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Executive summary

Ocean-wave power is a very persistent, spatially concentrated and predictable form of intermittent renewable energy. The worldwide estimated resource amounts several terawatts of yearly average power that could be converted into electricity, that represents a significant portion of the intermittent renewable energy mix in the future. However, harvesting energy from waves is very challenging and the sector is still immature. Existing wave energy converters (WECs) are complex and costly to construct, install, and maintain. They are also vulnerable to the marine environment and show limited energy conversion efficiency.

The technology of dielectric elastomer generators (DEGs) could provide the technological breakthrough that is required to make wave energy exploitable. DEGs are deformable capacitors made with dielectric rubber films and compliant electrode layers that can be used to convert mechanical energy into electricity by the variable capacitance electrostatic generation principle.

Differently from more conventional technologies, DEGs enjoy large energy densities, direct-drive and cyclic operation, good and rate-independent efficiencies, good shock and corrosion resistance, silent operation, and moderate-to-low cost. These attributes make them a potential breakthrough solution for the realization of solid-state rubber-made WECs that are free of metallic components, articulated mechanisms and/or rotary machines.

In this context, the project PolyWEC has carried out pioneering researches that demonstrated the feasibility and put the basis for the future development of this novel class WECs. PolyWEC gathered a highly focussed multidisciplinary research group which was able to study and produce innovations on materials, design, economic and environmental aspects of this new technology.

Specifically, within its 4-years of duration the PolyWEC project achieved the following main results:

- DESIGN TOOLS: modelling/design tools have been developed and validated; this made it possible to estimate the performance of the different solutions of DEG based WECs;
- MATERIALS: the most promising materials for the fabrication of effective DEGs have been initially identified/characterized; they include commercial silicones, acrylics and natural rubbers. Later on, novel materials for the construction of DEGs have been developed by introducing new formulations for dielectric materials and deformable electrodes;
- NEW CONCEPTS: new concepts of WEC that make use of DEGs have been conceived and studied. Small-scale prototypes were implemented and built including three different prototypes of OWC systems and one system based on a novel patented architecture;
- WAVE-TANK TESTING: Small-scale prototypes have been tested for performance verification within wave-tank experiments. Demonstration of wave-to-electricity conversion up to a power of 3.8W (at 1:25/1:30 scale) in operational conditions has been achieved.
- LONG TERM OPERATION TEST: a set of preliminary laboratory tests revealed a very promising response to fatigue and degradation of DEGs in long term operation conditions;
- EVALUATION: techno-economic and environmental evaluations were conducted on two different types of WEC based on DEG in real-scale. These analyses revealed important contributions of DEG technology to the reduction of investment and operational costs of WEC systems;
- ROADMAPPING: a research roadmap has been drawn for the future development of DEG based WEC and a preliminary commercialization roadmap has been defined which includes (1) the growth plan of the spin-off company CHEROS that was founded by a group of researchers working on the Project and (2) the exploitation of a Patent that has been filed in co-ownership by several partners of the consortium.

Project context and objectives

Ocean waves have a great potential as renewable source of electricity. Studies have demonstrated that a significant percentage of world electricity could be produced by Wave Energy Converters (WECs). However, electricity generation from waves still lacks of spread because the combination of harsh environment and form of energy makes the technical development of cost effective WECs particularly difficult.
Several research and development (R&D) trajectory paths for wave energy development have been proposed over the past decade. To date, and after more than 30 years of intense R&D activities, no fully commercial wave energy device has emerged yet. Recently, some of the pioneering and leading WEC device developers went into administration. Other technology developers have also recently manifested negative signs regarding their ambitious business plans while some have achieved new milestones in their development. Overall, many experts of offshore renewable energies agree that there is a need for disruptive and innovative solutions building upon the invaluable lessons learnt from the experienced setbacks.

In this context, in November 2012, within the European Commission FP7, the project PolyWEC (www.polywwec.org) has started a collaborative research on a new class of WECs, characterized by the employment of Dielectric Elastomer Generators (DEGs). The main goal is to introduce a radical change in the traditional architecture of WECs by using converters characterized by deformable lightweight and low-cost polymeric elements. PolyWEC assumes a multidisciplinary approach that includes competencies on WEC design/tests, fluid dynamics, control/mechatronics and material science.
PolyWEC aims at (1) generating new knowledge in different fields of science and with specific scientific objectives, (2) developing novel concepts of WEC devices based on DE, new tools for their design control and improvement and (3) creating innovative materials and transducers. Additionally, the Project aims at demonstration and assessment of the proposed technology from the point of view of technical, economic and environmental feasibility. To this aim technological challenges are considered such as: experimental validation of innovative small-scale DEG-based WECs based on new types of transducers that are specifically conceived for wave energy harvesting; design, implementation and tank testing of innovative small-scale DEG-based WECs within a Watt-scale; and initiation of a test campaign for evaluating the long-term performances of DEGs.
The project is conducted according to an increasing-complexity approach that goes through the development of two generations of devices. First-generation PolyWECs are characterized by indirect interaction between water and DEG. Second-generation PolyWECs are devices in which the DEG is directly interacting with a fluid, thus allowing a reduction in the number of parts and components.
Specifically, the Project aims at the achievement of the following main objectives:

Study of PolyWEC concepts and models
The development of Wave Energy Converters based on DEGs (namely PolyWECs) is a completely new technical problem which requires the understanding of the physic principles involved. To this aim, one of the main Project goal is to study the formulation of new WEC concepts, and the creation of the mathematical/engineering tools and techniques required for their design, optimization, implementation and assessment.

Formulation/design of new materials and transducers:
The viability and success of PolyWEC devices for wave-energy conversion heavily relies on the performances of the materials employed for the implementation of the polymeric electro-mechanical transducers (here called Polymeric Energy Conversion Units, or PECUs). Such materials should possess large energy efficiencies, large energy densities, good reliability, and be compatible with the

marine environment. DEG technology is still immature, and the available materials and PECUs are not optimized for energy-scavenging applications (and specifically for wave-energy harvesting). In this context, the Project aims at the design, manufacturing, experimental characterization and assessment of novel materials and PECUs with superior properties and that are compatible with the marine environment.

Development of design tools/prototypes and study of controllers

In order to develop effective WECs based on DEGs, basic procedures for their design control and physical implementation have to be defined. Mechanical, electrical, electronic and control aspects such as implementation, manufacturing and integration have to be addressed.
To this aim the Project studies design solutions of PolyWEC devices including basic aspects of hydrodynamic shapes optimization and control but also more general issues concerning structural, mooring, array arrangements, electrical connections etc. Additionally, in order to verify the proposed approach, design procedures are implemented for the development, manufacturing and integration of three test-benches and five complete small-scale prototypes of WECs based on DEG.

Assessment and demonstration within wave-tank tests

According to the best practices defined by the Wave Energy Community, a fundamental step for the assessment and validation of the proposed WEC concepts is the tank testing of small-scale prototypes. In line with these practices, scaled physical models of PolyWECs are tested in Edinburgh University's wave tanks: a wave flume, the Curved Wave Tank and the new Flowave facility. Specifically, small-scale PolyWEC devices are tested for regular and irregular waves with a range of wave heights, wave periods, spectral properties and current speeds to verify the expected performances and to assess the conversion efficiency over different wave climates. Extreme wave tests are also conducted to assess the survivability of the most advanced prototypes.

Providing a preliminary economic/environmental assessment of the technology

The assessment of economic/environmental performances of PolyWEC technology is conducted through multi-parametric analysis tools and aims to understand the feasibility of an innovative concept of WEC. The aim is to compute techno-economic parameters such as the Levelised Cost of Energy (LCOE), the Energy Return on Energy Invested (EROEI) and the Carbon Footprint. Additionally, an assessment of the Marine Renewable Energy (MRE) environmental impact is conducted in order to identify the most relevant environmental effects of PolyWEC devices.

Dissemination the Project results

Dissemination of the knowledge and results generated by the Project is pursued through multiple channels including: scientific publications, website, publicity material, participation to conferences, patents, involvement of stake-holders, production of video and visual materials etc.

Definition of a Roadmap/Exploitation strategy

One of the final goals of the Project is to define a clear research and development road-map and the strategies for the exploitation of PolyWEC project results. A future research roadmap is drawn including research and identification of exploitable foreground (including patents) and related application fields.

S&T results/foregrounds

POLYWEC CONCEPTS AND MODELS

The development of new Wave Energy Converters (WECs) based on Dielectric Elastomer Generators (DEGs) is one of the main objectives of this Project. To this aim the following activities have been developed:

- studies on new concepts and architectures for wave energy converters that employ DEGs;
- study/implementation and verification of reduced electro-hyperelastic models of DEGs, which are based on relevant material properties, to be used for generator design and optimization;
- study/implementation and development of coupled electro-hyperelastic-hydrodynamic models able to mathematically describe the behaviour of first- and second-generation DEG-based WECs;
- study and dimensioning of selected kinds of DEG-based WECs including the formulation of control strategies and comparison between different architectures;
- study and development of models that are required for the global techno-economic analysis of DEG-based WECs.

MAIN RESULTS:

Main results can be summarized as follows:

- Concept definition: Five different architectures of DEG-based WECs have been proposed/refined (see Figure 1). Some of them rely on a single oscillating rigid body that deforms a polymeric Power Take Off (PTO), like a heaving buoy and a surging flap; others concepts are based on the oscillating water column principle; the most complex concepts are based on the direct interaction between DEG and sea water.

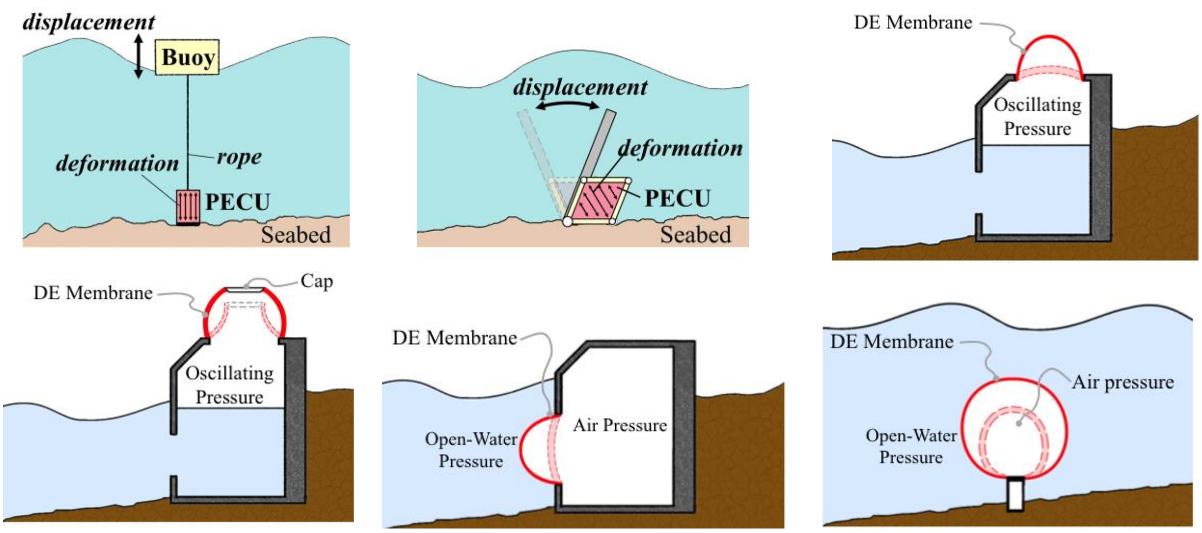


Figure 1. Overview on different PolyWEC concepts (left to right, top to bottom): heaving buoy with a stacked cylindrical DEG (namely, Poly-Buoy); surging flap with parallelogram-shaped DEG (namely, Poly-Surge); Oscillating water column (OWC) with inflating diaphragm DEG (Poly-OWC); OWC with conical inflating DEG; pressure differential WEC with DEG diaphragm in contact with water; submerged inflating DEG balloon.

- Modelling approach definition: The definition of a general methodology to set up coupled models has been achieved, relying on a simplified hydrodynamic approach based on potential theory (as proposed by the literature on wave energy) and analytic models for the electro-hyperelastic response of generators. Such models provide a time-domain prediction of the dynamic response of PolyWECs.

- Scaling rules definition: Geometrical scaling rules for conventional WECs (based on Froude number scaling) have been extended in order to describe appropriate scaling rules for converters equipped with DEG PTOs;
- Development of numerical examples: Numerical examples and models for the Poly-Buoy, Poly-Surge and Poly-OWC concepts depicted in Figure 1 have been made available. In particular, using the proposed models, the computation of the power matrix for given wave climates and given engineering specifications of the WEC has been conducted.
- Performance verification at real-scale: Dimensioned systems have been evaluated in simulation environments showing very promising performances in terms of power/energy produced in comparison with equivalent systems equipped with conventional PTOs;
- Techno-Economic Models: An evaluation strategy has been defined for the economic performance analysis of DEG-based WECs.

NEW MATERIALS AND TRANSDUCERS:

Development of effective and affordable DEG-based WECs requires the availability of elastomeric materials with suitable electromechanical properties and of appropriate procedures for DEG-PTO manufacturing. To address these issues, the following activities have been pursued in the Project:

- Identification of the material properties that play a major role in the conversion of mechanical energy into electricity;
- Development of procedures and test-benches for the measurement of these properties;
- Experimental characterization of commercial elastomeric materials for DEG implementation;
- Development of new materials with improved electromechanical properties;
- Development of procedures for realizing the DEG PTO by the preparation of dielectric and conductive layers, and their assembly.

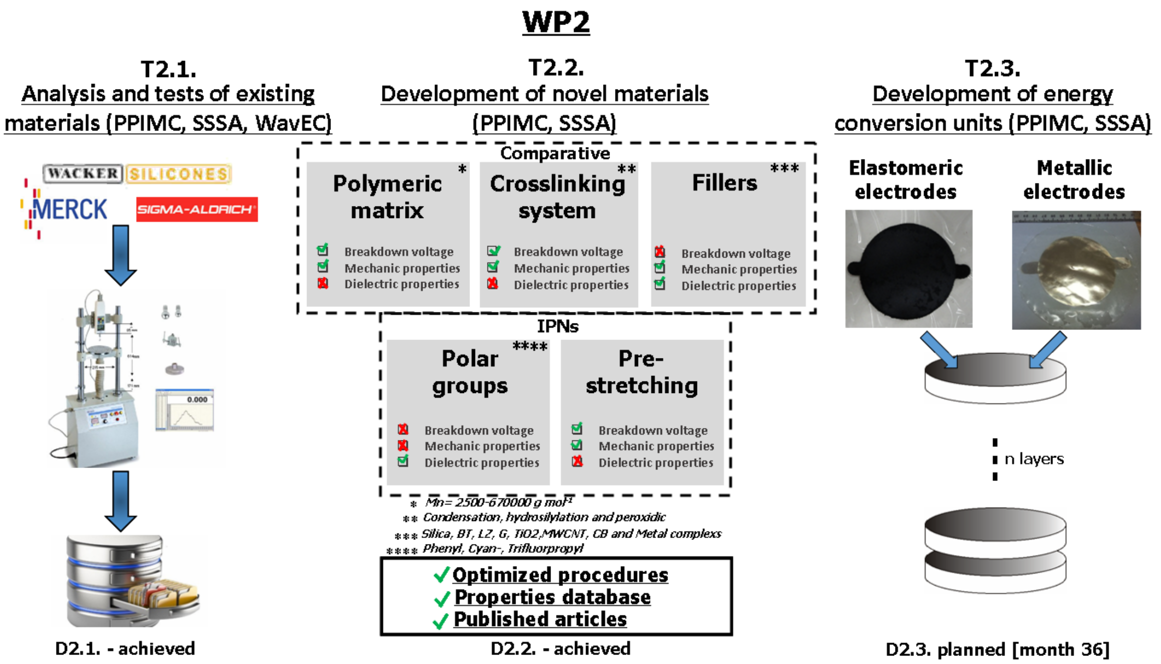


Figure 2. Overview on PolyWEC WP2 activities.

MAIN RESULTS:

- Identification of relevant material properties for dielectric elastomer layers: The maximum amount of mechanical energy that can be converted into electricity by a unit volume (or mass) of DEG PTO depends on the following material properties of the dielectric elastomer layers:

- *Dielectric Permittivity*: with linear dependence, meaning that an ideal dielectric elastomer should have a permittivity that is as large as possible.
- *Dielectric Strength* (breakdown electric field): with quadratic dependence, meaning that an ideal dielectric elastomer should have a dielectric strength that is as large as possible. In a number of elastomeric materials dielectric strength increases with strain. Knowledge of this dependency is important since the energy harvesting performances of DEG with given architecture and size may be improved by acting on the pre-tensioning of the dielectric elastomer layer.
- *Elongation at break*: with direct dependence (the specific law depending on the specific DEG PTO architecture), meaning that an ideal dielectric elastomer should have an elongation at break that is as large as possible.
- *Elastic modulus*: on one hand, stiff materials are not suitable for wave energy harvesting applications, as they provide PTOs with excessive stiffness which cannot be deformed by the sea waves action; on the other hand, a large shear modulus prevents the DEG material from buckling when electrically activated due to electro-elastic instability phenomena. The optimal value for the elastomer shear modulus strictly depends on the specific application and on the device specifications.
- *Fatigue resistance*: DEG PTOs are subjected to high-cycle loading of mixed electromechanical nature. For wave energy harvesting applications, DEG PTOs are required to last several millions of cycles, with these numbers to be guaranteed even in presence of salty and aggressive sea water. Since rubber already demonstrated this level of resistance when subjected to high-cycle mechanical loadings only, a fundamental issue is to first assess rubber resistance to high-cycle electrical loading.

- Identification of relevant material properties for conductive elastomer layers: DEG dynamics and conversion efficiency depends on the following material properties of the conductive elastomer layers:
  - *Electrical conductivity*: electrical conductivity (i.e., low electric resistivity) should be as large as possible in order to limit the losses due to Joule effect; large deformation (at least equal to that of the underlying DE layers); this property should not exhibit significant dependency of deformation, even in presence of large stretches;
  - *Elastic modulus*: conductive layers should feature very low rigidity in order not to provide the DEG with a further relevant stiffness.
- Development of material testing procedures and apparatus: material testing procedures and apparatus have been developed for the characterization of:
  - *Stress-strain response* (including elastic modulus, elongation at break, mechanical hysteresis);
  - *Electrical conductivity* (including strain dependency);
  - *Dielectric Strength* (including strain dependency);
  - *Fatigue resistance to cyclic electrical loading*.
- Characterization of commercial materials: five commercial materials have been identified and characterized with the developed test benches to determine relevant electromechanical properties. The considered materials are: one acrylic elastomer (VHB4905); three natural rubbers (OPPO BAND RED 8012; OPPO BAND GREEN 8003; ZRUNEK A1040) and one styrenic rubber (THERABAND YELLOW 11726). Acquired data has been arranged in a material property data-base. The best performing commercial materials resulted to be the OPPO BAND GREEN 8003 and the THERABAND YELLOW 11726, showing energy and power conversion densities higher than 700 J/kg and 1kW/kg, and mean cycles to failure in the order of several millions of cycles that are compatible with wave energy harvesting

applications. Limits identified in the usage of these materials (in place of silicone elastomers) for the development of DEG PTOs are related to the difficulties in making suitable compliant electrodes and assemblies made thereof, that is an issue that deserves future instigations.

- Development of new materials: In the development of DEG PTOs based on silicone elastomers the following findings have been achieved:
  - It was proven that the best electromechanical performance can be obtained with elastomers based on high molecular weight PDMS filled with nanoparticles having high dielectric constant and high aspect ratio (namely, barium titanate or goethite nanorods) and also with bimodal full silicone interpenetrated networks with high content of low molecular weight component.
  - The most effective filler was barium titanate with high dimensional ratio (nanorods), which led to a three-fold increase of dielectric permittivity of the resulted composite elastomer as compared with the matrix, with the mechanical characteristics remaining in the domain of interest (a Young's modulus of 0.0196 MPa and an elongation at break around 900 %). The electromechanical sensitivity and gained energy capacity proved to be the more than 12 (which is also three times higher than that of pure crosslinked PDMS). These effects were obtained at lower load (5 wt%) than those reported in the literature for similar researches.
  - Although one would expect the incorporation of large percentage of goethite nanorods in PDMS matrix to make these materials conductive, the films were homogeneous and had good dielectric behaviour: low conductivity values ($\sigma < 10^{-7}$ S/cm), adequate dielectric constant values (3.5 – 6.1), low values of the loss factor ($\varepsilon'' < 0.2$) and dielectric strength above 40 kV/mm. The use of goethite nanorods also improves the mechanical properties of the samples in comparison with those of pure PDMS. Unfortunately, shear modulus also increases by incorporation of this filler, which could affect the usage of these elastomers in energy harvesting devices.
  - Interpenetrating polymer networks (IPN) have been obtained based on two silicone systems, one of them containing various percents of trifluoropropyl (IPN-F), phenyl (IPN-P) or 3-cyanopropyl (IPN-CN) groups along the chain. Samples containing siloxane components with polar groups, even in low contents showed phase separation. From mechanical point of view, the IPN-CN sample showed the best strain (about 700%) as compared with the blank IPN-R. The dielectric permittivity showed a significant increase only in the low frequency range where the dielectric loss is also high as compared with the blank samples but decreasing as frequency increases. At higher frequencies, the effect of the polar groups on the dielectric permittivity was insignificant in the tested composition range.
  - All the developed materials have been studied by dielectric spectroscopy, mechanical tests, thermal analysis, scanning electron microscopy (SEM), dynamic vapour sorption (DVS) and the influence of various parameters on the properties of interest has been determined.
- Procedures for realizing the DEG PTO: A study has been conducted which considers the most relevant aspects for the production of effective systems such as chemical composition of dielectric/conductive layers, procedures for thickness control and bonding of dielectric and conductive layers. Several experimental work has been done to obtain effective alternative procedures to produce different types of conversion units. Specifically, different solutions have been tested for the manufacturing of deformable conductive electrodes based on elastomeric conductors or metallic sputtered layers. Solutions for the stacking several electrode-dielectric systems have been conceived and implemented at small scale. The produced DEG PTOs have been tested in the framework of test-bench experiments.

DESIGN AND CONTROL:

In the Project, the concepts devised in the first stage have then been engineered via design optimization, control system development and implementation of small-scale physical prototypes. To this aim, the following main activities have been performed:

- Development and operation of laboratory test-benches for the dry-run test of DEG PTO prototypes: Three dry-run test benches have been designed, built and provided with control and sensing electronics; specifically: a test-bench for the characterization of the parallelogram-shaped DEG (PS-DEG) PTO for Poly-Surge converters; a test-bench for the characterization of circular-diaphragm DEGs (CD-DEGs) PTOs for Poly-OWC; a test-bench for the characterization of CD-DEGs operating in direct contact with water, in an asset suitable for application on pressure differential WECs.
- Development of small-scale prototypes of PolyWEC systems for wave-tank testing: The following PolyWEC prototypes have been designed, manufactured and integrated: four Poly-OWC prototypes (with progressively increased scale, from 1:50 to 1:30); a second-generation pressure differential PolyWEC concept featuring a DEG membrane in direct contact with water.

MAIN RESULTS:

Main results are summarized below:

- Dry-run test-benches

  The following three tests-benches have been developed:

  1) PolyOWC test-bench

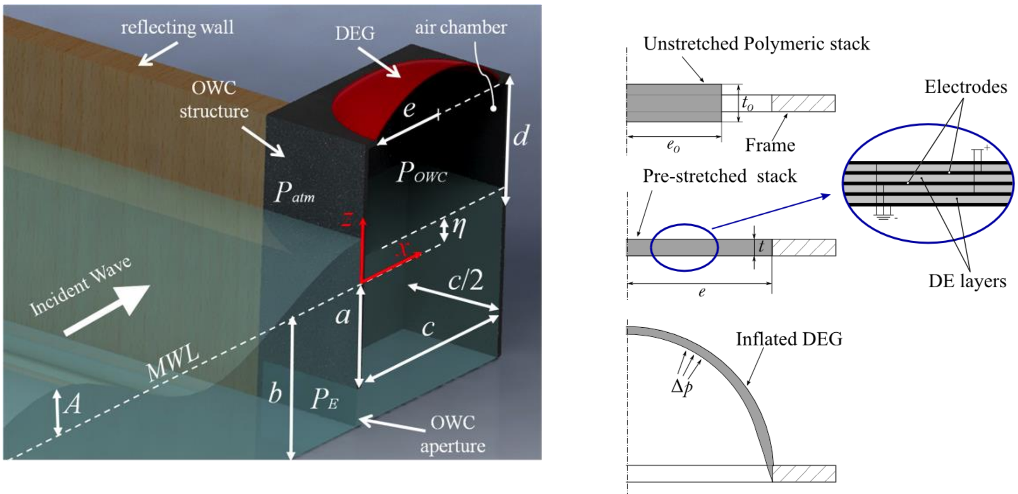


Figure 3: Polymeric Oscillating Water Column (Poly-OWC) wave energy converter (left); schematic drawing of a CD-DEG (right).

The PolyOWC concept is shown in Figure 3 (on the left). It features a semi-submerged hollow collector (in the same fashion of traditional OWCs) and a Circular Diaphragm DEG (CD-DEG) PTO.

The CD-DEG (Figure 3, on the right) is a generator constituted by a sandwich of one or more DEG membranes alternatively stacked with conductive electrode layers to from a deformable capacitance. The variable capacitance is obtained by inflating the membrane with pressurized air.

The test-bench that has been developed for the experimental study of CD-DEGs is schematized in Figure 4.a. The test-bench comprises: a CD-DEG specimen; a mechanical sub-system; a high-voltage (HV) electronics sub-system; a real-time controller subsystem.

The test-bench allows to test different CD-DEG specimens, made of different materials and featuring different thickness and pre-stretch, but with a (pre-stretched) radius of 130 mm. Pictures of a CD-DEG prototype are reported in Figure 4.b, with right and left images showing the specimen in its deflated and inflated states, respectively.

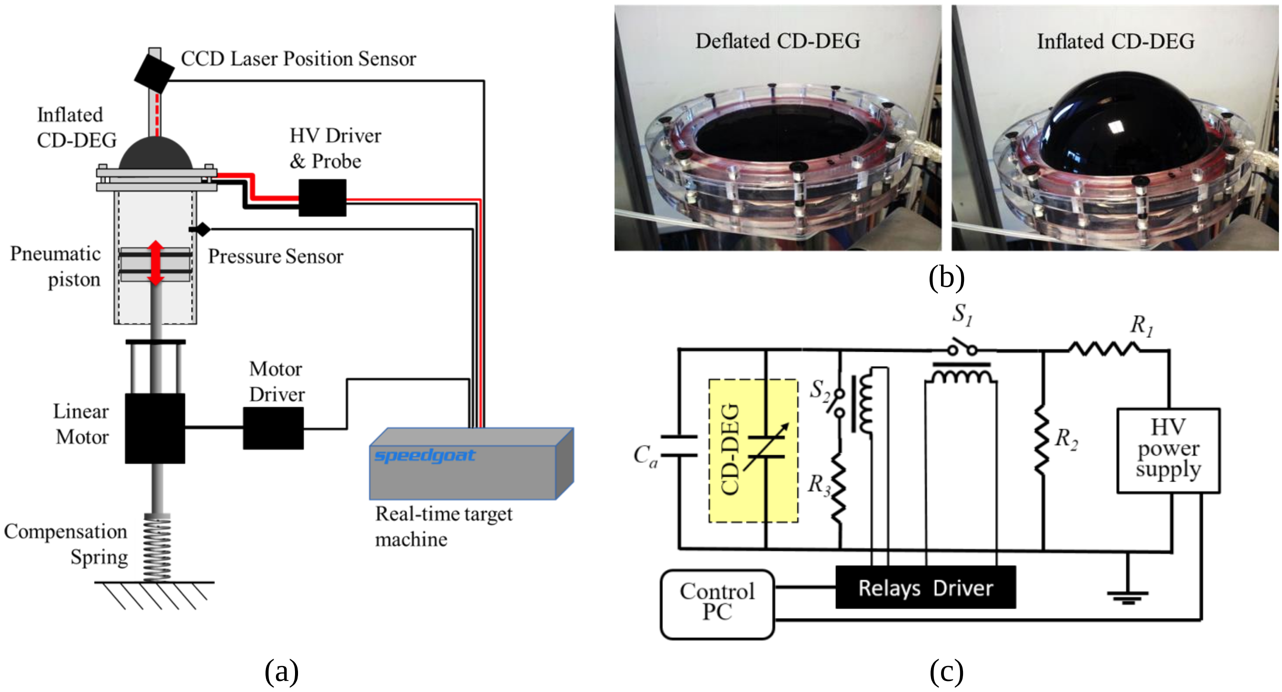


Figure 4: (a) Schematic of the experimental test-rig and schematic of the ICD-DEG assembly; (b) CD-DEG prototype: deflated state (left), inflated state (right); (c) Example of HV driving electronic for CD-DEG prototypes control

To simulate the Poly-OWC air chamber, a custom made pneumatic cylinder has been constructed that features: a polycarbonate cylinder tube; a movable piston; the CD-DEG specimen as upper end cap (see Figure 4.a). The piston is actuated via a linear motor, and sensing equipment includes: a pressure sensor on the cylinder tube, a high-speed high-accuracy CCD laser displacement sensor used to measure the CD-DEG tip displacement.

Several high voltage (HV) electronic circuits have been designed throughout the project to drive the different DE-based PTOs according to different control strategies (an example is in Figure 4.c).

In general, the control circuit includes: a power supply needed to prime the DEG (i.e., to supply an amount of charge needed to initiate the cyclic conversion process); HV switching components that alternatively connect the CD-DEG electrodes either to the power supply, to the ground, or to other components; resistors to drain the DEG and to limit the current on the different circuit nodes; constant capacitors (usually connected in-parallel to the DEG) used to optimize the control cycle; HV probes to measure the potential difference between different nodes.

With the above-mentioned setup, hardware-in-the-loop simulations have been implemented and different controllers, which rely on different types of sensors and strategies, have been tested and assessed for performance. Specifically, strategies to control the systems in panchromatic unknown waves have been conceived and tested.

2) Pressure differential WEC test-bench

A concept of direct-contact second-generation PolyWEC device is the so-called DrumWEC. A schematic of DrumWEC is shown in Figure 5.a. The device consists in a CD-DEG that acts as both primary interface with the waves and as PTO. The CD-DEG is mounted on top of a submerged air chamber. It contacts air with its bottom face, and sea water and incoming waves with the upper face. Wave-induced pressure variations on the CD-DEG upper face induce DEG deformation and enable the cyclic energy conversion mechanism.

A test bench to test CD-DEGs in direct touch with water has been obtained by modifying the Poly-OWC dry-run test-bench. The setup comprises: a mechanical sub-system based on a piston (moved by a linear permanent-magnet motor) sliding inside a polycarbonate air chamber; a second polycarbonate cylindrical chamber partly filled by a vertical column of water; a CD-DEG sample that closes the second cylindrical chamber at its bottom, thus contacting the water volume through its upper face. The two chambers are connected by an air hose. Alternated motion of the piston provides compression/expansion of the air in the camber, which results in a cyclic displacement of the water volume and a resulting cyclic deformation of the CD-DEG.

As in the Poly-OWC test-bench, the setup is equipped with sensing and control electronics. The deformations of the CD-DEG are tracked by a high-speed camera. An overview of the setup is in Figure 5.b.

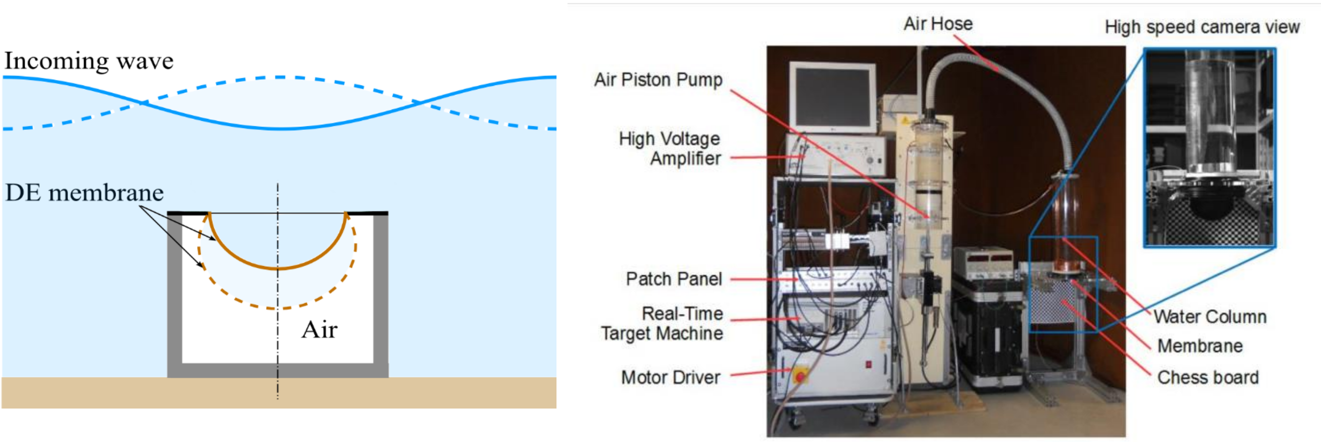


Figure 5. (a) Schematic of DrumWEC operation. (b) Dry-run test-bench for characterization of CD-DEGs I pressure differential asset.

3) The PolySurge Test-bench

The Parallelogram-Shaped Dielectric Elastomer Generator (PS-DEG) (see Figure 6.a) is a planar generator that can be employed as PTO for the Poly-Surge WEC (see Figure 6.b). PS-DEG is constituted by one or more DEG membranes with conductive electrodes attached along their perimeter to the links of a four-bar mechanism with opposite sides of equal length. Functionally, the PS-DEG is a rotary generator with reciprocating motion that can convert into electricity the mechanical work produced by an oscillating torque applied to one of its rotating links.

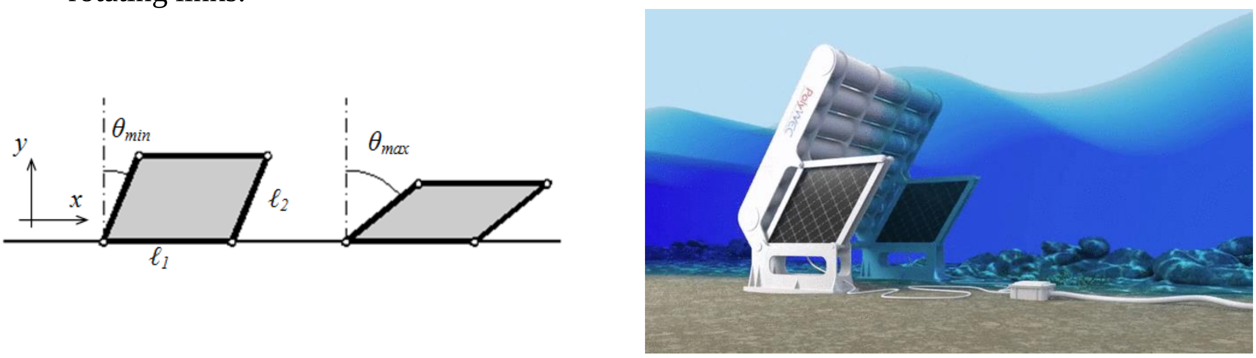


Figure 6: (a) PS-DEG angular operating range. (b) Rendering of PolySurge

A prototype of a PS-DEG generator has been designed and built (see Figure 7). A set of experimental tests has been conducted with the aim of validating the proposed generator concept along with its model. This concept showed promising performances; however, it has not been considered for further steps in the Project in order to focus the efforts toward the more promising concepts of Poly-OWC and Drum-WEC.

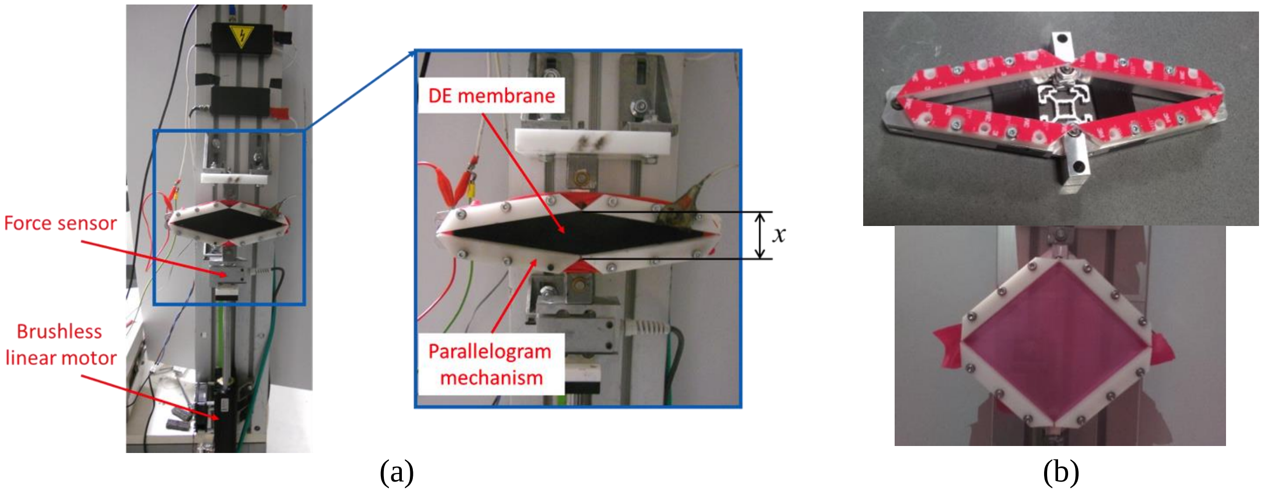


Figure 7: (a) PS-Dielectric Elastomer Generator prototype mounted on the test-bench; (b) Shot of the PS-DEG prototype during membrane mounting phases and mechanical characterization tests.

- <u>Small-scale PolyWEC prototypes</u>

  The following five small-scale prototypes of PolyWEC systems have been designed, built, and integrated with a driving electronics for sensing and DEG PTO control:

  1) Fixed-structure OWC – first iteration design

  A first prototype of bottom-fixed Poly-OWC (see Figure 8) has been designed and built using a simple parallelepiped-shape water column collector. The prototype has been built for testing in the wave flume facility at the University of Edinburgh; it features a scale of approximately 1:50; its collector geometry has been designed by scaling the dimensions of the Pico OWC plant (in the Azores), without any further design refinement aimed at optimizing the coupled DEG-WEC system response.

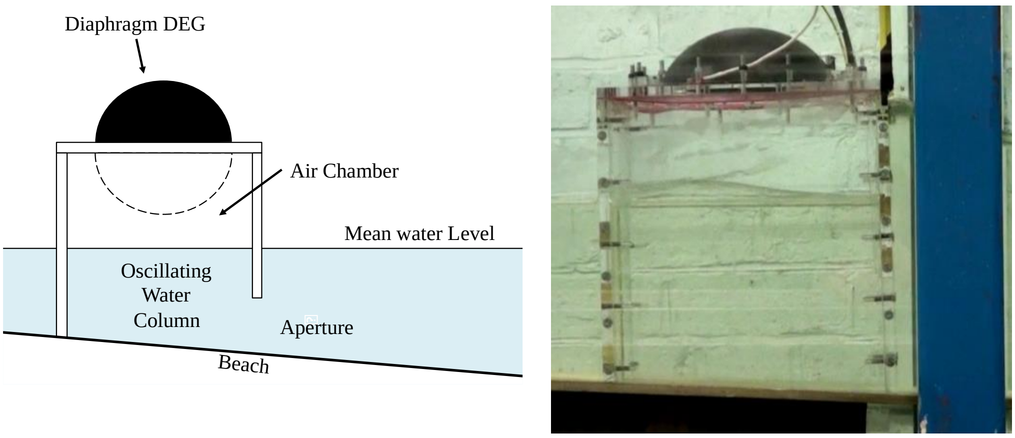


Figure 8. Schematic of the small-scale Poly-OWC (left) and picture of the prototype during the tests (right).

2) Fixed-structure OWC – advanced design

A second on-shore OWC system with a scale of 1:45 has been designed and built for tank-testing in the wave flume facility at the Edinburgh University.

The prototype implements an optimized design of the hydrodynamic interface (i.e., the collector), as it features a horizontal added mass duct at the bottom of the main parallelepiped OWC chamber (Figure 9). The added mass duct allows to effectively set the device natural frequency within the testing frequency range.

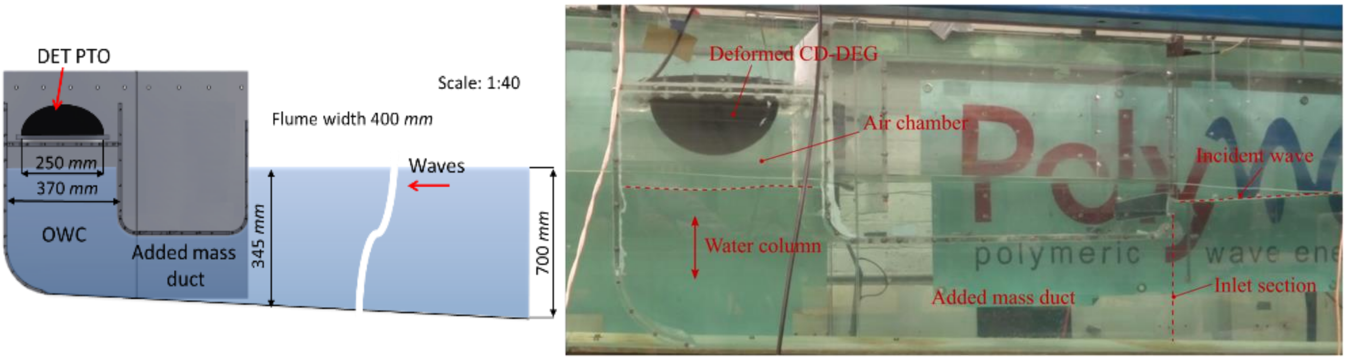


Figure 9. Schematic of the prototype dimensions (left) and picture of the device in operation in the wave flume of the University of Edinburgh (right).

3) Floating tubular Poly-OWC

A moored concept of Poly-OWC, based on the collector design proposed by the Spanish company Sendekia, has been set up and equipped with a functional CD-DEG and control electronics. The tested OWC collector is a 1:50 reproduction of the Sendekia concept, and it consists of an axisymmetric collector whose upper part is an hollow cylinder, with a bottom aperture (towards sea) with a peculiar shape, aimed at increasing the added mass of the water column to bring the device to resonance with typical sea waves (see Figure 10).

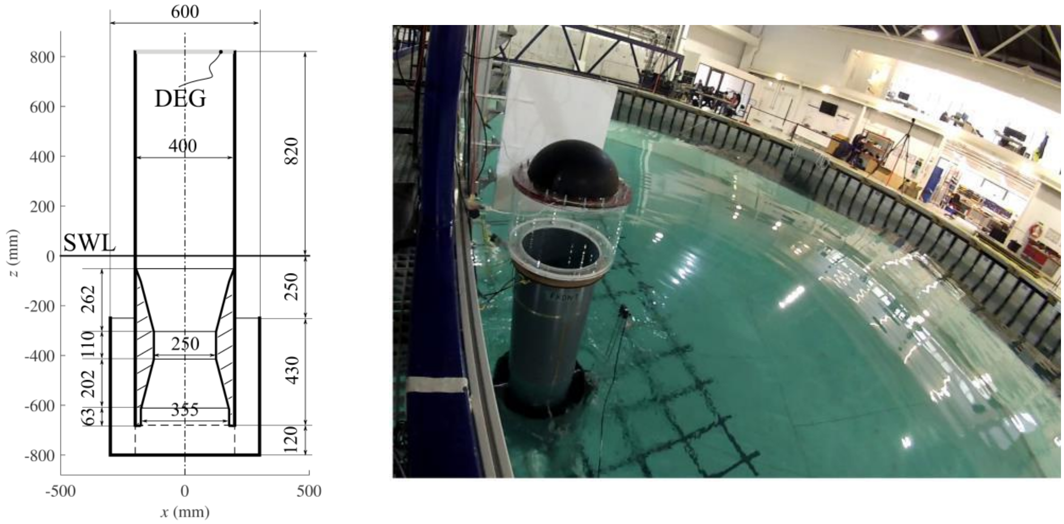
Figure 10. Tubular moored Poly-OWC prototype based on the Sendekia collector in operation at Flowave.

4) Axi-symmetric bottom-fixed Poly-OWC point absorber

In order to provide a relevant example of scalable PolyWEC architecture (suitable for installation in different configurations, such as bottom-fixed or floating), an axisymmetric OWC point absorber system has been developed at an intermediate scale level. The constructed device features a scale of approximately 1:30 and is conceived for installation and test at Flowave facility (Edinburgh).

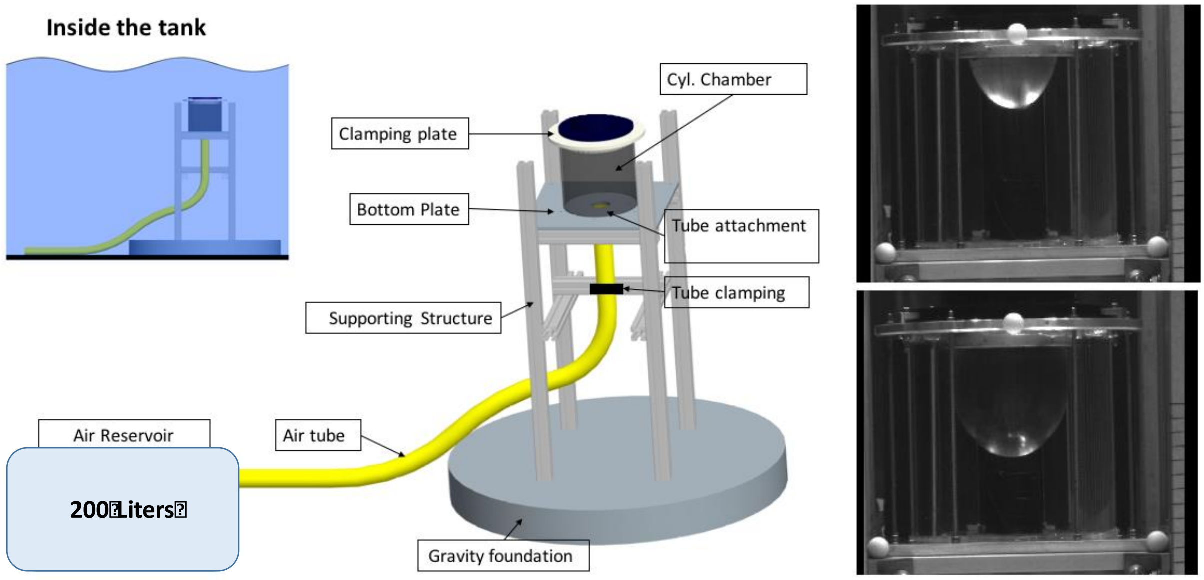
The designed prototype has a U-shaped collector, and it includes a cylindrical main water column (equipped with a convergent-divergent duct) and a vertical added-mass duct with

circular ring cross-section. The device is referred to as Poly-U-OWC. The choice of the peculiar collector geometry (U-shape + convergent-divergent duct) owes to the requirement of a large hydrodynamic added mass, needed to tune the system with the incoming waves.
A schematic of the collector dimensions is in Figure 11.a, while a shot of the device in operation is in Figure 11.b. The system is designed for a maximum electric power output in the range of 1-10 W (max of 20W handled).



(a) (b)

Figure 11. (a) Poly-U-OWC prototype dimensions and collector architecture. (b) Picture of the prototype during tests at Flowave.



(a) (b)

Figure 12. (a) Drum-WEC experimental setup. (b) Pictures of the air chamber and of the CD-DEG membrane installed in the Curved Tank of the University of Edinburgh.

5) Pressure differential direct contact WEC

A prototype of the Drum-WEC, i.e. a submerged pressure differential system shown in Figure 5.a has been developed for small scale testing conducted in the curved tank at the University of Edinburgh. The system, reported in Figure 12, includes: a gravity-based foundation, a submerged cylindrical air chamber housing a circular DEG membrane at its top, an external air tank (connected to the air chamber by a pipe) aimed at reducing and properly scaling the mechanical stiffness of the air volume.

The system has a scale of approximately 1:40 with respect to a hypothetic full-scale device, and it is conceived for purely mechanical (fluid-structure interaction) tests, in the absence of electric activation, to prevent the risk of damaging the wave-tank apparatus.

<u>WAVE TANK TESTING</u>:

In the project, the developed small-scale prototypes have been subjected to performance assessments via tests in wave tanks. In particular, six sessions have been conducted for a total of 10 weeks of testing (3 weeks in Edinburgh University's wave-flume, 1 week in Edinburgh University's curved tank, and 6 weeks at Flowave, Edinburgh).

All of the scaled models tested in the wave flume and at Flowave were equipped with small scale DEG PTOs that implemented wave power conversion into high voltage DC power. Only the prototype of the pressure differential device that was tested in the curved tank was not provided with electric activation due to security restrictions related to the utilization of the facility.

Major objectives were:

- Assess prototype power production ability and energy conversion efficiency in monochromatic waves;
- Assess prototype power production ability and energy conversion efficiency in panchromatic waves and with combined waves and current;
- Asses prototype performance in combination with real-time control strategies that do not rely on any a-priori knowledge of the incoming waves.

MAIN RESULTS:

Main results are summarized below:

- <u>Fixed-structure OWC – first iteration design</u>: The first test session on a PolyOWC prototype (see Figure 8) has been carried out in Dec. 2013 in the wave flume facility. This set of tests was aimed at demonstrating the PolyOWC operation and its capability of actively converting wave power into electrical power.
  The tested system is a 1:50 scaled prototype that makes use of a simple OWC structure. The performances of the system have been validated and analysed in monochromatic sea states in a frequency range of 0.6 – 1.1Hz and wave amplitudes between 1 and 5 cm.
  The following quantities have been measured during the experiments: pressure in the air chamber, voltage on the CD-DEG membrane, membrane tip displacement (obtained from the frames of a high-speed camera). The energy output of the CD-DEG has been measured indirectly, based on the estimated CD-DEG capacitance obtained from DEG tip displacement measurements.
  The energy output for each cycle has been compared with theoretical predictions showing disagreements in the range of 10-20% that are in line with the experimental uncertainties. Although this experiment has been designed just for a preliminary proof-of-concept validation, the measured energy output reached values that are definitely interesting for such a small scale prototype, with a maximum power output of 76.8 mW (that corresponds roughly to 68kW in real scale) and a wave-to-wire conversion efficiency of approximately 5%. Detailed results of this analysis have been reported in the scientific paper by Vertechy et al., SPIE 2014 and in deliverable D4.1.
- <u>Fixed-structure OWC – advanced design</u>: In the second test session (Nov 2014), an improved Poly-OWC model (scale between 1:45 and 1:40) with enhanced dynamic response has been designed, built and tested still in the wave flume facility (see Figure 9). The system has been experimented in monochromatic and panchromatic sea states. Results of the monochromatic

tests have been analysed showing strongly improved performance with respect to the first test session. In particular, experimental results demonstrated device resonance (maximum oscillation amplitudes, DEG deformations, and converted power) within the testing frequency range.

Maximum power output of 0.87W (corresponding to 350-500 kW in full scale) and maximum wave-to-wire efficiency of approximately 20% have been measured. As an example, Figure 13 shows the prototype electrical power output and wave-to-wire efficiency in presence of different regular sea states. Peak powers are obtained at intermediate frequencies within the testing range, owing to the desired dynamic tuning. The system has also been tested in panchromatic sea states with different control strategies.

Other than for performance verification, results have also been used to validate advanced wave-to-wire models of the device. Such models allow to describe the coupled dynamics of the OWC-DEG system predicting the modifications in the device natural frequency due to DEG parameters variations.

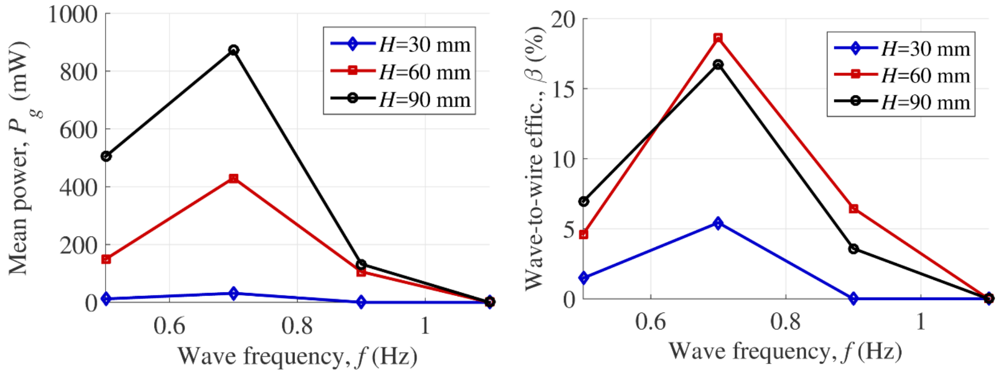


Figure 13. Performance parameters (converted power and wave-to-wire efficiency) of the second PolyOWC prototype.

- Floating tubular Poly-OWC: In the third test session (Feb. 2015), a prototype of a floating Poly-OWC system (1:50 scale), based on the design proposed by the Spanish company Sendekia, has been tested in the Flowave circular wave tank (see Figure 10). The system has been tested in monochromatic and panchromatic sea states. Results of the monochromatic tests have been analysed showing very interesting performances. A maximum power output of 0.25W (corresponding to 220kW in full scale) and maximum wave-to-wire efficiency of approximately 10% have been measured. The system has also been tested for performance verification in panchromatic sea states with different control strategies.
- Axi-symmetric bottom-fixed Poly-OWC point absorber: A larger scale prototype of Poly-OWC has been tested at Flowave for four weeks in total (2 weeks in May 2016 and 2 weeks during Sep. 2016). The device (see Figure 11), featuring a scale of 1:30, was a bottom-fixed axi-symmetric device, equipped with a U-shaped collector providing advantageous hydrodynamic features (e.g., large added mass).

  The system has been equipped with different CD-DEGs featuring a diameter of 390 mm, a stacked multi-layered structure and a rated power of up to a few Watts. Such DEGs are among the largest and most powerful ever built and tested, and their manufacturing and operation represents an important progress towards scaling up of DEG technology in general (beyond wave energy conversion application). An optimized energy scavenging circuit has been designed and built to optimize system performance.

  The following variables have been measured during the tests: voltage on the CD-DEG, pressure in the OWC air chamber, CD-DEG tip displacement (measured by a high-speed camera), water column elevation and water free surface elevation outside the device (acquired with a wave gauge network).

A large variety of tests have been performed, both in regular and irregular waves, in particular: mechanical tests on open collector (open towards the atmosphere), to characterize the dynamics of the water columns; mechanical tests on U-OWC with idle DEG; generation tests (with active control and electric activation); survivability tests on the DEG PTO subjected to exceptional waves; tests with combined waves and current.

As regards the characterization of the dynamic response of the system, the device has been observed to resonate at the target frequency (0.5 Hz) predicted by theoretical calculations and used as target natural frequency for design. Mechanical tests have thus confirmed the effectiveness of the established design methodologies and allowed to validate couple hydro-electro-hyperelastic numerical models.

Mean electric power output over 3 W (440 kW full-scale equivalent) was registered in monochromatic tests at the resonance frequency (see, for instance Figure 14.a, which shows power outputs in different monochromatic wave conditions), and peak power outputs over 3 W were also observed in panchromatic tests (see Figure 14.b).

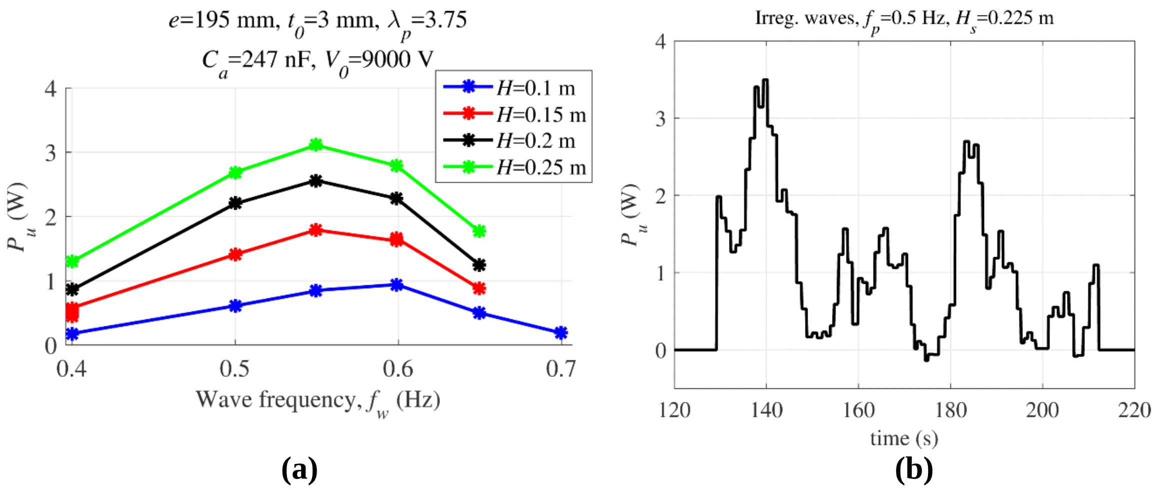
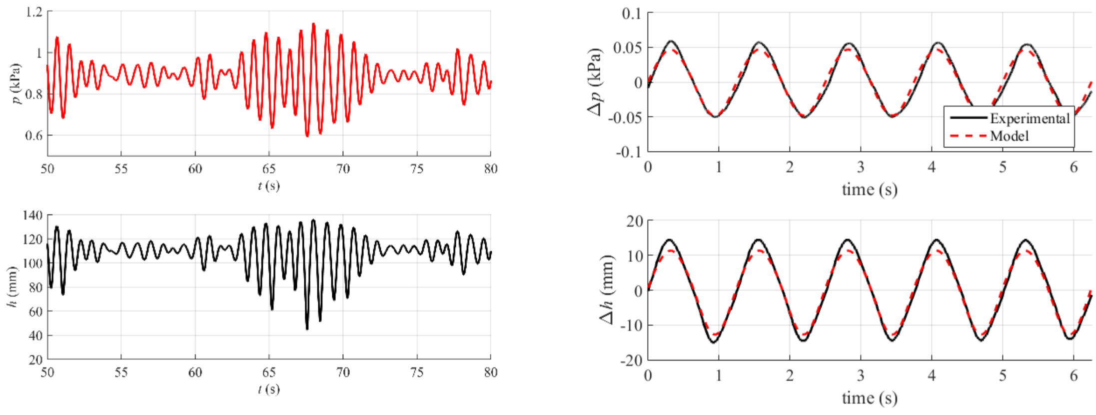


Figure 14. (a) Experimental electric power output of the U-OWC in different sea conditions. (b) Instantaneous power time-series for a panchromatic sea state.

- Pressure differential direct contact WEC: A prototype of DrumWEC pressure differential WEC prototype (Figure 12) has been tested in the curved tank facility during Feb. 2016. Differently from the other experimental campaigns, these tests were addressed at characterizing the passive fluid-structure interaction between the submerged polymeric membranes and the surrounding fluid, and no electric power generation was pursued. The device has been tested both in regular and irregular waves, using different materials: a synthetic rubber, and a silicone elastomer (relevant time-series are, e.g., in Figure 15.a).



(a) **(b)**

Figure 15. (a) Experimental time-series of air gauge pressure and membrane tip elevation (with respect to the membrane pre-stretching plane) in a panchromatic test (f_p=1.2 Hz, H_s=80mm). (b) Comparison between experimental time-series (black solid lines) and theoretical time-series obtained with the established model. Plots refer to a regular sea state with f=0.8 Hz and H=80 mm.

The performed tests have provided relevant insight on the complex fluid-structure interaction involved in DrumWEC operation. In particular, it has been shown that, by properly calibrating the operating parameters (e.g., DEG pre-stretch and thickness), it is possible to compensate the positive elastic stiffness (owing to DEG deformation) with the negative hydrostatic contribution (i.e., increasing hydrostatic pressure with increasing downward DEG deformation) intrinsic to DrumWEC operation. This feature allows to reach large CD-DEG deformations over a wide set of wave frequencies and heights, and potentially allow to build dynamically tuned (i.e., resonant) DrumWEC devices with relatively small size.
Experimental data have been used to validate established numerical models (an example of time-series comparison is shown in Figure 15.b. In particular, it has been demonstrated that, although apparently complex, the problem of DEG-fluid direct interaction can be efficiently described through lumped-parameter models, which still use non-linear time-domain approaches without the need of resorting to complex CFD techniques.

TECHNO-ECONOMIC ASSESSMENT

Following the performance validation of small-scale prototypes, two PolyWEC concepts have been selected for a complete techno-economic study: namely the Poly-U-OWC (Axisymmetric OWC system) and the Drum-WEC (submerged pressure differential system), representing 1st and 2nd generation devices. In particular, the techno-economic study considered the deployment of a pre-commercial wave farm of the two PolyWEC concepts in the Portuguese pilot zone.
A special effort has been spent in an attempt to display thorough and clear results, accompanied with a detailed indication and motivation of all the key assumptions that have been made.
The same methodology has been applied to the techno-economic study of the two WEC systems. Specifically, the procedure went through the following steps:

- First iteration design of the unit device (dimensions choice for the collector and the DEG);
- Design of main structural components of the WEC system;
- Design of the unit device foundations. This step has been carried out using the "Moorings & Foundations (M&F)" software module provided in the framework of a previous EU project, DTOcean, and has been carried out in close collaboration of DTOcean project staff.
- Iterative optimization of the PTO for the prescribed site, design of the array layout, and finalization of dimensioning of the WEC system;

- Computation of power matrix and annual production for the specific site;
- Design of an electric HVDC network layout for power transmission to the shore;
- CAPEX estimation and evaluation of CAPEX breakdown;
- OPEX estimation and evaluation of OPEX breakdown;
- Sensitivity study on:
    - Different Electrical Network Topology and different working voltages considering the subsequent choice of cabling.
    - Different material unit cost
    - Different DEG lifetime.
    - Different structural solutions for the WEC collector.
    - Different DEG dielectric parameters, providing PTOs and WECs with different power output. This analysis was aimed at foreseeing how the techno-economic indicators might change in a future scenario in which optimized DEG materials will be available.

MAIN RESULTS:
Main results are summarized below:
- LCOE performance: The main finding suggests that the Poly-U-OWC and the DrumWEC can achieve LCOE values within the projected range by the SI Ocean project for pre-commercial WEC farms (514€/MWh for the Poly-U-OWC and 532€/MWh for the DrumWEC). Although these values remain largely above commercial targets (approx. 100€/MWh), it should be noted that the underlying assumptions are mostly conservative.
- CAPEX performance: Detailed costs breakdown information reveals the residual impact of the DEG-PTO on the total capital costs; specifically, the DEG-PTO provides a contribution to the overall CAPEX of the WEC device in the range of 0.5% and 2%. While operational expenditures remain largely unknown, the low costs associated with the procurement of DEG modules presumes that the possibility of multiple DEG replacements during the project lifetime would not impede the competitiveness of a commercial plant of PolyWECs. The results from the sensitivity analysis show how alternative design choices and uncertain parameters can influence LCOE estimation. Having shown promising energy production performance metrics, the Poly-U-OWC and, to a greater extent, the DrumWEC have the potential to become economically viable through a detailed engineering optimization process. For instance, combining alternative structural materials, so as to decrease the cost of the collector, with enhanced DEG materials, so as to improve energy capturing efficiency, can significantly reduce the LCOE. Future prospects to achieving competitive cost of energy targets with DE PTOs are therefore realistic.

ENVIRONMENTAL ASSESSNMENT

In addition to the techno-economic assessment, the potential environmental impacts associated with DEG-based WECs have been assessed and looked into. The aim has been to understand how this innovative technology can distinctively affect the environment; for instance: collision risk of wildlife, electric discharges, water quality, etc. Information compiled has been based on currently existing knowledge and most up-to-date information on the identification of environmental effects. Aspects that have been considered are:
- The evaluation of the carbon footprint of the Poly-U-OWC and DrumWEC farms considered for the techno-economic assessment;
- A laboratory study of DEG materials degradation in the marine environment.

MAIN RESULTS:
Main results are summarized below:

- Carbon Footprint performance: The carbon footprint of the Poly-U-OWC and DrumWEC farms were found to be 203 and 171g CO2eq/kWh, respectively. These are relatively high when compared to mature renewable energy generation technologies, but significantly lower than conventional fossil-fuelled technologies, and correspond to carbon paybacks of 8.1 and 6.8 years. Similarly, the embodied energy was found to be relatively high, at 2.4 and 2.0 MJ/kWh for the Poly-U-OWC and DrumWEC respectively, corresponding to an EROEI of 1.5 and 1.8, which demonstrates that energy payback will be achieved, but there is a significant scope for improvement.
- Degradation resistance of DEG materials: a study has been conducted to improve the current understanding of how materials used in DEG PTOs will wear-off due to heavy loads or due to accidental membrane disruptions. The analysis made it possible to identify a series of risks and unplanned events that can occur and whose effects can largely vary throughout the course of the project. Major criticalities are associated with the use of commercially available elastomers, since they contain a lot of additives (for instance, curing agents, accelerators, antioxidants, processing aids, reinforcing, etc.) that beside affecting degradation resistance are also contamination sources. By analysing available information about several types of commercial rubber (comprising natural rubber, silicones, styrene-butadiene), silicones elastomers seem to possess the premises to be the least prone to degradation and the least polluting in the marine environment. This is due to the fact that these elastomers have the most stable polymer chain both to oxidation and photolysis, and contain the fewest additions besides silica reinforcing which does not constitute a hazard.

ROADMAP:
An analysis of the status of the technology was drawn considering aspect such as TRL and MRL for the main sub-systems that compose PolyWEC devices.
Additionally, a study has been conducted towards the definition of a (1) research roadmap and (2) preliminary commercialization roadmap.

MAIN RESULTS:
Main results are summarized below:

- The road-mapping activity lead to the definition of a specific architecture of DEG-PTO, which consists of an inflatable multi-layered circular membrane made by a stack of dielectric elastomer layers separated by stretchable electrodes, referred to as Circular Diaphragm DEG (CD-DEG). The CD-DEG can be employed as PTO in Oscillating Water Columns (OWCs), in place of traditional air turbines, or as PTO in fully submerged WEC concepts such as in Pressure Differential (PD) systems.

The potential impact and the main dissemination activities and exploitation of results

Potential Impact:
PolyWEC is a Future Emerging Technology project that has mainly developed basic research on new materials and new concepts of wave energy converters based on Dielectric Elastomer Generators (DEG). Such emerging research could generally have a major impact in the power sector by enabling the production of electricity from renewable sources with a lower Levelized Cost of Electricity and in a more sustainable manner, i.e. with a higher Energy Return on Energy Invested (ERoEI), as compared to state-of-the-art renewable-energy systems and zero-emission power-plants.
PolyWEC project has contributed to the development of the DEG in the wave energy sector bringing this technology to a TRL level between 3 and 4. Specifically, within the framework of the Project the DEG technology has been demonstrated in wave-tank laboratory tests up to a scale of few watts and several advancements have been achieved in the field of modelling, new materials and assessment.
The achieved results pave the path for further developments that are (partially) already started with the initiation of further research projects and collaborations.
Moreover, a company called Cheros Engineering (spin-off of SSSA) have been founded at the beginning of 2016 with the aim of developing the technology of DEGs toward a commercial exploitation.

More specifically, the following results of the PolyWEC projects are identified for their relevant potential impact:

- Demonstration of intermediate power (scaled) DEG-based PolyWEC devices in operating conditions.
  The experimental proof of the devices with a power in the range of 1-4 watt (with 1:25/1:30 scale) has been achieved. Such devices have been designed according to specific models and tested through the employment of simple control strategies that make use of a reduced set of sensors.
  This achievement is an important milestone that has an important impact on the future development of DEGs for the wave energy sector. Before the beginning of PolyWEC project only few prototypes in the range of few watts were conceived, however it was not clear how and if these systems could scale-up.

  This demonstration represents a significant step forward which can help in building confidence in the technology of DEG for public bodies, investors and other research institutions.

- New coupled Electro-hypereleastic-hydrodynamic models and design guidelines.
  The accurate/validated electro-hypereleastic-hydrodynamic models that have been developed make it possible to mathematically describe the response of DEG based WEC. These represents a fundamental tool for future designers of PolyWEC systems, which make it possible for them to forecast the performances of real-scale devices.
  The use of these models has already started since they have been successfully employed/exploited in three follow-up projects that aim at further advancing the technology of Dielectric Elastomer Generators in the Wave Energy sector:

  - H2020 project WETFEET (prj.n. 641334): Models and guidelines have been exploited for the preliminary design of a DEG-PTO to be coupled with two novel WECs;
  - ENEA project: Models and guidelines have been employed for the design of a DEG-PTO to be integrated in a OWC system that is currently being developed at University of Reggio Calabria (Italy).
  - Wave Energy Scotland: Models have been employed for the design of a submerged pressure differential WEC with a new collector.

  Other future concepts are currently being investigated employing the modelling approach that has been developed.

  Beside the wave energy sector, such models could be successfully employed in other fields such as: (1) Biomedical sector: for the simulation of the interaction between fluids and soft electro-mechanical medical devices; (2) Marine Engineering for the development of special elastomeric component.

- New-materials:

  Novel materials and conversion unit assemblies, namely Polymeric Conversion Units (PECUs), have been developed for the implementation of dielectric elastomer transducers. Specifically, new dielectric elastomers have been synthetized together with new deformable conductive electrodes. Integrated PECUs have been also developed demonstrating the feasibility of manufacturing at small scale. This achievement represents an important step toward further studies for the manufacturing of up-scaled devices and systems. The obtained materials and understanding of procedures for their integration can have an important impact for the next development step of the DEG but also for the development of several other devices based on dielectric elastomer transducers such as: actuators for automation or biomedical sectors and sensors to be employed in different fields.

Dissemination activities and exploitation of results

PolyWEC project strategy to spread its results in terms of dissemination and exploitation followed focussed on three main directions: (1) reaching out to the scientific community, (2) fostering research exploitation by initiating new R&D projects to complement and continueing PolyWEC research, and (3) preparing PolyWEC results transfer and teke up in the industrial context.

Direction (1) sought scientific and societal impact through general dissemination of the project approach and its results, and more specialised dissemination through the publication of journal articles and conference papers and through the indirect academic impact generated by MS, BS and PhD students working on PolyWEC themes. The figures achieved during the project for such activities are the following:

- www.polywec.org (project website with links to project publications and up-to-date dissemination material)
- PolyWEC general leaflet and PolyWEC general presentation and poster
- PolyWEC videos
- Peer-reviewed journal articles published: 19
- Peer-reviewed conference papers I proceedings: 15+ (EuroEAP and EWTEC conference proceedings, and ASME and SPIE proceedings)
- 3 PhD projects achieved, 3 MS and 2 BS awarded with theses on PolyWEC themes

Direction (2) sought exploitation of PolyWEC R&D mainly through applications for funding aimed to develop concepts related to PolyWEC. Below a list of the applications submitted (all funded but one) during the PolyWEC project funding period:

- WETFEET (WavEC, SSSA, SELMAR and other non-PolyWEC partners – H2020-LCE-2014-/LCE-02-2014); funded and started in May 2015.
- WavePump (PolyWEC consortium with other Partners – H2020-LCE-2014-/LCE-02-2014)
- Study of a PTO based on electroactive polymers (SSSA with the Italian National Agency for New Technologies, Energy and Sustainable Economic Development and the Italian Ministry of Economic Development)
- Direct contact dielectric elastomer PTO for submerged wave energy converter (SSSA, UEDIN and UNIBO in May 2015 for Wave Energy Power Take-Off Competition – Stage 1, issued by Wave Energy Scotland)
- Inflatable dielectric elastomer generator PTO (SSSA, UEDIN and UNIBO in June 2016 for Wave Energy Power Take-Off Competition – Stage 2, issued by Wave Energy Scotland)
- "Silicone-based energy conversion units built up by green chemistry", (PPIMC – project number PN-III-P2-2.1-PED-2016-0188, within PNCDI III (Grant 68PED ⁄ 2017). Funded by the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI-UEFISCD. The project started on January 3, 2017)

Direction (3) sought the transfer or at least preparation for the transfer of PolyWEC results to industries. The initiatives to this aim are summarised in the following:

- A patent application (No. 102016000130691) with joint ownership has been filed in initially in Italy (extensions are foreseen)
  Patent title: "Generator based on a dielectric elastomer with compensated stiffness.".
- A spin-off company (CHEROS S.r.l.) has been established from SSSA young researchers working on PolyWEC, as a means to foster PolyWEC technology transfer, starting from pre-commercial activities. The company is involved as consultant in a project funded by Wave Energy Scotland on Dielectric Elastomer Generators.

Project public website

www.polywec.org

Furthermore, project logo, diagrams or photographs illustrating and promoting the work of the project (including videos, etc…), as well as the list of all beneficiaries with the corresponding contact names can be submitted without any restriction.