:

- Stress concentrations at cell/module transitions, which can lead to premature mechanical failure if not properly managed.
- Electrical terminations which also must accommodate to this strain without cracking or delamination.

Due to the immaturity of this technology, only one real-world example exists. Examples from the SBM S3 experience highlighted:

- UV-cured silicone within moulds can be used as encapsulation to create watertight DEG rings during the assembly stage.
- Liquid metal terminations (gallium-based alloys) to maintain conductivity under deformation.

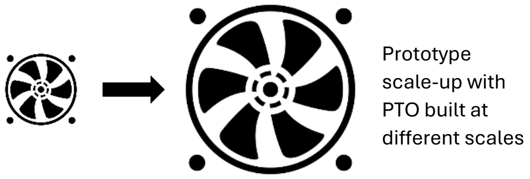
Much of the module assembly remains conceptual at this stage, as there is limited prior industry applications for this scale of manufacturing. The SBM programme has pioneered techniques through large-scale development of DEGs which is the best place to start when considering new designs.

5.3.3.1.4 Quality Control

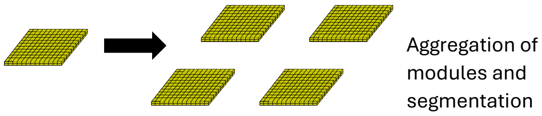
A key challenge in scaling up from lab-scale demonstrations to intermediate and large-scale devices is the probabilistic effects of micro-void defects within bulk material. As the amount of bulk material increases between the terminations, the likelihood of a defects or flaws increases. To mitigate this, maximising modularity in cell design reduces reliance on large volumes of bulk material between terminations and should be considered a core principle of future design strategies. As illustrated in Figure 27, scaling should follow a *'Lego-brick'* analogy: traditional monolithic PTOs scale by enlarging components, whereas a distributed PTO maintains component size and scales through duplication.

Nevertheless, rigorous inspection of samples prior to assembly is critical to avoid costly early replacements. Examples from the SBM laboratory facilities included:

- Dielectric breakdown testing of sampled films.
- Localised defect repair (insulation plugs) for damaged films.
- Strict environmental controls during curing and coating.



Monolithic PTO



Distributed PTO

Figure 27: Scaling up of monolithic PTO vs distributed modular PTO

5.3.3.1.5 Deployment

Due to the absence of real world DG deployments, the method of deployment remains largely conceptual, with limited empirical data to guide best practices. The best technologies to draw experience from are inflatable offshore structures used in marine transport (e.g., hovercraft skirts, inflatable boats) and oil and gas industries (e.g., flexible risers). As identified, there are potential advantages such as compact packing and on-site inflation which could significantly reduce transport and installation costs, but these benefits remain unproven. Project teams have proposed assembly strategies tailored to existing vessel deployment infrastructure, leveraging modular designs to enable incremental scaling and iterative learning. This modularity supports phased deployment, where insights from smaller-scale installations inform decisions for larger systems at later stages.

5.3.3.1.6 Ongoing Maintenance

The expected lifespan of these material systems is shorter than that of conventional steel-based structures, making an effective module replacement strategy a critical design requirement. Incorporating modularity and ease of access for maintenance should be prioritised from the outset. Innovations such as self-healing materials could extend operational life, but these remain unproven at large scales and for commercial applications. One advantage of DFG systems is the inherent self-healing capability of dielectric fluids, which degrade over time but can be drained and replaced periodically. In contrast, DEG systems would require decoupling modules from the existing structure or adopting alternative shorter lifespan economic models to support cost effective WEC deployments.

5.3.3.2 Manufacturing Readiness Level

The manufacturing readiness level[57] ranks the maturity of the processes identified above and gives an insight into what are next steps are necessary to achieve further maturity, it is ranked on a scale of 1-10, where 1-3 represent identification of processes and proof-of-concept manufacturing, 4-6 indicate development of production relevant environments and integration of components, while 7-10 correspond to larger-scale and full-scale commercial production capability.

- DEGs (MRL 3–5): Multiple proof-of-concepts have been developed, and small-scale production lines are emerging. However, there is limited experience with assembly and deployment.
- DFGs (MRL 2–3): Lab-scale prototypes exist, but manufacturing processes remain largely conceptual.
- Conventional WECs (MRL 5–8): Pre-commercial device components and pilot projects are underway, with some technologies approaching full-scale development.

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[57] https://www.dodmrl.com/MRL_Deskbook_V2.pdf

Summary: The practical implementation of DG technologies draws the manufacturing challenge away from traditional marine engineering and closer to the precision manufacturing standards found in electronics, and high-fidelity aerospace sectors. Although there are limited case studies that directly inform DG fabrication and integration, there are meaningful overlaps with adjacent industries, e.g., flexible electronics, soft robotics, thin-film manufacturing and marine elastomeric structures. DG technologies possess a unique advantage in modularity and scalable manufacturing, enabling developers to leverage repeatable cell and module production rather than relying solely on large, monolithic structures. This modular scalability should be considered a core design principle when developing new production processes and deployment strategies.

5.3.4 Sustainability

The sustainability of DG systems is influenced by three key factors:

1. Carbon emissions over the device's lifetime
2. Material sourcing and manufacturing impacts
3. Ecological footprint during operation and end-of-life

NLR's *Life Cycle Greenhouse Gas Emissions from Electricity Generation*[58] provides a useful benchmark for comparison. For example, wind, solar and natural gas technologies exhibit embodied carbon intensities of approximately 13 gCO_2/kWh, 43 gCO_2/kWh and 486 gCO_2/kWh, respectively (see Figure 28).

Currently, there is insufficient empirical data to precisely position DG within this spectrum. However, minimum thresholds can be estimated based on material carbon intensity and projected energy output. Assuming dielectric metamaterials have an embodied carbon of 4–8 $kgCO_2$/kg[59], calculations for different lifetime energy densities reveal the following trends:

- **Short lifespan devices (<5 years at 5 W/kg)** result in embodied carbon significantly higher than wind and solar, particularly if recyclability is not considered.
- **Extending operational life or increasing power density (e.g., 10 years or up to 20 W/kg)** substantially improves performance, bringing embodied carbon closer to the range observed for wind and solar technologies.

Industry expectations point toward changes in silicone feedstock, replacing petrochemical-derived inputs with bio-based alternatives. This transition could significantly reduce the embodied carbon of silicone production over time. A major concern with a DG module is recyclability, particularly given the potential need for frequent replacement. Without effective recycling strategies, material waste and disposal issues could undermine sustainability goals. Investigations into silicone recyclability such as methods for separating electronic and dielectric components are essential to lower both embodied carbon and ecological impact. Operational considerations include the risk of microplastic leakage into the marine environment. This can be mitigated through robust encapsulation techniques and by avoiding harmful additives in material formulations.

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[58] Assessment LC. Life cycle greenhouse gas emissions from electricity generation: update. Life. 2021 Sep;800(1).
[59] Brandt B, Kletzer E, Pilz H, Hadzhiyska D, Seizov P, Bocher C, Cooper J, Hartlieb S. Siliconchemistry carbon balance—an assessment of greenhouse gas emissions and reductions. Global Silicones Council. 2013.

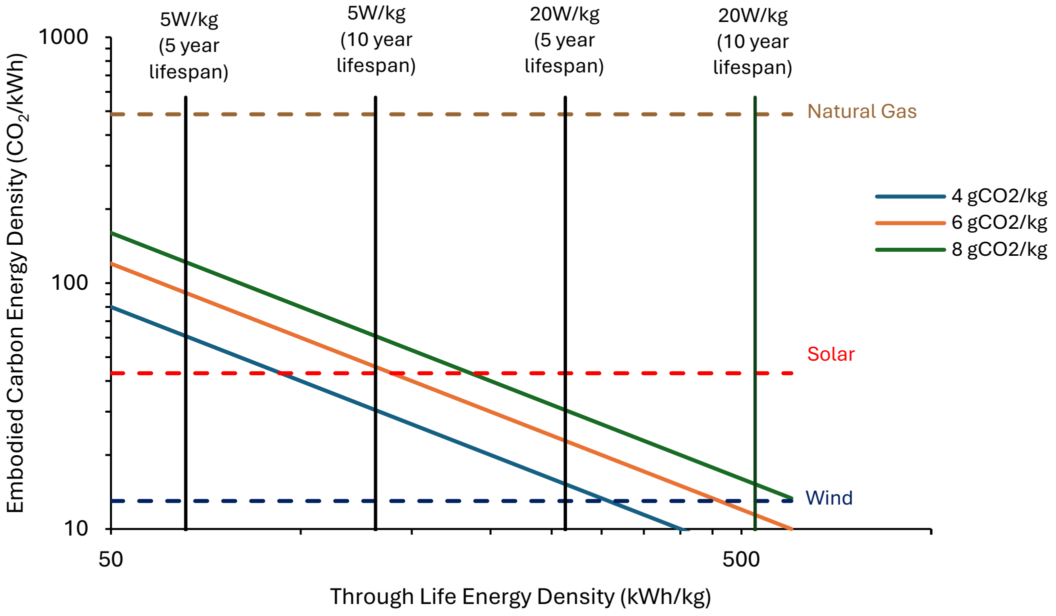

Figure 28: Embodied carbon energy density relative to through life energy density sensitivity study

5.3.5 Cost of Energy

The levelised cost of energy (LCOE) is the primary determinant of DG viability and can be considered as the end output of all aforementioned metrics. At this early stage, **uncertainty is very high**, so the most meaningful analysis comes from sensitivity to key cost parameters. Three dominant factors emerge: metamaterial cost, longevity and power density, as these govern CAPEX, OPEX, and annual energy production respectively. As of now, these parameters form the most meaningful discussion around feasibility and, crucially, what needs to be done to make DG commercially attractive.

5.3.5.1 Power Production

As specified in Section 4.3.1, the current state-of-the-art power density is relatively low compared with other PTO methods when designing for longevity, but there is a clear roadmap for improvement. Innovations in materials, device architecture, and control strategies could increase energy density by an order of magnitude over the coming years. Achieving this is critical because power density directly influences device size, material usage, and ultimately energy yield per unit cost. Right now, taking this **as less than 5 W/kg seems reasonable**, however there is the **potential of greater than 40 W/kg if innovations are realised**.

5.3.5.2 Structural Costs

DG devices use a relatively limited set of materials compared to conventional technologies. Raw material costs for basic silicone can be relatively low **(typically <10 £/kg**), but advanced grades optimised for DEGs may **exceed 50 £/kg**, based on trends on medical-grade silicone. These figures reflect material processing only; assembly and integration costs could push effective costs well beyond **100 £/kg** at present. For DFGs, these costs are expected to be even greater due to the more complicated manufacturing process.

However, a key advantage lies in the modular *"Lego-brick"* design philosophy, which enables scaling through duplication. If standardised across designs, this approach could unlock huge reductions in cost through economies of scale. Additionally, the potential for recycling and repurposing elastomeric components at end-of-life offers a pathway to compounding cost reductions over time. Current costs are expected to remain well above **100 £/kg**, but with process optimisation and volume scaling, a reduction to below **60 £/kg** range appears achievable.

Outside the DG structure, lighter structures will likely require ballast to achieve the desired hydrostatic state. Therefore, although mooring costs could come down, the extent of this is limited.

5.3.5.3 Operations and Maintenance

Estimating O&M costs at this TRL is challenging. If the modular segmented approach is realised, downtime could be minimised, with faults manifesting as gradual performance decay rather than catastrophic failure. However, fundamentally, if the longevity of the cells is too low then this makes frequency of replacement prohibitively expensive. Self-healing concepts may improve life, but current evidence suggests that adding healing agents or fillers often dilutes performance properties for negligible gains in restored functionality. This makes this option commercially unattractive for now. While fatigue life predictions are still difficult to establish, lifetimes beyond 5 years appear challenging with the present state of materials. However, with innovations, this could be stretched to 10 or more years. Therefore, designing machines with **2-3 major replacements** within a **20-year lifespan** seems reasonable at present.

5.3.5.4 Development Costs

Development costs are expected to follow a trajectory similar to other renewable energy technologies, with early deployments incurring higher costs due to novelty and lack of installation experience. However, the reduced mechanical complexity of DG systems should allow for lower costs over time, provided that learning effects and standardisation are achieved after several deployments.

5.3.5.5 Decommissioning Costs

DG decommissioning costs are largely unknown at this stage but could be significantly improved with **design for circularity**, e.g., recycling and repurposing of materials. To achieve this, there is the need to be able to easily and economically separate the different materials at end-of-service-life, which is challenging with multi-layer systems and electronics embedded within flexible materials. If not possible, DG seems less attractive due to the requirement of frequent replacement of modules and large material wastage compared to conventional steel-based WECs.

5.3.5.6 Thresholds

Building on the assumptions outlined above, the techno-economic opportunity space can be organised into three primary innovation domains: metamaterial cost, power performance, and system longevity. Figure 29 illustrates the potential progression within these three-dimensional domains. In this representation, green denotes the current state-of-the-art, orange reflects performance levels that may be achievable through targeted engineering and material innovation, and red indicates the fundamental physical limits that cannot be exceeded.

To understand how these parameters influence overall feasibility, a sensitivity analysis was undertaken using the WES LCOE tool[60]. This approach evaluates parameter combinations capable of meeting an idealised £150/MWh LCOE target, chosen as a representative threshold for future economic competitiveness. The underlying CAPEX breakdown used by the tool is shown in Figure 30, where a conventional WEC typically allocates 38% of CAPEX to the primary mover and 23% to the PTO/Control. The remaining 39% covers structure, installation, mooring, and auxiliary systems, reflecting Carbon Trust and LCICG TINA (2012)[61] cost baselines. For a DG WEC, the primary mover and PTO merge to form a single cost centre: the *'Direct Generation Structure'*, based on the multiplication of metamaterial power density and material cost per kilogram. This becomes the first sensitivity variable, while all other WEC cost centres are kept at default. The second crucial DG component is the OPEX costs, which are dependent on the longevity of individual DG modules. The cost and method of replacing modules is highly speculative, but a conservative assumption is each module replacement costs **80%**

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[60] https://www.waveenergyscotland.co.uk/research-strategy/design-and-modelling-tools/levelised-cost-of-energy-tool/

[61] Low Carbon Innovation Coordination Group. Technology innovation needs assessment (TINA) marine energy summary report. Low Carbon Innovation Coordination Group. 2012 Aug.

of the total CAPEX. This is based on the total cost of the WEC structure, installation, and decommissioning of existing modules. When considering reliability, two replacement cycles at ~7 and ~14 years are assumed for the baseline analysis of a 20-year plant life. All inputs are summarised in Table 6.

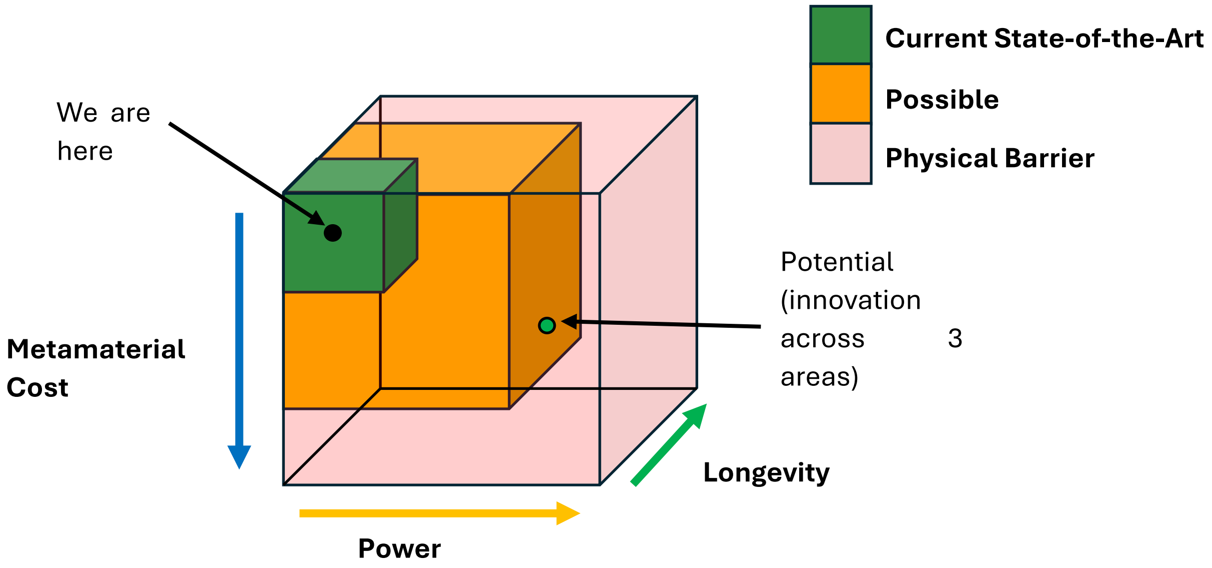

Figure 29: Feasibility of three different metrics, which include metamaterial cost, longevity, and power density

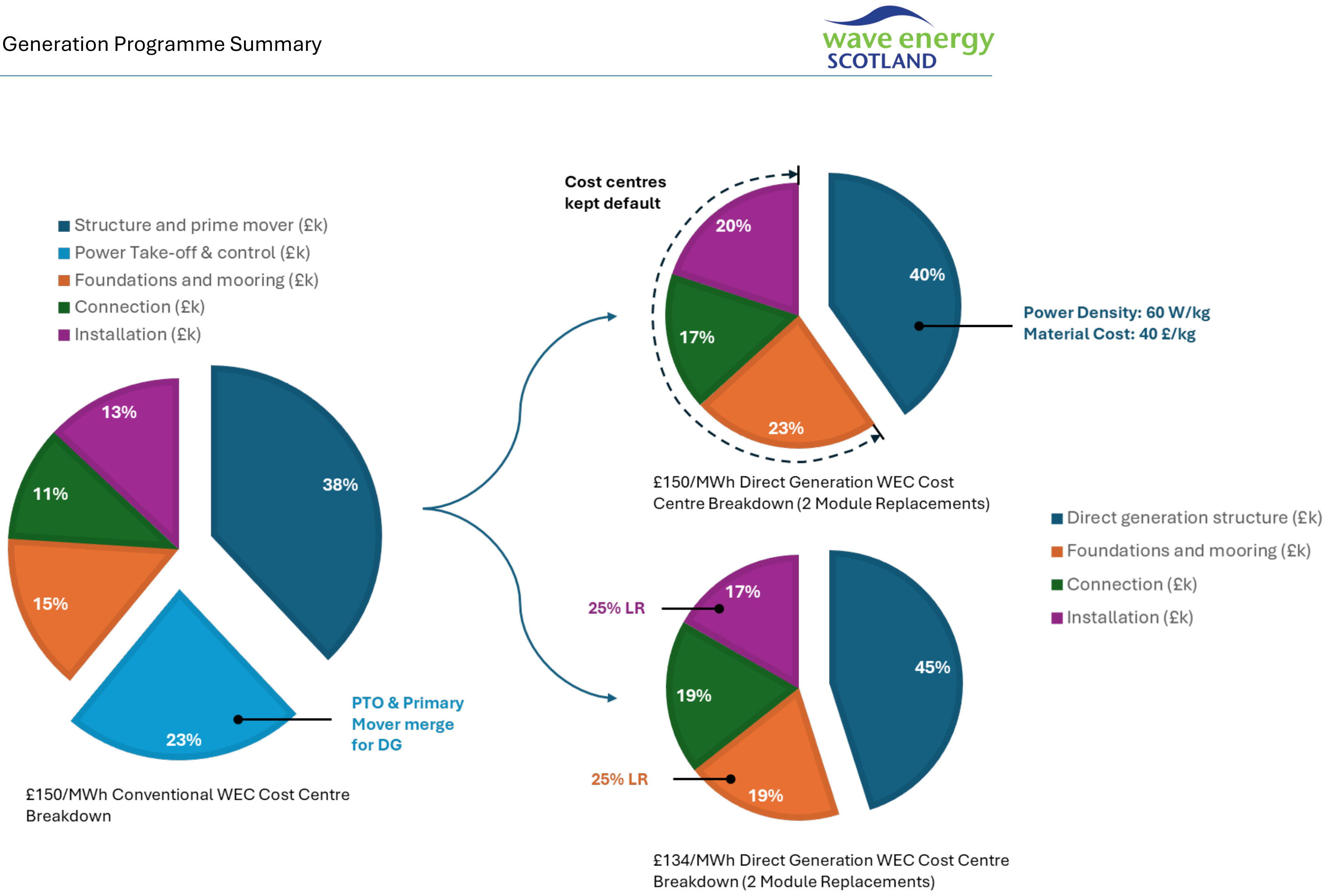

Figure 30: Example pie chart of cost breakdown for a Conventional WEC vs Direct Generation WEC. An example metamaterial with ~60 W/kg power density and ~£40/kg cost achieves £150/MWh target.

Table 5: Cost and power inputs for generic Direct Generation WEC

Area	**Value**	**Unit**	**Assumptions**
Power density range	0-100 W/kg	W/kg	Range of power densities considered, ranging from currently expected to that predicted by theory
Metamaterial Cost	10-60 £/kg	£/kg	The cost of metamaterial includes assembly. Based on expected cost reduction for large-scale production
Capacity Factor	35%		35% efficiency of rated value, which is the standard average for WECs
Connection Cost	286	£k/MW	The cost of connection is kept the same as a traditional WEC
Installation Cost	338	£k/MW	The cost of installation is kept the same as a traditional WEC
Foundations & Mooring	390	£k/MW	The cost of mooring is kept the same as a traditional WEC
Longevity	7 years (Module), 20 years (Plant)		2 major module replacements, equating to 80% CAPEX each time
Maintenance	4% CAPEX (Annual)	-	Kept the same as traditional WEC

This is not the full story as these parameters have a huge range of possibilities, so the most meaningful analysis comes from sensitivity to the cost-performance thresholds. Figure 32 presents three metamaterial cost scenarios and their corresponding relationship between power density and LCOE. Across the ranges examined, the analysis indicates that high power densities are required to achieve the £150/MWh target. Figure 32(a) – (c) gives the performance thresholds for learning rates of 0%, 25%, and 50% for other WEC CAPEX centres. As discussed in previous sections, these areas could be influenced by DG-related design simplifications. Even in favourable assumptions, however, substantial non-structural costs remain. In Figure 32(a), under optimistic conditions with the highest power-to-cost ratios, the LCOE asymptotically approaches £95/MWh, suggesting that substantial non-structural cost components continue to dominate overall expenditures. However, with very high learning rates applied to CAPEX outside of the DG structure, this value comes down significantly to £65/MW, as shown in Figure 32(c). This outcome implies that meaningful cost reduction will likely require complementary innovations beyond the metamaterial itself, including improvements in installation, balance-of-plant, and operational costs.

From the combined sensitivity ranges, a broad conclusion emerges: **DG metamaterial requirements are extremely demanding.** Competitive LCOE outcomes generally require costs **below ~£50/kg** and power densities **above ~40 W/kg**. However, if material costs can be reduced to very low values (e.g., £10/kg), the required power density drops significantly to just **~10 W/kg.** This highlights the inter-dependent nature of these parameters, and a major breakthrough in one area significantly lowers the requirements of the other areas.

A further sensitivity analysis on DG module longevity is shown in Figure 33. This explores scenarios involving 0 to 3 module replacements over a 20-year plant life, for a material cost of £40/kg. The results show that longevity plays a strong role in economic feasibility: each additional replacement imposes a substantial LCOE penalty. For example, achieving economically attractive results in a 3-module replacement scenario requires **four times** the power density performance compared to a system requiring no replacements. This highlights the importance of balancing metamaterial performance with durability and maintenance strategy.

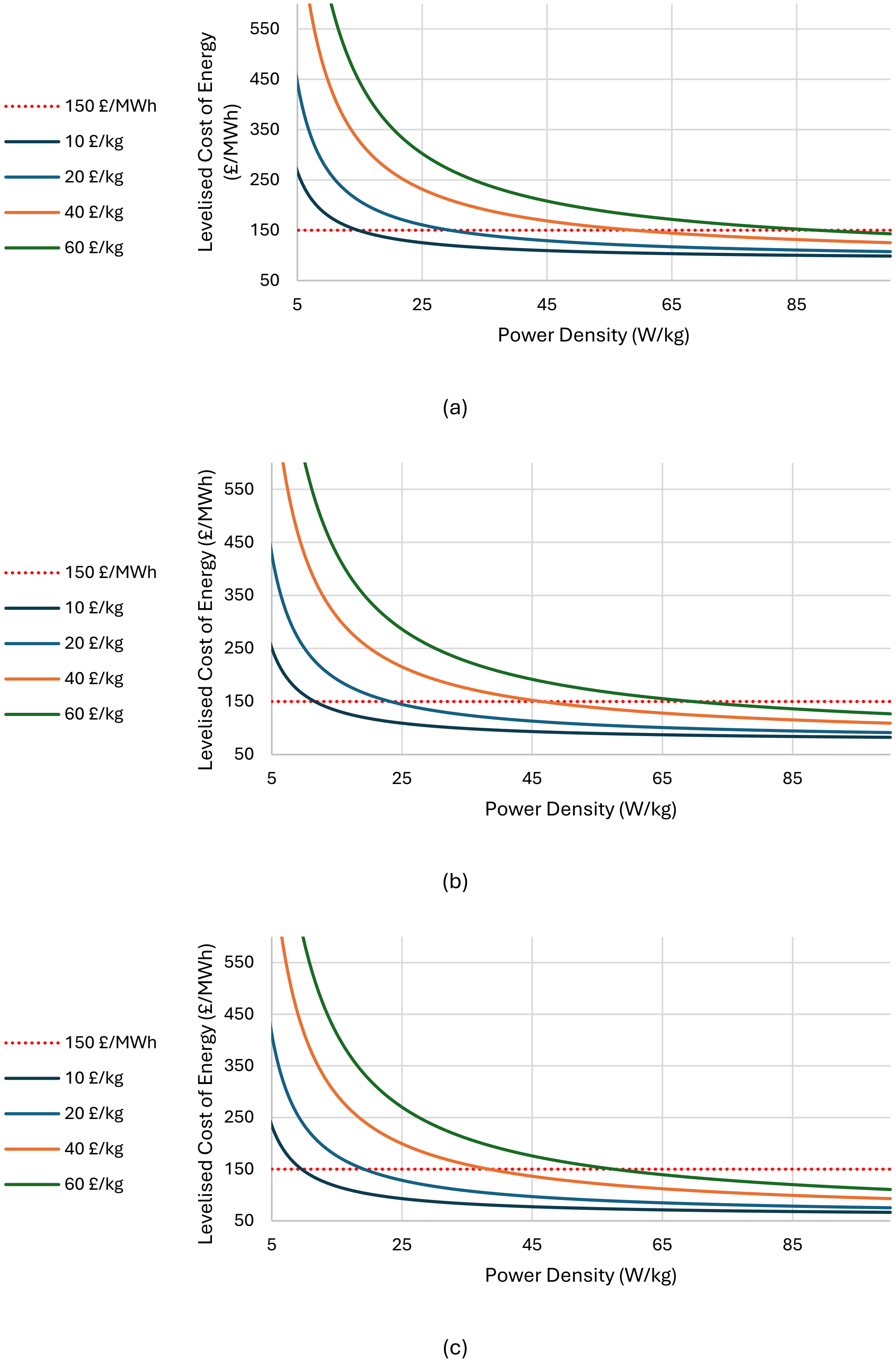

Figure 31: Cost sensitivity analysis for different material power density and material costs. (a) Default external WEC costs, (b) 25% LR applied to Installation & Mooring, (c) 50% LR applied to Installation & Mooring.

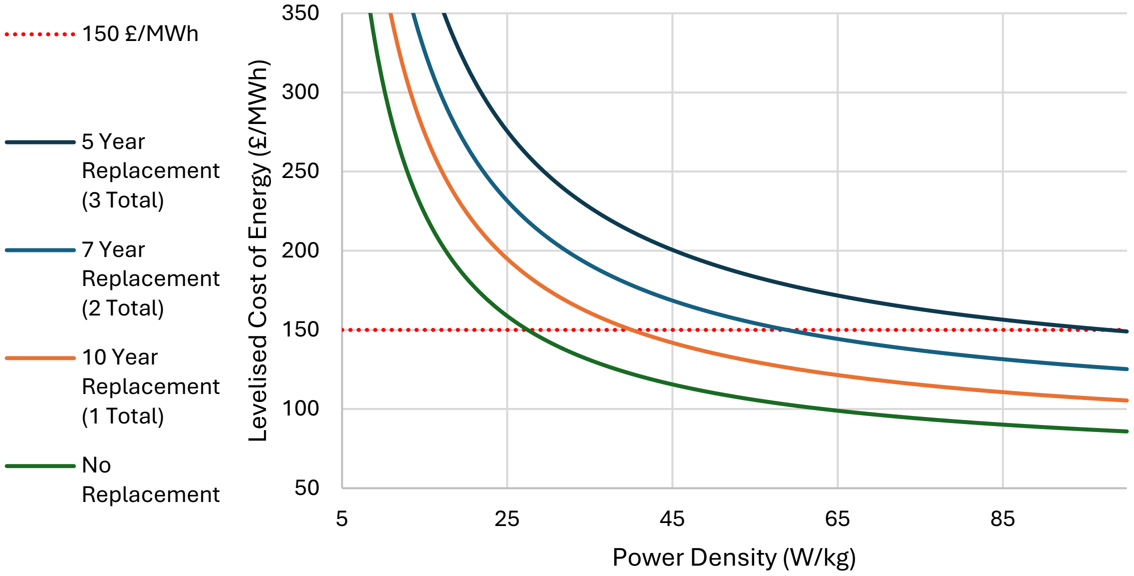

Figure 32: Performance assessment for different module lifetimes, assuming 80% CAPEX replacement and £40/kg.

Based on the above discussion, taking the medium values in the ranges analysed yield the performance thresholds required to achieve an economic system. These are presented in Table 7. It is important to emphasise that these values **should not be interpreted as prescriptive or fixed.** At this early stage of technological development, uncertainties remain large across material performance, system architecture, and deployment environment. These should be viewed as directional targets for guiding research, highlighting the ranges within which DG-enabled WEC systems may begin to demonstrate credible economic potential. Furthermore, because many parameters interact non-linearly, improvements in one domain can reduce the degree of improvement required in another. As such, **a balanced, system-level optimisation approach,** rather than isolated performance gains, is likely to deliver the most impactful advances.

Table 6: Performance thresholds across three-core metrics.

Metric	Minimum Threshold	Comments
Longevity	≥ 7 years per module	Enables ~2 replacements over 20- year system life
Power density	≥ 40 W/kg	Controls device size and structural cost
Metamaterial cost	≤ £50/kg	Potentially achievable with scale and duplication

5.4 Research Activities

To meet the thresholds mentioned above, significant R&D innovations are required across the DG spectrum. These include research tasks amongst four core themes, which are discussed in detail within the DG Research Agenda document. The four following themes are:

1. Material/Metamaterial Selection, Characterisation and Development
2. Generating Module Design and Development
3. Manufacture and Integration Process Development
4. WEC Architecture Development

A high-level summary of these topic areas is shown in Figure 32, with more detailed explanations on the sub-tasks required in these areas given in Sections 4.4.1 and 4.4.4.

5.4.1 Material/Metamaterial Selection, Characterisation and Development

Developing the appropriate materials and metamaterials requires the characterisation testing and optimisation. This allows for improvements to material properties, potentially enhancing energy density, the fatigue life and environmental footprint of the device. It is considered one of the key levers for elevating performance of DG devices. The tasks required include:

5.4.1.1 Electrodes and Energy Efficiency

- **Energy Harvesting Cycle:** Exploring advanced strategies to maximise energy capture during charging and discharging. This extends beyond conventional constant-charge and resistive-charge cycles, focusing on optimised transfer cycles that enhances energy harvesting efficiency through precise control mechanisms.
- **Electrical Losses:** Development of ultra-thin electrodes with low resistivity and minimal dissipation to reduce electrical losses throughout the charging and discharging processes.
- **Stretchable Electrodes:** Designing electrodes that integrate seamlessly with the mechanical substrate, enabling deformation without inducing inter-layer shear forces. Promising approaches include nanocomposites and spray-coated layers homogenised within the dielectric material.
- **Electrode Ageing:** Understand the prolonged effects from electrical cycling on the electrode performance and resulting degradation profile or number of cycles until failure.

5.4.1.2 Mechanical Performance and Structural Integrity

- **Mechanical Dissipation:** Analyse the viscoelastic properties of polymers to minimise energy losses and dissipative heating between layers, which could lead to thermal runaway.
- **Multi-Layer Performance:** Examine the mechanical behaviour of inter-layer metamaterials to mitigate risks of delamination and ensure structural integrity under operational conditions.
- **Fatigue Cycles:** Assess the endurance of materials/metamaterials under varying loading modes and strain levels to determine the cycles to failure thresholds. Combine both mechanical and electrical testing to understand the coupled electro-mechanical fatigue. Use these insights to guide material optimisation and inform future design strategies. Target ranges above 10^7 cycles at moderate strains. Build these values into a dataset which is balanced against power density using the metrics outlined in Section 4.3.2.

5.4.1.3 Material Innovations

- **Filler Systems:** Investigate cost effective functional fillers (e.g., Titanium Barite) in dielectric materials to enhance dielectric properties while minimising compromises in fatigue resistance and dielectric breakdown strength.
- **Chemical Modification**: Investigate the applicability of applying dipole-oriented chemical modifications to polymers to increase permittivity enabling higher power density performance. Ensure these modifications are commercially viable in terms of manufacturing feasibility, stiffness response and overall lifetime.
- **Dielectric Materials and Fluids:** Identify and evaluate base dielectric elastomers, films, and fluids for integration into DG systems. Investigate methods to synthesise and develop new materials with enhanced properties for the DG application.
- **Dielectric Self-Healing Capabilities:** Explore mechanisms for self-healing within dielectric materials to extend operational life and improve reliability. Understand the cost to benefit ratio of incorporating these self-healing systems into commercial-scale DG systems.
- **Self-Clearing Electrodes:** Investigate the applicability of self-clearing electrodes that oxidise and isolate flaws in electrodes to avoid complete failure

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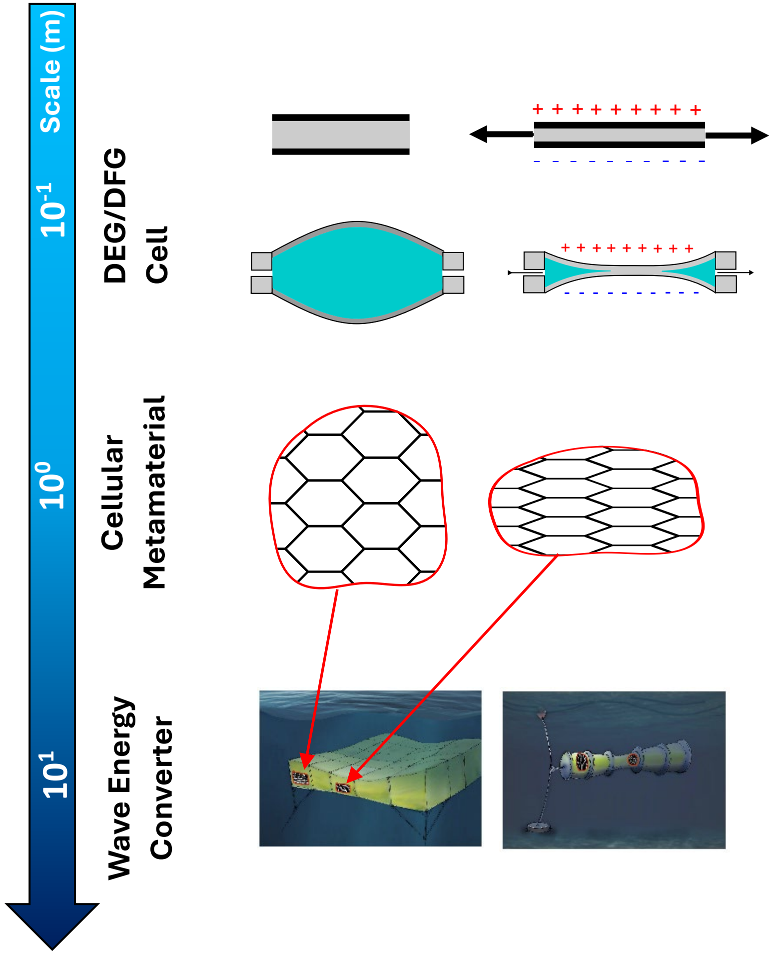

MATERIAL/METAMATERIAL SELECTION, CHARACTERISATION AND DEVELOPMENT

- Dielectric material/fluid solutions and electrode development
- Material characterisation of mechanical/ electrical properties
- Seal-healing materials
- Environmental resistance (UV, marine environment and biofouling)

GENERATING MODULE DESIGN AND DEVELOPMENT

- Segmentation of DG-enabled WEC
- Auxetic Structures
- Reliability testing and verification
- Embedding electrical circuitry
- Multi-physics cellular and large-scale homogenised FEM modelling

MANUFACTURE AND INTEGRATION PROCESS DEVELOPMENT

- Vulcanisation, lamination, printing, coating methods for DG membranes
- Scale of production, e.g., factory size, mass of feedstocks
- Verification processes
- Ensuring tolerance levels and minimising voids

WEC ARCHITECTURE DEVELOPMENT

- Understanding load path from wave excitation to cell deformation
- Solutions for folding and unrolling at deployment site
- Development of modular design solutions to enable replacement of units
- High fidelity flexible fluid-structure interaction tools

OVERLAPPING R&D

Soft Robotics

Medical

Automotive

Other renewable energy

Figure 33: Summary of Research & Development tasks for progressing Direct Generation

5.4.1.4 *Environmental Protection and Sustainability*

- **Seawater Resistance:** Develop materials with high resistance to seawater ingress and biofouling to prevent degradation. Incorporate protective encapsulation layers and design scalable solutions suitable for commercial deployment.
- **Environmental Impact:** Assess and mitigate risks of microplastic leakage into marine ecosystems. Implement containment strategies such as robust encapsulation and explore environmentally benign compounds that degrade safely without harming wildlife.
- **Material Sourcing:** Ensure sustainable sourcing practices that minimise supply chain vulnerabilities and comply with the Critical Raw Materials Act for large-scale commercial manufacturing.
- **Design for Circularity:** Engineer polymers that can be efficiently separated from electroactive components to maximise material recovery and reuse at end-of-life.

5.4.1.5 *Scaling and Experimental Validation*

- **Size Effect:** Ensure testing is conducted at representative scales, with sufficient segmentation to prevent excessive bulk material between terminals, as this increases the probabilistic likelihood of defects. Understand if laboratory performance equates to real-world full-scale performance.
- **Laboratory Facilities:** Establish and equip laboratory facilities capable of performing layered materials and cell testing at development representative scales to validate design and functionality. Ensure access to long-term fatigue and seawater ageing testing, which is currently restricted to a few specialised laboratories, so that material and device validation can progress without bottlenecks.

5.4.2 Generating Module Design and Development

Developing designs of metamaterial and modules for WEC integration will require building solutions with segmentation, control, and ease-of-access practical design requirements. This requires designing concepts, testing these concepts in the respective environment and optimising based on learnings.

5.4.2.1 *Modular Architecture and Segmentation*

- **Architectural Design:** Develop flexible and scalable device architectures in which modular units can be aggregated to form a complete WEC system. This includes ensuring that electrical and control system interconnections are straightforward, robust, and do not introduce unnecessary complexity.
- **Structural Integrity:** Analyse load transfer mechanisms at both the cellular and module levels to understand the system’s wave frequency response and accurately predict survivability loads. Incorporate redundancy mechanisms within design principles to ensure that localised module failure results in only minor performance reduction and does not compromise the overall structural integrity or survivability of the device.
- **Sensing for Control:** Control of DG functions throughout the device (distributed generation) using self-sensing capabilities.

5.4.2.2 *Intelligent Structural Design*

- **Auxetic Structures:** Investigate intelligent structural solutions such as auxetic structures (e.g., honeycomb) that can enhance wave energy response through adaptive load distribution which enhance operational range of DG.
- **Dual-Fluid Zipping Structures:** Investigate dual-fluid zipping mechanisms that can tune or amplify the system’s frequency response, enabling more efficient operation across a broader spectrum of sea states.

5.4.2.3 *Testing and Demonstration*

- **Scaled Demonstration:** Conduct progressive scale demonstrations of DG-modules, supported by both individual module scale-up and module multiplication strategies. Select the scale-up pathway based on emerging insights into WEC performance requirements to validate system behaviour and integration at representative scales.

- **Wet-Testing:** Perform testing in realistic hydrodynamic environments to characterise the coupling between wave excitation and DG cell activation. Use these tests to refine control strategies, assess durability, and validate mechanical and electrical performance under simulated operational conditions.

5.4.2.4 Numerical Modelling of Metamaterial

- **Reduced-Order Models:** Simple mathematical models to describe metamaterial behaviour under loading through homogenisation. This gives an indication on power capture for different deformation and mode shapes for wave energy and adjacent applications.
- **Multi-Physics High-Fidelity Models:** Detailed modelling of individual cell behaviour and metamaterial materials to understand intricate performance effects from cell design.

5.4.2.5 Practical Design Decisions

- **Maintenance and Decommissioning Planning:** Develop strategies for maintaining, replacing, and refurbishing individual modules to support long term operational reliability. Establish end of life pathways such as recycling or repurposing to ensure sustainable lifecycle management.
- **Power Electronics and Control:** Design robust, high performance power electronics and control architectures with sufficient switching speeds and responsiveness to enable optimal DG functionality and efficient power extraction.
- **End-Stop and Pre-Strain Capability:** Investigate the use of secondary materials and structural inserts within the metamaterial system to provide reliable pre-strain management and effective end-stop behaviour, ensuring protection during extreme loads.
- **Environmental Considerations:** Implement containment and protective strategies to prevent the leaching of harmful substances into the environment. Ensure material choices and system architecture align with environmental compliance and marine acceptability requirements.
- **Ad-Hoc Repair Solutions:** Investigate the ability to repair membranes, modules with ad-hoc repair solutions such as insulation plugs to extend module life, consider these methods for pre-deployment and in-situ maintenance.

5.4.3 Manufacture and Integration Process Development

Manufacturing modules for Direct Generation devices will require the development of scalable production processes supported by a robust and reliable supply chain. Membrane materials must undergo strict quality assurance and defect screening protocols, and innovative bonding, sealing, and assembly techniques will be needed to form reliable multi-cell DG modules.

5.4.3.1 Film and Dielectric Membrane Manufacturing Methods

- **Raw Processing:** Investigate suitable base materials optimised for DG applications with good supply chain links and ease of processing.
- **Material Processing:** Develop controlled vulcanisation and advanced additive manufacturing (3D printing) processes for producing DG membranes with highly uniform material properties. Emphasis should be placed on minimising voids, defects, and variations in thickness to ensure predictable dielectric and mechanical performance.
- **Thin Films:** Manufacture ultra-thin dielectric elastomer films with tight tolerance control to reduce the voltage and switching-speed requirements of downstream power electronics while maintaining high breakdown strength.

5.4.3.2 *Module Assembly*

- **Bonding of Materials:** Develop reliable bonding techniques such as lamination, precision printing, spray-coating or adhesive bonding to combine membranes and flexible structural layers into durable DG cells with controlled pre-strain and minimal interfacial defects.
- **Cell Integration:** Integration of cells or segments to form modules, allowing the functional characteristics of the DG-enabled WECs to be realised, e.g., continuous strain distributions throughout flexible WEC bodies.
- **Electrical Integration:** Integration of electrical systems throughout the WEC, i.e., interconnection of electrical connections of multiple modules, device-level electrical control and power electronics solutions.
- **Module Aggregation:** Develop robust methods for combining modules into a complete hydrodynamic body while preserving modularity across different architectural configurations. This includes mechanical joining strategies, encapsulation approaches, and alignment mechanisms suited for large-scale deployment.
- **Production Scale Planning:** Assess the practical requirements for mass production including facility footprint, equipment needs, throughput capacity, and feedstock volumes to support large-scale commercial manufacturing and supply chain resilience.

5.4.3.3 *Quality Control*

- **Verification Process:** Establish dedicated facilities for the systematic verification of electrical and mechanical properties, including dielectric breakdown strength, permittivity, viscoelastic characteristics, and defect detection. This ensures consistency across batches and improves confidence in scale-up.
- **Reliability During Scale-Up:** Establish verification processes tailored to different manufacturing scales to detect flaws, voids, misalignments, or inconsistencies that may arise during large-scale production. This ensures that reliability is maintained as output volume increases.

5.4.4 WEC Architecture Development

Developing the WEC for the hydrodynamic loading environment will require building on the existing set of tools and procedures for conventional WECs. This methodology should evaluate the performance in different sea-states and optimise the design accordingly.

5.4.4.1 *Design Optimisation and Principles*

- **Maximised Energy Generating Geometry:** Prioritise layouts where most of the device surface or volume contributes to energy generation, reducing passive mass and improving overall efficiency.
- **Extreme Loading Mitigation for Survivability:** Enable strategies within the design to allow for load-shedding, e.g., decoupling frequency response, deflation etc.
- **Modular and Replaceable Architecture:** Enable replacement of individual modules or sections of modules throughout the device’s operational lifetime for improved maintainability and reduced downtime.
- **Operational Practicality:** Support practical deployment and recovery features such as folding, rolling, or unrolling mechanisms for transport. Ensure ease of access and module modularity for maintenance, reducing offshore intervention costs.

5.4.4.2 *Physical Testing and Demonstration*

- **Scaled Demonstration:** Conduct scaled physical demonstrations, both in laboratories and open-sea conditions, to validate the hydrodynamic interaction between waves and the DG-enabled body. These tests should quantify energy capture efficiency, dynamic response, survivability behaviour, and strain distribution across modules.

- **Accelerated Life Testing:** Conduct tests of prototype DG WECs to understand degradation mechanisms as result of loading at a realistic representative scale. Use these tests to inform design and eliminate weak spots.

5.4.4.3 Numerical and Computational Modelling

- **Multi-Fidelity Modelling Framework:** Develop a complementary suite of low- and high-fidelity computational models to analyse wave-structure interaction and electro-mechanical response. This should include:
    - Frequency-domain models for efficient assessment of device dynamics and early-stage design trade-offs.
    - Time-domain models to capture transient loads and nonlinear behaviour.
    - High-resolution CFD, FEM, and SPH models to analyse complex hydrodynamics, fluid-structure interaction, and localised stresses at module and cell levels.
    - Electro-mechanical modelling of cells and materials for different wave loading mode shapes.
- **Digital Twins:** Based on the aforementioned models and experimentation, if sufficient confidence is achieved, a digital twin can be developed to inform annual energy production and expected maintenance procedures for DG, providing insights when moving from protype to commercial WEC arrays.

6 Progressing Direct Generation

Addressing these research tasks will require drawing on expertise from a wide range of international research groups, industrial partners, and funding bodies. Identifying overlaps with adjacent sectors and capitalising on cross-sector synergies will be essential to broaden the available funding base and accelerate progress. To maximise impact, research activities should offer the highest return on investment and the greatest cross-disciplinary relevance before progressing to more specialised or resource intensive tasks, except where critical-path dependencies dictate otherwise, e.g., fatigue testing.

6.1 Co-development

6.1.1 Identification of Research Overlaps

DEGs and DFGs share significant research common ground with other soft structure and electroactive materials industries. Consolidating these overlaps is essential for enlarging the funding base and accelerating development. Key cross-cutting themes include:

- DE materials and compliant electrode development
- Sustainable material sourcing, circularity, and recyclability
- Metamaterial design, architected structures, and scale-up routes
- Large-scale elastomer and laminate manufacturing methods

These overlaps span sectors such as soft robotics, wearables, biomedical actuation, automotive textures, flexible sensing, and smart composites, widening opportunities for shared R&D and joint funding bids.

6.1.2 Cross-Sector R&D

Pooling early-stage research questions across sectors enables foundational challenges, such as material durability, electrode reliability, or electromechanical characterisation to be addressed at lower cost and reduced risk. This de-risks material choices before medium to large-scale DG specific testing is performed.

Funding mechanisms such as Horizon Europe, EPSRC, and industry/academic partnerships naturally support multidisciplinary proposals, making cross-sector R&D an effective gateway to maturing DG-relevant technologies.

6.1.3 Stepping-Stone Applications

Finding applications which have an easier route to market to demonstrate commercial success is an important stepping stone between now and generators.

- **Sensors:** Operate at **low voltages** and experience **moderate capacitance swing**. These applications provide the most accessible entry point due to simpler operational requirements and established market pathways.
- **Actuators:** Require **moderate voltages** and operate under **moderate capacitance swing**. They represent a natural progression from sensors, enabling demonstration of greater functionality and performance.
- **Small-Scale Generators (Watt to 1kW):** Involve **high voltage outputs** and **large capacitance swing** but at small scales. These applications allow validation of generator technology in offshore and less other less demanding environments before scaling up. This might include self-powering devices and small WECs.
- **Large-Scale Generators (1kW+):** Demand both **high voltage** and **large capacitance swing** on a large scale. These represent the ultimate commercial target and benefit significantly from success in earlier

stepping-stone applications. This might involve medium to large-scale WEC applications powering larger offshore infrastructure through to utility-scale energy.

The potential workflow following the DG programme is given in Figure 34.

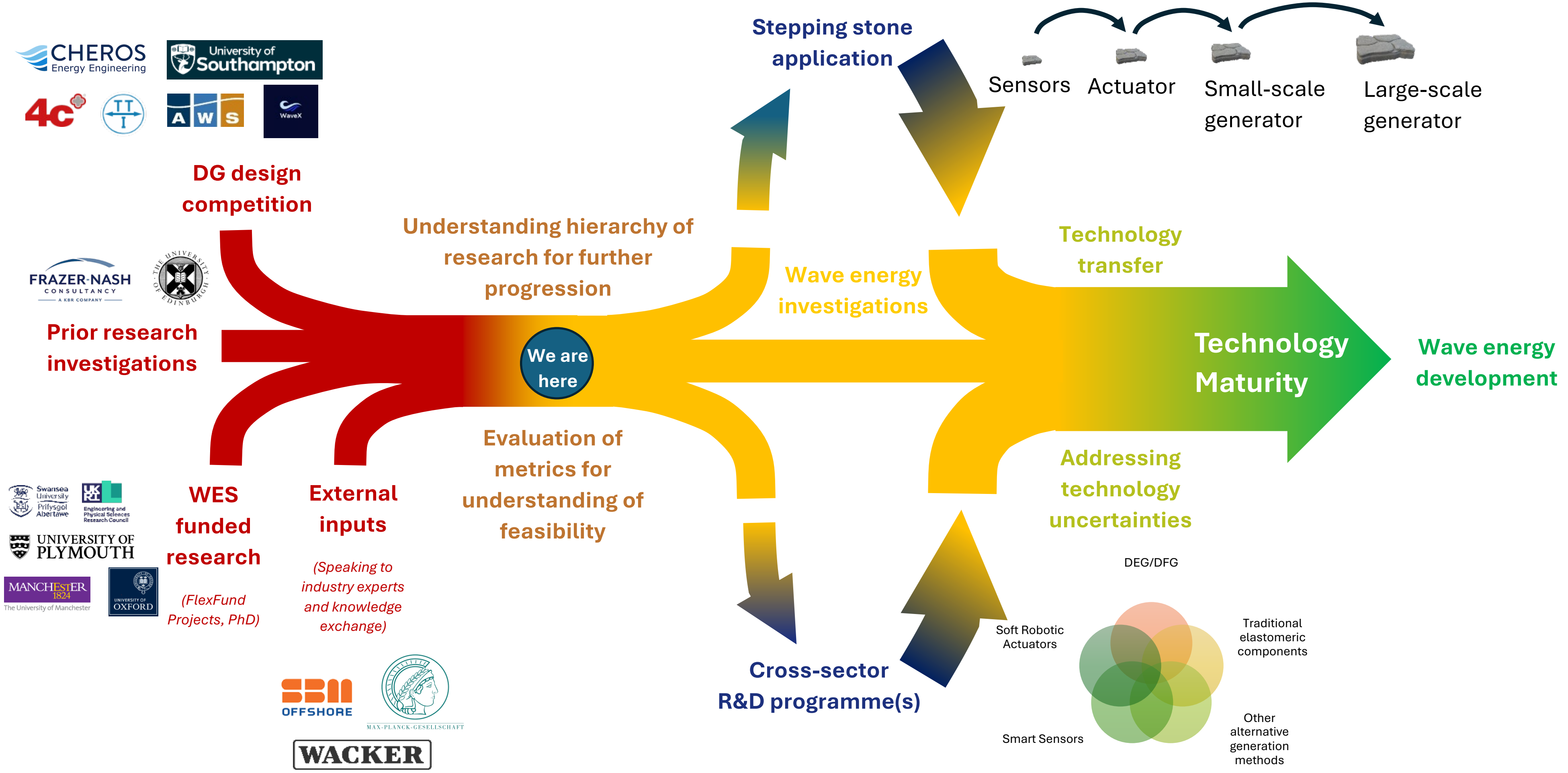

Figure 34: Direct Generation Programme and Next Steps

6.2 Stakeholder Map

6.2.1 United Kingdom

The UK is home to world-leading facilities for the testing and development of WECs, including advanced multi-directional wave basins such as Edinburgh's FloWave facility, which supports hydrodynamic modelling and prototype validation for emerging technologies. This infrastructure underpins a strong national ecosystem of marine energy technology developers, complemented by a growing base of innovative start-ups and SMEs engaged in flexible, soft-structure, and DG concepts.

6.2.1.1 DG-Related Marine-Energy Developers

The UK has a deep legacy in wave energy, and this experience now extends into emerging DG pathways. 4c Engineering *'Ebb-Flow'* and TTI Marine Renewables, both WES DG finalists, are advancing their technologies through prototype testing and early market trials. Complementing these DG-focused firms, the UK also hosts existing elastomeric WEC developers:

- **Bombora Wave Power:** Built a 1.5 MW demonstrator which is largest elastomeric WEC prototype, but this is yet to be tested in open-water conditions.[62]
- **Checkmate SeaEnergy:** Built and tested several iterations of its Anaconda device in the 2010s. Currently, progressing its Lobe-Tendon Anaconda concept through an Innovate UK programme in Wales.[63]
- **AWS:** Developer of the AWS-III which included large elastomeric diaphragms with different scale prototypes tested in Loch-Ness and Orkney.[64]

Together, these companies provide valuable lessons in deploying compliant structures offshore, informing practical pathways for future DG technologies.

6.2.1.2 Flexible-Body Hydrodynamics & Prototype Testing

National testing capability is anchored by **FloWave (Edinburgh)** and the **COAST Laboratory (Plymouth)**, which have expertise in flexible-body hydrodynamics and soft structure evaluation, e.g., PolyWEC, Sea-Clam[65]. Furthermore, both these universities have modelling expertise in frequency and time domain modelling of flexible structures. High fidelity modelling work by **Strathclyde University** provides complementary strength in fluid–structure–electromechanical modelling, including simulations of dielectric-elastomer membranes and deformable tubes[66].

6.2.1.3 DE Materials & Device Innovation

The UK's DE materials innovation base is distributed across these leading universities:

- **Manchester:** Developed flexible electrodes using nanocomposites for DEGs via the Graphene Institute.
- **Bristol:** Robotics Lab with work spanning DEA actuation and soft robotics[67].
- **Swansea:** Biaxial fatigue and electro-mechanical characterisation for dielectric elastomer performance testing.

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[62] https://bomborawave.com/

[63] https://checkmateseaenergy.com/

[64] https://awsocean.com/multi-cell-wave-power/

[65] Yang J, You Z, Cheng S, Wang X, Puzhukkil K, Cox M, Rainey R, Chaplin J, Greaves D. Origami-adapted clam design for wave energy conversion. InProceedings of the European Wave and Tidal Energy Conference 2023 Sep 2 (Vol. 15).

[66] Huang Y, Xiao Q, Idarraga G, Yang L, Dai S, Abad F, Brennan F, Lotfian S. Novel computational fluid dynamics-finite element analysis solution for the study of flexible material wave energy converters. Physics of Fluids. 2023 Aug 1;35(8).

[67] https://www.bristolroboticslab.com/soft-robotics

- **Nottingham:** Rolls-Royce University Technology Centre in Manufacturing and On-Wing Technology with investigations into DEA-based soft robotics for maintenance activities.
- **Oxford & Plymouth:** Worked with origami-adapted deformable generator concepts for DFGs.

These institutions collectively support advances in DE membranes, compliant electrodes, flexible structures, and soft robotics integration.

6.2.2 Europe

Europe has the most complete DE value chain globally, offering capabilities that fill key gaps in the UK, especially in industrial DE manufacturing, high-performance materials, and DEG/DEA component production. The **DACH region** (Germany–Austria–Switzerland) leads in upstream materials, stack manufacturing, and applied research.

6.2.2.1 Industrial Supply Chain

Europe has several companies with upstream manufacturing strength which is anchored by:

- **Wacker Chemie (DE):** Industrial manufacturing of electroactive silicone films and NEXIPAL multilayer laminates, applied in actuation and sensing.
- **Michelin (FR):** Advanced composite and inflatable structures which could be used in large DG WECs.
- **Momentive (DE/CH), Datwyler (CH) and BSC Computer (CH):** Innovation collaboration between these companies which cover the full supply chain. Momentive covers raw material manufacturing, while Datwyler makes DEA stacks and BSC Computer makes provides high-voltage drive electronics and integration interfaces. [68]
- **Fraunhofer ISC/IAP (DE):** Applied research institute that links materials and devices through work on multilayer systems, electrodes, encapsulation, and actuator architectures, enabling reliable DE subsystems suitable for deployment.[69]

6.2.2.2 DG-Related Marine-Energy Developers

Europe has deployed DEGs in real world marine settings. The **SBM S3 programme (FR)** developed a full-scale WEC using flexible electroactive polymer DEGs, advancing hydrodynamic modelling, elastomer manufacturing, HV integration, and offshore assembly and reliability. **Cheros Srl (IT)** has done lot of work in DEG/DFG integration, providing hydrodynamic modelling and control/power-electronics expertise.

6.2.2.3 Material & Device Innovation

Europe sustains research clusters that translate fundamental DE science into industrial prototypes, most notably:

- **EMPA/ETH Zurich/CTSystems (CH)**: Cluster of Swiss stakeholders working on high permittivity elastomers, modelling, wearable DE actuators, biomedical systems, and industrial stack manufacture.[70]
- **Max Planck Institute-Intelligent Systems (DE):** Working on advanced soft-actuators, HASELs, ionic conductors, self-healing elastomers and energy generators.[71]
- **TU Dresden (DE)**: Working on soft robotics, DE electronics, multifunctional membranes.[72]

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[68] https://www.momentive.com/en-us/news-events/innovative-collaboration-dielectric-elastomer-actuators-dea-ready-for-industrial-market-launch-in-2024

[69] https://www.iap.fraunhofer.de/en/research/functional_polymer_systems/sensors_and_actuators.html

[70] https://www.empa.ch/web/s304/eap

[71] https://www.mpg.de/23489134/electrohydraulic-modules

[72] https://tu-dresden.de/ing/elektrotechnik/ihm/ms/die-professur/news/flexible-robotic-structures-based-on-dielectric-elastomer-actuators?set_language=en

- **JKU Kepler Institute (AT):** Works with dielectric actuators and are specialists in electro-mechanical modelling such as dielectric instabilities.[73]
- **Trento/Pisa/Bologna (IT):** Cluster of Italian universities, working on PolyWEC lineage in DEG research; materials; system integration expertise via Cheros.
- **Ifremer (FR):** Marine testing facility offering hyperbaric seawater chambers, fatigue and creep testing, and long-duration polymer ageing studies.[74]

6.2.3 Rest of the World

Beyond Europe, the United States has been a leading centre of early development, with multiple universities and companies continuing to advance the field. Significant progress is also being made in Asia and Oceania. The examples presented here are illustrative rather than comprehensive, and the global research community is broader than this list captures:

- **Standford University/SRI International (USA):** Pioneered electroactive polymer muscles e.g., EPAMs/DEAs/DEGs, laying the foundation for modern dielectric elastomer artificial muscles.[75]
- **University of Colorado/Artemis Robotics (USA):** University of Colorado has research group investigating DE applications, leading to a spin-out tech start-up that specialises in HASEL-style actuators for robotics applications. Recently, they were part of the InDEEP prize where these were operated in reverse to act as generators.[76]
- **University of Florida (USA):** Flexible wave energy converter tank testing and motion capture.[77]
- **University of Auckland/StretchSense (NZ):** The Auckland Bioengineering Institute has an extensive research group investigating dielectric elastomers and HASEL-type actuators.[78] StretchSense is a spin out utilising dielectric elastomer sensors for gloves.[79]
- **Tsinghua University (CN):** Materials investigations into appropriate DE-based materials and soft robotic development.[80]

6.3 Roadmap of Potential Activities

Mapping out the next steps requires prioritising research activities so that the highest value questions are addressed first. This work should be carried out in collaboration with other electroactive polymer sectors to pool resources and share expertise. Once sufficient confidence has been built through early findings, initial demonstrators can be deployed, focusing on niche applications. These deployments will provide practical insights into factors such as installation, operation, and maintenance. The resulting learnings can then guide a scalable approach based on modularity and duplication, ensuring that knowledge gained from small-scale trials can be efficiently transferred to larger systems.

A summary of recommended next steps is provided below:

Short-term: Early Prototyping, Material Maturation and Collaborative Innovation

- **Early Prototyping & Benchmarking:**

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[73] https://research.jku.at/en/projects/electrostatic-actuators-with-multilayered-dielectrics-for-vacuum-/
[74] https://www.ifremer.fr/en/research-infrastructures/resources-studying-durability-polymer-and-composite-materials
[75] https://www.sri.com/75-years-of-innovation/75-years-of-innovation-artificial-muscle/
[76] https://www.artimusrobotics.com/
[77] https://www.nlr.gov/news/detail/program/2024/aquatic-acrobatics-university-collaboration-visualizes-the-future-of-flexible-wave-energy
[78] https://www.auckland.ac.nz/en/abi/our-research/research-groups-themes/biomimetics-laboratory.html
[79] https://stretchsense.com/
[80] https://www.tsinghua.edu.cn/en/info/1418/11541.htm

  - Build and test the first generation of DG prototypes for benchtop and tank-testing, which validates cellular architectures and their hydrodynamic interaction. This gives indications on expected strain duty, capacitance swing and energy conversion opportunity.
  - If prototyping is successful, develop small-scale DG energy harvesters (watts to low-kilowatt range) targeting niche applications such as offshore sensors and auxiliary systems.
- **Material Development:**
  - Work with material specialists to improve electro-mechanical performance, durability and manufacturability of DEGs/DFGs. This involves performing critical R&D tasks, outlined in Sections 4.4.1 and 4.4.3.
  - Ensure these tasks are performed relative to defined DG metrics (Section 4.3) and there is standardisation across testing methodologies for benchmarking DG materials, avoiding duplication of research.
- **Cross-Sector Research**
  - Identify cross-research opportunities within the wider electroactive polymer landscape (e.g., sensing materials, artificial muscles, soft actuators), where breakthroughs in high permittivity composites, self-healing polymers, and fatigue-resistant elastomers can accelerate DG progress. A stakeholder map of potential innovation communities is given in Section 4.5.2.
  - Ensure materials innovation remains grounded in scalable, commercially relevant manufacturing routes, avoiding highly specialist laboratory chemistries that cannot transition into industrial DG production.
- **Stepping Stone Markets:**
  - Seek applications in adjacent fields, such as marine robotics, smart moorings and strain-sensor systems that share environmental and mechanical requirements with future DG devices.
  - Use these stepping-stone technologies to derisk key DG challenges (material fatigue, encapsulation, modular assembly, sensing integration), as detailed in the roadmap in Section 4.5.1.

Medium-term: System Integration, Control, Maintenance

- **Marine Demonstrators:**
  - Deploy medium-scale demonstrators (1 kW–100 kW class) in controlled marine test sites to validate structural performance, degradation behaviour and power conditioning performance.
  - Investigate the applicability for the integration of DG with offshore robotics to co-develop hybrid or charging systems (e.g., DG-powered AUV docking stations, recharging buoys, long-duration drifters).
  - Investigate the applicability of DG for hybrid platforms, e.g., solar and aquaculture platforms.
- **Module Scale-Up and WEC Architecture Maturation:**
  - Perform WEC architecture R&D tasks such as design optimisation and numerical modelling assessments as outlined in Section 4.4.4.
  - Develop multi-module DG architecture that can demonstrate coordinated hydrodynamic control and power synchronisation.
  - Establish larger-scale manufacturing for cellular architectures (roll-to-roll processing, automated patterning of electrodes, and module encapsulation).
  - Move from proof-of-concept materials to large-scale production formulations which have been tried and tested at smaller-scales with significant performance enhancements.
  - Develop large-scale power electronics solutions for multi-module designs.
- **Deployment and Maintenance:**
  - Develop predictive maintenance models: monitor DG module health via embedded strain/impedance sensing.

    - Design WECs around module replacement with slot-in module cartridges.

Long-term: Commercial Utility-Scale WECs

- **Utility-Scale DG WEC Development:**
    - Progress toward 100kW+ class DG WECs, shifting from material feasibility to full system optimisation (moorings, hydrodynamics, survivability, array interactions).
    - Achieve grid competitive Levelised Cost of Energy (LCOE).
    - Standardise module architectures enabling scaling through modular replication rather than custom engineering.
    - Enable higher power density performance through material innovation aiming for a minimum of 40 W/kg.
- **Scalable, fully-circular low-cost manufacturing and supply chain:**
    - Build supply chains capable of high-volume DG module production at <£50/kg metamaterial cost.
    - Establish closed-loop recycling routes for metamaterials and other consumables.
- **Long-term reliability:**
    - Deliver module lifespans of a minimum of 7 years with predictable degradation profiles.
    - Validate performance over multi-year open-sea trials demonstrating operational performance to ensure a reliability dataset for certification.
- **Job growth and Gross Value Added (GVA):**
    - Regional economic growth with jobs added across the materials, electronics and marine engineering sectors. Enable growth of new SMEs in these areas and provide regeneration of coastal economics.
    - High-skilled STEM jobs in DG technologies with new training pathways.
    - Export DG technologies to Europe and to the rest of the world with a sustained innovation pipeline of new IP and high-value industrial activity.

7 Final Remarks

The DG programme has significantly advanced the prior understanding of electroactive structures for WECs, elevating the field to a new level of maturity. It has delivered progress on two fronts: (1) top-down system-level insights, demonstrating the wider techno-economic benefits of DG architectures, and (2) bottom-up foundational R&D, building early momentum in metamaterials and their integration into WEC systems.

The programme's design competition has successfully produced two highly capable development teams, each now progressing market-orientated product concepts with clear pathways for future commercialisation. In parallel, the research projects have established a collaborative cluster of academic and industrial groups equipped to tackle the critical R&D questions surrounding materials, structures, reliability, and manufacturability.

The current performance metrics carry substantial uncertainty so should therefore not be taken as direct conclusive evidence, but early assessments indicate that several parameters remain at the lower end of what would be required for commercial attractiveness at utility scale. Nevertheless, there are numerous innovation pathways capable of elevating these technologies to competitive performance levels and are already being investigated through targeted R&D across the world.

The key challenge now is maintaining continuity. This requires expanding the scope beyond electricity generation alone and engaging with the broader electroactive polymer landscape, where cross-sector innovations can accelerate DG's progress, e.g., soft robotics and sensors. Much of the optimisation needs for DG, especially around materials performance, durability, and manufacturing, are likely to be addressed first through these "*stepping-stone*" technologies. It is therefore sensible to allow this broader ecosystem to mature before pushing directly toward larger-scale DG. That said, near-term opportunities for generation still exist at smaller scales, such as powering auxiliary systems and remote sensors. The inherent simplicity and modularity of DG architectures means that early deployments at these scales can provide valuable operational learning and directly inform later systems for later stages. The scale-up pathway may resemble that of solar PV, where many identical small units are replicated to create larger arrays.

Once material costs fall and electro-mechanical performance improves through ongoing research in electroactive polymers and related applications, the sector will be suitably positioned to progress toward larger, utility scale DG-enabled WECs in the future.