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A pan-European Network for Marine Renewable Energy with a Focus on Wave Energy

WECANet COST Action CA17105
General Assembly 2019

BOOK OF ABSTRACTS

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- Matt Folley
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- Evangelia Loukogeorgaki
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About the WECANet European COST Action CA17105

The pressure of climate change and the growing energy demand has increased interest in marine renewable energy resources, such as wave energy which can be harvested through Wave Energy Converter (WECs) Arrays.

However, the wave energy industry is currently at a significant juncture in its development, facing a number of challenges which require that research re-focusses onto a techno-economic perspective, where the economics considers the full life-cycle costs of the technology. It also requires development of WECs suitable for niche markets, because in Europe there are inequalities regarding wave energy resources, wave energy companies, national programmes and investments. As a result, in Europe there are leading and non-leading countries in wave energy technology. The sector also needs to increase confidence of potential investors by reducing (non-)technological risks. This can be achieved through an interdisciplinary approach by involving engineers, economists, environmental scientists, lawyers, regulators and policy experts. Consequently, the wave energy sector needs to receive the necessary attention compared to other more advanced and commercial ocean energy technologies (e.g. tidal and offshore wind).

The formation of the first pan-European Network on an interdisciplinary marine wave energy approach will contribute to large-scale WEC array deployment by dealing with the current bottlenecks. The WECANet (Wave Energy Converter Array Network) European COST Action, introduced in September 2018, aims at a collaborative approach, as it provides a strong networking platform that also creates the space for dialogue between all stakeholders in wave energy. An important characteristic of the WECANet Action is that participation is open to all parties active in the development of wave energy. Previous activities organised by WECANet core group members have resulted in a number of joint European projects and scientific publications. WECANet's main target is the equal research, training, networking, collaboration and funding opportunities for all researchers and professionals, regardless of age, gender and country in order to obtain understanding of the main challenges governing the development of the wave energy sector. Currently, 31 partner countries are active in WECANet.

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Abstracts

Abstracts for Working Group 1:

Numerical hydrodynamic modelling for WECs, WEC arrays/farms and wave energy resources

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Towards a multiphysics computational package for WECs analysis

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The simulation of Wave Energy Converters (WECs), and arrays of WECs, is a complex task due to the high variety of spatial scales and physical processes involved. On the one hand, sea states must be accurately propagated at the WECs, being the distances much higher than the typical dimensions of the devices. On the other hand, the dynamics of the floating devices can be complicated when their movement is constrained by a mooring system. In addition, the devices consist of multiple pieces that can move independently due to the action of water. Consequently, no particular model can describe the dynamics of WECs under the effect of waves.

Our effort over the last few years has been focused on the development of a simulation package whose cornerstone is the open-source code DualSPHysics, which should be coupled to:

- A wave propagation model to propagate the sea state near the device (or among devices). Essays with SWASH and OceanWave3D have shown the suitability of the approach [1,2].
- A model responsible for the movement of the device and, in particular, of articulated pieces, springs and dampers. Previous research with Project Chrono has provided promising results [3].
- A model to simulate the mooring system which will constraint the degrees of freedom of the device. Initial tests have been conducted using MoorDyn to mimic the mooring system [4]

Our goal within the framework of WECANet for the next few years is to integrate all the components previously mentioned in a single package.

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Coupling methodologies in multi-physics and multi-scale numerical modelling of WEC and WEC Array

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Numerical modelling of WEC and WEC Array is an essential step in the optimal design of WECs. There is an open-cycle between the numerical modelling and experiment ending with an optimal product. To be able to model such complex phenomena as the WECs is not only single mathematical model is employed but we need a wide assortment of models. Each mathematical model it is new numerical story, and many different approaches and codes are used to solve it.

Numerical modelling of WECs system is a complex task where we have different physical phenomena on a similar scale or a different scale (spatial or temporal). Different solutions come from different solvers that can be open-source or commercial type. Not rarely, groups develop their software for tailored cases. How to combine such software diversity on a single platform is challenging task?

The mentioned task is possible to solve in many ways and solution is based on a problem, software and platform type. Based on our previous experience, generic answer is not unique. We want to investigate different systems, different platforms and try to combine input/output data universally. In most cases we are interested in the computational data, but there is another issue related to geometry representation used for fluid-structure interaction. In this case it is crucial to project result correctly, that is in some conservative way, thought the body boundary (interface). Until now we have identified three possible ways:

- direct communication between different open-source codes via socket communication,
- communication via files in a standardised format (based on NETCDF),
- using NURBS geometry with IsoGeometric Analysis approach to computing FSI problems.

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A coupling methodology for modeling near-field and far-field wave effects of floating structures and wave energy devices

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This research focuses on the numerical modelling of wave fields around (oscillating) structures such as wave energy converters (WECs), to study both near and far field WEC effects. As a result of the interaction between oscillating WECs and the incident wave field, additional wave fields are generated: the radiated and the diffracted wave field around each WEC. These additional wave fields, together with the incident wave field, make up the perturbed wave field.

Several numerical methods are employed to analyse these wave fields around WECs. For example, for investigating wave-structure (wave-WEC) interactions, wave energy absorption and near field effects, the commonly used and most suitable models are based on Boundary Element Methods for solving the potential flow formulation, or models based on the Navier-Stokes equations, often referred to as 'wave-structure interaction solvers'. On the other hand, for investigating far field effects of WEC farms in large areas, 'wave propagation models' are most suitable and commonly employed.

However, all these models suffer from a common problem; they cannot be used to model simultaneously both near and far field effects due to limitations. In this research, we developed a generic coupling methodology to combine the advantages of the above two approaches; (a) the approach of wave-structure interaction solvers, which are used to investigate near field effects because they can more correctly model wave energy absorption and the resulting wave fields induced by oscillating WECs or WEC farms. These solvers suffer from high computational cost and thus are mainly used for limited: (i) areas around WECs; (ii) number of WECs, and (b) the approach of wave propagation models, which are used for predicting far field effects and which can model the effect of WEC farms on the wave field and the shoreline in a cost-effective manner, but usually cannot deliver high-fidelity results on wave energy absorption by the WECs. In addition, in our research we developed a wave generation technique for generating the perturbed wave field induced by an oscillating WEC, in a wave propagation model. The results obtained from the proposed coupling methodology and wave generation technique along a circle have been validated ([1], [2]) and show very good agreement.

This research is situated in the topics of "Working Group 1: Numerical hydrodynamic modelling for WECs, WEC arrays/farms and wave energy resources" of WECANet.

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Uncertainty in the estimation of annual energy production and the selection of numerical modelling tools

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Accurate estimates of the annual energy production (AEP) of wave energy converters is critical for the future development of wave energy. In particular, the identification of the optimal WEC configuration it may be necessary to produce multiple estimates of the AEP, which means that some compromises on the accuracy of the numerical modelling tool used to estimate the AEP would need to be made. The methods of calculating the AEP are detailed by Kofoed and Folley [1] where different combinations of the representation of the wave climate and power performance are presented. For example, a highly accurate estimate of the wave climate could be used, but this would require a more gross approximation of the power performance to limit the computational requirements. Conversely a highly accurate estimate of the power performance could be used, but this would require a more gross approximation of the wave climate, which would have a similar computational requirement. The fundamental question is what combination of accuracy of the wave climate and power performance models will provide an estimate of the AEP with an acceptable degree of uncertainty.

It is proposed that a specific device and wave climate are identified that can be used for a comparative study. In addition, a standard measure of the computational requirement for the calculation of the AEP is generated that is independent of the computational platform. It is proposed that the AEP is calculated based on a time-domain model and 10-years of fully spectral wave data to provide a truth model against which alternative estimates of the AEP can be judged. Different groups could then produce estimates of the AEP using their preferred methodology, together with an estimate of the uncertainty if possible. This data would then be collated to show the error in the estimate of the AEP, the computational requirements and how this varied with the methods used to estimate the AEP. It is anticipated that this would lead to the production of a paper on the calculation of AEP, which demonstrates the expected uncertainty and how this varies with methodology and computational requirements.

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Arrays of Heaving Wave Energy Converters in front of a Wall

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Contemporary technological advances seek the efficient exploitation of wave energy. Aiming at enhancing the performance of heaving Wave Energy Converters' (WECs) arrays, a vertical barrier (say a wall) in the leeward side of the array could be utilized. In that case, the WECs' hydrodynamic behavior and, thus, their power absorption efficiency may be improved by exploiting the near-standing waves generated by the interaction of the incoming and the reflected waves. This idea can also support the integration of WECs with other marine facilities (e.g. vertical breakwaters, floating pontoons) leading, therefore, to cost-efficient solutions through costs' sharing. Although some investigations have recently dealt with this problem (e.g. [1]-[3]), there are still issues that should be adequately addressed.

In this context, numerical-based studies considering the wave reflections' effects combined with the disturbances induced by the WECs, have to be implemented aiming at: (a) investigating and, ultimately, optimizing, in terms of maximizing the array's energy absorption ability, critical design parameters and/or (b) proposing new, novel design concepts of the leeward barrier that can lead to enhanced energy absorption. Indicatively, critical design parameters include the array's distance from the wall, the array configuration (e.g. linear or staggered), the distances between the WECs and, finally, the wall's geometrical features. The deployment of different WECs' geometry (e.g. cylinder, spheroidal) introduces additional challenges. On the other hand, novel design concepts of the barrier can be investigated by utilizing the "parabolic reflector" concept for the wall (e.g. [3]). All the above can be examined in the frequency domain by utilizing/developing numerical models based on semi-analytical or boundary integral equation formulations, which could be also coupled with appropriate optimization algorithms.

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Evaluation of the climate change impact on future wave energy resources with a focus on the Black Sea basin

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In the last years, increasing investments in marine renewable energy were made and because these resources are affected by climate changes an estimation of their future evolution is important. The wave energy has a relevant potential among marine renewable resources and an important issue is to find the best places to catch this energy. This can be made based on the assessment of the wave energy potential in various locations using the data provided by the wave models or measurements when these are available. As regards the expected future wave energy resources, this evaluation can be made based only on the numerical simulations.

With the objective to observe the dynamics of the wave energy in the context of climate changes until the end of the 21st century, a wave modelling system based on the SWAN (Simulating WAves Nearshore) model was implemented in the Black Sea basin. As forcing factor for the wave model are considered only the wind fields, in this case those provided by SMHI (Swedish Meteorological and Hydrologic Institute) through the EURO-CORDEX database. These high resolution wind fields are simulated by a Regional Climate Model (RCM), namely the Rossby Centre regional atmospheric model (RCA4) under various Representative Concentration Pathways. For the Black Sea region were considered only those simulated under RCP4.5 and RCP8.5 scenarios for two time periods covering the near future (2021-2050) and the distant future (2071-2100). Also the historical wind fields simulated by the same RCM were considered.

SWAN simulations over each 30-year period were performed and as output the wave power components are considered. A comparative analysis of the mean wave power values projected for the future and the historical values were performed. Important differences are observed mainly in the seasonal analyses when different patterns of changes can be observed.

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Novel tools for WEC performance and optimization in variable bathymetry regions

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The performance of WECs in nearshore and coastal areas, where the bottom topography may present significant variability, has important effects on the power take-off levels and is strongly connected with the determination of operational characteristics and design aspects of the system, both individually and in a farm layout. Appropriate design optimization will further contribute in increased power output levels and efficiency of the devices.

We propose a hybrid method based on Boundary Element Method (Belibassakis 2008), in conjunction with a Coupled Mode Model and Perfectly Matched Layer model for the solution of the propagation/diffraction/radiation problems of floating bodies in variable bathymetry regions (Belibassakis et al 2001). An important feature of the methodology is that it is free of mild-slope assumptions and restrictions. The method has been applied to the case of heaving WECs with vertical cylindrical or axisymmetric floaters over a region of general topography (Belibassakis et al 2018), and recently extended to the case of WECs multiple degrees of freedom (Bonovas et al 2019). Numerical results concerning the details of the wave field and the power output are presented and discussed concerning shape and PTO optimization considering heave in conjunction with pitch oscillation modes indicating possible increase of performance. In the case of heaving-pitching devices, the most efficient designs is found to be the Cylindrical and the Nailhead type WECs reaching a performance index of 30% over flat and sloping seabed. Modelling of the interactions between WECs in an array arrangement in general bathymetry regions will support optimization studies in realistic nearshore/coastal sites.

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Evaluation of the Wave Energy Resources in the Cape Verde Islands

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The Cape Verde islands form an archipelago off the African coast in the Atlantic Ocean that is highly dependent on fossil fuels. For this reason, Cape Verde has started to take into account the potential of renewable energies, especially wind and solar. The present work aims to be a first step in the evaluation of another renewable energy source, the waves. Using a methodology already implemented in other island environments, reanalysis data from ECMWF, was used to force the SWAN model that was run for a 10-year period, covering the time interval 2004-2013. Three years of obtained high resolution data were compared with the available altimetric data. In this way, a dataset of the sea state conditions around Cape Verde Islands was produced. This dataset was further used for wave climate analyses and wave energy resource assessments. This study indicates that the coastal environment of the Cape Verde Islands, and especially some particular areas, present considerable wave energy resources that should be taken in consideration for extraction in the near future.

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A New Hybrid System Concept Capable to Harvest both Wind and Wave Energy

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The research group that presents this study is working for some time with the development of a new hybrid system, capable to support Offshore Wind Turbines (OWTs) of very large power output, carrying simultaneously an array of cylindrical Wave Energy Converters (WECs), shaped as uniform truncated cylinders. The idea conceived, is based on the availability of the support structure (jacket), which by construction provides a secure foundation, and aside from the WT, the efficiency of the system can be increased by harvesting both wind and wave energy. However, the existence of the WECs, which are considered distributed evenly around the jacket skeleton legs, leads unavoidably to the distortion of the (assumingly) regular wave field due to wave diffraction. Accordingly, the platform will be subjected to complicated velocity and pressure fields that will be governed by the diffraction phenomena.

The goal is to achieve a methodology for the computation of the hydrodynamic loading induced on the jacket, which is of paramount importance for its secure operation. The jacket will experience the loading acting upon the WECs that is directly transmitted to the platform, as well as the forces on its tubular members. The forces on the tubular members should be calculated based on the actual, modified, wave field. This task can be achieved by enhancing the underlying Morison's equation, to account for the realistic wave kinematics and the linear hydrodynamic pressure. The potential of the hybrid system is explored through the numerical analysis of two reference cases, aiming to quantify the energy absorption of the array of WECs and the total hydrodynamic loading exerted on the jacket support system. The results show that the presented hybrid system can be efficiently used for the extraction of offshore renewable energy.

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Domain Decomposition strategies for modelling survivability conditions of WECs

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The increasing TRL of WECs requires that their survivability both in Ultimate Limit States (ULS) and Accidental Limit States (ALS) should be assessed. However, the definition of these conditions is not easy because they depend largely on the deployment site and on the kind of WEC. In fact, because of the use of resonance conditions for the amplification of the waves, the largest response in terms of motions and/or loads is not always triggered by the largest waves [1].

Generally, nonlinear free-surface effects and important flow-separation phenomena take place. To guarantee accuracy and preserve computational efficiency, the use of multi-methods numerical simulations can become very useful. We have already experience with Time and Spatial Domain Decompositions (DD): a potential-flow and a full Navier-Stokes solvers were coupled to investigate violent wave-body interaction and occurrence of green-water events [2] and a Harmonic Polynomial Cell Method (HPC) and OpenFOAM were coupled to model the behavior of a damaged ship section [3].

We propose to apply these kind of DD strategies to WECs and to study the local non linear and viscous effect by a Navier-Stokes solver around the WEC and couple it with a method that can accurately and efficiently describe the flow field afar. For the latter, we propose also the use of a Depth-Semi-Averaged model [4] to accurately describe the WEC motion in the deployment site.

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Study of "far field" effects of arrays of WECs using a linear coupled model

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This work refers to my recently finished doctorate research at the Civil Engineering department of Ghent University (Belgium) focusing on the numerical modelling of "far field" effects of Wave Energy Converter (WEC) arrays [1]. During this research a numerical coupled model has been developed between the wave propagation model MILDwave [2] and the wave-structure interaction solver NEMOH [3] using the generic coupling methodology introduced by [4,5].

The aforementioned coupled model combines the advantages of both wave-structure interaction solvers and wave propagation models in order to simulate the "far field" effects of WEC arrays with precision and with an efficient computational time over large domains. The coupled model has been implemented as a one way coupling, and is used for regular, long-crested and short-crested irregular waves, and for different types of WECs operating under linear waves,. having been validated for all these wave types. Therefore, the performed work fits in **Working Group 1**: Numerical hydrodynamic modelling of WECs, and more specifically in the topic that focuses on coupling between codes for WEC simulation.

The next steps for extending the capabilities of the numerical coupled model are to validate a recently implemented new wave generation technique for short crested irregular waves, the introduction of a direct simulation of irregular waves by means of Inverse Fast Fourier Transforms (IFFT) and to provide the numerical coupled model with a Graphical User Interface (GUI). The release of this updated coupled model Is expected soon in 2019-2020.

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Hydrodynamic modelling for wave energy converters: explore the computation/fidelity continuum

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Wave energy is a tremendous untapped energy resource that could make a decisive contribution to the future supply of clean energy. However, numerous obstacles must be overcome for wave energy to reach economic viability and compete with other energy sources. The amount of energy extracted from ocean waves, and therefore the profitability of the extraction, can be increased through a holistic optimization of the geometry and control strategy of the wave energy converter, both of which require accurate mathematical hydrodynamic models that are able to correctly describe the WEC-fluid interaction. While the effectiveness of the optimization/simulation is tightly linked to the accuracy of the model, the computational demand brutally limits the realm of applicability. Therefore, it is essential to be able to univocally measure the fidelity/computation compromise of each model, and consequently select which application it is appropriate for.

However, despite its mature age, the "modelling problem" is far from being settled. This is certified by several recent collaborative projects, such as the OES-TASK-10 or the CCP-WSI Blind Test Series. Despite high expectations, the main conclusion was the lack of a definitive conclusion: although differences were clear, it was difficult to evaluate the goodness of different models. In order to pursue the essential objective of confidence in mathematical model, some main issues need to tackled:

- **Lack of standardization in benchmarking**: what are the best-practices to conduct real/numerical wave tank experiments in order to generate reliable benchmarking data?
- **Lack of a set of standardized, unambiguous, and representative comparison metrics**.
- **Lack of structured sharing platforms**: it is essential to share knowledge, expertise, and experience, in order to avoid redundancy, hence waste of resources.

My personal effort in this field is focused on the development and experimental validation of a novel nonlinear modelling approach, which realizes a good compromise between accuracy and computational time (about real-time computation). After validation, the objective of the project is to create an open-source software in order to allow the community to avoid the learning curve and easily test the model.

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Assessment of wave energy resources along the Azores Islands

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Aiming to provide information on the best sites for the implementation of energy devices, this work presents a numerical study of the sea state conditions and wave energy availability in the Azores Islands.

Spectral boundary conditions from WW3, provided by Ifremer, with time resolution of 3h, are used to force the SWAN model, to study the evolution of the waves in the area of the Azores Islands (35°N-41°N, 36°W-24°W). The wind input fields used are from ERA5 data base, produced by the European Centre for Medium-range Weather Forecast (ECMWF), with time steps of 6 hours, provided over a grid of 0.25°x0.25° resolution.

A quantitative analysis of the results is performed for the complete period of 2015. The numerical results have been compared and validated against satellite data and buoy measurements from three wave buoys provided by the Azores University (UAC - Universidade dos Açores - Portugal). The results demonstrate that, in general, Significant Wave Height, Mean Period, and Peak Period are well reproduced by SWAN.

Wave models provide awareness on the available wave resource. The geographical distribution of the significant wave height shows that mean values range between 2-3m. Also the Hs 90th percentile varies between 4-4.5m for the occidental areas and 2.5-3m for the oriental areas.

Regarding the wave power, the results show a mean wave power resource between 30-35kW/m at the occidental area and 15-20kW/m at the oriental area. In the central area of the archipelago the wave power resource varies between 25-30 kW/m within the areas more exposed to north Atlantic waves and 15-20 kW/m in the others. Also the Hs 90th percentile varies between 60-70 kW/m and 20-30 kW/m for the occidental and oriental areas, respectively.

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Wave energy resources in the Baltic Sea

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Ocean waves are considered as a clean and renewable source of energy with a tremendous worldwide potential for electricity generation. This energy can be extracted in different ways, which has given rise to a large variety of available and deployed technologies (Kempener and Neumann, 2014). The Baltic Sea is one of the inland seas of Europe. A study by Latvian experts (Avotiņš et al., 2008) concluded that the wave potential of the Baltic Sea is satisfactory for converting energy. Lithuanian experts also acknowledge that the southeastern Baltic Sea provides a great potential and possibilities for electricity production from offshore renewable energy sources (Blažauskas et al., 2015). On average, the wave energy flux of the Baltic Sea is 1.50 kW m^{-1}. The present assessment of wave energy resources in the Baltic Sea Lithuanian nearshore indicated that the mean wave energy flux was equal to 1.21 kW m^{-1} (Jakimavičius et al., 2018). At the moment, there are no a practical application of WECs in the Baltic Sea (Lithuanian territory) on the Lithuanian coast. Contributing to WECANet (WG1), we propose the following activities, which may be useful in evaluating the feasibility of using WECs in the Baltic Sea:

1. Mapping of the Baltic Sea wave energy related research activities, projects, and publications of participants across Baltic Sea (together with PL, DE, DK, SE, and EE partners).
2. Review of methodologies, methods and models related with wave energy research in the Baltic Sea (together with PL, DE, DK, SE, and EE partners);
3. Best practice for wave energy estimation and planning of WEC in the Baltic Sea (together with PL, DE, DK, SE, and EE partners);
4. Estimation of wave energy potential in the Baltic Sea (Lithuanian territory) using MIKE21 SW model (Lithuanian Energy Institute, LT);
5. Possibility of WEC farms (in the Baltic Sea nearshore – Lithuanian territory) using best practice of wave energy research in the Baltic Sea region (Lithuanian Energy Institute, LT).

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A Post-Boussinesq Model for Wave – Floating Body Interaction

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The realization of large-scale commercial wave energy projects requires among others the deployment of a large number of Wave Energy Converters (WECs) arranged in arrays. The installation and operation of WEC arrays should be implemented by considering, additionally to economic and engineering factors, their impact on the wave climate. This is crucial, especially for coastal areas, where undesirable effects of WECs on the local wave climate may affect directly human activities and operations in the coastal environment. In this context, high-fidelity numerical models enabling the accurate prediction of near-shore hydrodynamics in the presence of hydrodynamically interacting WECs are required.

Motivated by this, in the present work, the post-Boussinesq model proposed by Karambas and Memos [1] is adapted for the simulation of nonlinear wave-body interaction, aiming at modelling WECs (e.g. heaving buoys) and corresponding WEC arrays. Both the free surface flow and the flow under the floating body are treated with the depth-integrated approach. For this purpose, the unified Boussinesq approach proposed by Lannes [2] is adopted. This approach includes the simultaneous solution of: (a) the depth integrated continuity and momentum equations (including an extra surface pressure term), (b) an elliptic equation for the interior pressure and (c) the equation of motion of the floating body.

The model is applied to test cases of a heaving cylinder subjected to finite-amplitude waves. The cases of one and three cylinders are examined. The results obtained are compared with well-confirmed numerical solutions (e.g. BEIM models, analytical solutions). The model is shown to have satisfactory accuracy and is relevant for applications of waves interacting with wave energy devices.

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Tensions in Catenary Cables Calculated by a Coupled Model

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Wave energy converters (WEC) and floating offshore wind turbines (FOWT) use catenary mooring cables for station-keeping purposes in deep waters. If the computationally costly CFD models are to be avoided, numerical modelling for mooring dynamics usually relies on the Morison approximation that adapts hydrodynamic coefficient-based approach (inertia coefficient C_m and drag coefficient C_D) for calculating fluid-induced forces (inertial forces, and drag forces, respectively). The choice of such coefficients is based on calibrating them to fit experimental data if available, otherwise recommended coefficients are used. In this study, the structural response and cable tensions of a semi-submersible platform were investigated by a coupled numerical model. Hydrodynamic examinations were performed by commercial software, ANSYS-AQWA. Experimental results done by DeepCwind consortium (Helder and Pietersma, 2013) were used for calibration and verification studies. Verification results showed that cable tensions range is lower than expected if calibrated using a regular wave case. Therefore, even with the existence of experimental data, the calibration of coefficients according to one case does not necessarily guarantee its veracity under different environmental conditions. Therefore a code was developed to calculate the hydrodynamic coefficients in flexible long catenary cables with special treatments under different situations. Flow characteristics change with depth. The upper part is usually wave-dominant region whilst the lower part is under current or current-like flows. Catenary lines resist motions through geometrical compliance resulting in high cable oscillation in the mid-line portion, leading to potential vortex-induced vibrations (VIV). When the vortex shedding frequency matches with one or more natural frequencies of the tensioned cable (lock-in), in-line and transverse response amplitudes develop enduring drag amplification at that portion. The code detects lock-in phenomenon through frequency-based (ensuring uni-modal lock-in), and reduced velocity-based calculations. Nonlocked-in regions contribute through structural and hydrodynamic damping to the exponential decay of the response creating transitional regions between locked-in and nonlocked-in portions. Cable interaction with the seabed is also considered. The code calculates temporally averaged, spatially variant drag coefficients along the cable, imported to the coupled model to calculate the tensions in the cable. Comparison results show that the agreement between the experimental and the model results is much better. The next step in the study is to model catenary mooring cables for the WECs using the developed code.

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Modeling of Wave Energy Converters Arrays using the Generalized Modes' Approach

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The deployment of Wave Energy Converters (WECs) arrays is considered essential towards the large-scale exploitation of the available wave energy. For assessing the hydrodynamic performance of WECs arrays (e.g. arrays of heaving WECs) in the frequency domain, numerical models based on the Boundary Element Method (BEM) can be deployed, which solve the relevant multi-body diffraction/radiation problem by including the hydrodynamic interactions among the WECs. For small-size arrays, BEM-based models provide accurate numerical solutions at a quite small computational time; however, this time increases rapidly when the number of WECs becomes large. For overcoming this drawback, suitable interaction theories can be utilized (e.g. [1]) or, alternatively, the generalized modes' approach introduced by [2] for the case of flexible floating bodies can be appropriately deployed.

In the present research, the latter approach is proposed for the BEM-based modeling of WECs arrays in the frequency domain. Initially, the diffraction problem is solved considering the whole array as a single body having spatially-distributed, hydrodynamically interacting elements (i.e. WECs). Then, the radiation problem is solved for an adequate number of appropriate generalized modes, which are introduced for physically representing each WEC's motion along its working direction. Reduction of computational time can be achieved by exploiting existing symmetries. The generalized modes' approach, already deployed for the case of a platform with multiple WECs [3], can be also utilized for hybrid systems that combine in one structure an offshore wind turbine with multiple WECs, in terms of calculating the required for the time-domain simulations exciting forces and frequency-dependent hydrodynamic coefficients.

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Numerical Modeling of Wave Energy Converter Systems by Smoothed Particle Hydrodynamics Method

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I have been working on the numerical modeling of free-surface hydrodynamics problems by a relatively young technique, namely, Smoothed Particle Hydrodynamics (SPH) method since the beginning of my PhD studies in 2008. I have developed an in-house, robust and accurate SPH-based code which can tackle challenging problems like dam-break, sloshing, open/closed channel flows around bluff bodies, water-entry of rigid-bodies, regular/irregular numerical wave generators and recently, numerical modeling of Wave-Energy Converter systems in 2D. Our CFD group is now working on simulating floating offshore oscillating water column systems (OWC) and Overtopping Wave Energy Converter (OWEC) by means of a Weakly Compressible SPH approach. The initial validation studies have been completed for both wave energy converter systems where the modeling of OWC system have been compared with the results of the recent study of Crespo et al. (2017) and the results of OWEC system simulations have been compared with the findings of Callach-Sanchez et al. (2018). Although assigning a relatively low particle resolutions in both test cases, our SPH code have compatible results up to ~5-6% discrepancy with the literature data. As these studies have been considered as preliminary researches on the modeling of WEC systems which aim to understand the pros and cons of the numerical modeling strategies, a low number of particles were employed to reduce the computational costs of the simulations. However, it can be said that the developed SPH code can generate quite promising results and increasing the resolution of domain discretization the accuracy of the results will be enhanced.

Along this line, I believe that our research group may contribute to the work group of the Cost Action (CA17105) entitled "A Pan-European Network for Marine Renewable Energy" given as WG1: "Numerical Hydrodynamic Modeling or WECs, WECs array/farms and wave energy resources". The details of the further possible collaborative studies can be discussed elaborately with the members of work group (WG1) if I can participate the Assembly which will be held on 28-29 November.

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Development of a Coastal Structure to Increase the Wave Energy Using Wave Reflection

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Although Europe is exposed to one of the most energetic sea areas on the planet, the eastern Atlantic, there are countries like Turkey, Greece, France Italy and Bulgaria which have coastlines along the closed sea basins of the Mediterranean, the Aegean and the Black Sea. The annual average power in those sea basins is estimated in the order of 5-10 KW/m (Clement et al.,2002, Akpinar and Komurcu, 2012, Ayat, 2013). Although Ozbahceci (2019) states that north-western coasts of Turkey in the Black Sea and south-western coasts of Turkey in the Mediterranean are the highest energetic coasts of Turkey, lower values of the estimated average power levels may discourage to deal with wave energy harvesting in those regions.

In this study, a new coastal structure is developed to concentrate and increase the wave energy using wave reflection, especially for the near-shore Wave Energy Converters (WEC). WECs deployed at the near-shore have many advantages of easier installation, maintenance etc. However, they would experience a much less powerful wave regime (Clement et al., 2002). Since the wave power is proportional to the square of the wave height, the main purpose of the current study is to increase the wave height using the developed coastal structure. Interactions between the waves and the developed structure are investigated by the numerical modeling using commercial software, ANSYS-AQWA. Not only the effect of structure dimensions like the length and diameter, but also the wave period, wave direction and water depth on the amplitude in front of the structure are investigated. Numerical model results show that it is possible to increase the wave amplitude up to five times. In the numerical model, regular waves are used and the water depth is constant.

In the second stage, it is planned to conduct 3-D hydraulic model experiments in the wave basin of Research Institute of Turkish Ministry of Transport. There is a multi-directional wave generator in the basin. The developed structure will be modeled with both constant water depth and varying bathymetry under irregular perpendicular and oblique wave attack ($\pm$45 degrees) and results will be compared with the numerical model. For varying bathymetry, ANSYS CFD and SWASH numerical tools will be used.

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Comparative study of the hydrodynamics of a heaving WEC using linear and non-linear wave theory

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This abstract refers to PhD research on numerical modelling of Wave Energy Converters (WECs). DualSPHysics [1], a numerical program that applies the Smoothed Particle Hydrodynamics (SPH), is employed in this research. SPH is a non-linear Lagrangian meshless method used in an expanding range of applications within the field of Computational Fluid Dynamics (CFD).

The defining characteristic of a WEC, distinguishing it from a simple floating body, is the power take-off (PTO) system. Within this PhD research DualSPHysics is employed for the modelling of a heaving WEC and results of the WEC's motion are compared to the results from WEC-Sim [2], which is based on linear wave theory and allows the modelling of a PTO system. In order to model such a PTO system in DualSPHysics, the coupling with Project Chrono is used [3]. Therefore the performed work fits in 'Working Group 1: Numerical hydrodynamic modelling of WECs' and more specifically refers to the topic of coupling between codes for WEC simulation.

It is possible to add a drag coefficient in linear models in order to get a better estimate of the WEC's motion. In this research it was studied how this drag coefficient can be estimated by using DualSPHysics. The results of the drag coefficient will then be compared with results that have been obtained from previous research with Computational Fluid Dynamics. The overall objective is to analyze the non-linearities that play an important role in the numerical modelling of WECs, especially when subjected to more extreme wave conditions.

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Reducing uncertainties on the long term power production of WECs

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Within the wide variety of marine renewable energy resources, wave energy appears as a promising, virtually untapped, alternative, with a lot of sites around the world with the potential of being exploited. On the other hand, there are some issues that must be addressed in detail so that wave energy becomes a fully-fledged renewable energy resource. Among them, the level of uncertainty in terms of long-term power production of Wave Energy Converters (WECs) stands out, which has been carried out primarily by the combination of resource and power matrices of WECs. In the field of wave resource characterisation, the International Electrotechnical Commission (IEC) has recently put forward a series of recommendations to develop a uniform methodology with the aim of ensuring consistency and accuracy in the wave resource characterisation: "IEC-62600-101 Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterisation". Overall, the IEC-62600-101 has proven to be a robust and coherent methodology, mainly intended for project and device developers, policy-makers and investors, which offers a set of recommendations related to the measurement, modelling, analysis and reporting of the wave energy resource, and the linkages between these activities.

However, and to the best knowledge of the authors, when estimating the long-term production of WECs no alternative standard to the power matrix method has been proposed, despite previous research has found that this methodology may produce results with levels of uncertainty close to 40%. In general, those uncertainties are related with the assumption of parametrical spectral shapes to compute the wave parameters ($H_{m0,}$ T_p) that define the energy bins of wave resource power matrices. This fact appears to be significantly relevant for WECs with limited band frequency response (heaving bodies). Against the foregoing backdrop, this work aims to explore different alternatives to reduce uncertainties such as (i) construct power matrices assuming real spectrum shapes, (ii) consider resource power matrices for the spectrum peaks of fetch and wind sea, respectively and (iii) assess the effects of wave directionality in power production of WECs.

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Classification of wave energy resources for the Atlantic coast of the Iberian Peninsula over the 21st century

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Wave energy arises as a potential renewable energy source, especially due to its higher density and predictability when compared with solar and wind energy. However, little is known on the impact of climate change on wave energy at regional scales. Thus, the use of this resource remains rather limited for the future exploitation. It is essential to take into account the climatic variability to predict the future energy since the resource is quite vulnerable to changes in the wind forcing. Our research aims to classify future wave energy resources for the Atlantic coast of the Iberian Peninsula under the RCP4.5 and RCP8.5 greenhouse gas emission scenarios.

The starting point are the coarse ($1^o \times 1^o$) WAVEWATCH III simulations driven by historical and future wind data obtained within the context of the CMIP5 project. In a first step, data provided by WW3 forced with eight different models during the historical period are compared with data provided by WW3 forced with reanalysis data from NCEP Climate Forecast System Reanalysis (CFSR). This first step allows assessing the skill of the different wind models to reproduce historical data.

In a second step, a dynamical downscaling based on the best models identified in the previous step is carried out by means of the SWAN model. This approach provides a much finer resolution ($0.03^o \times 0.03^o$) for the Atlantic coast of the Iberian Peninsula, covering a surface around 1500 km long and 50 km wide.

Finally, the best emplacements for future wave energy development are then identified by means of seven indices, whose weights were established following a Delphi method [1]. Five indices are directly related to the energy resource (mean wave power energy, temporal and monthly variability, downtime and risk) and two related to installation and maintenance costs (water depth and distance to coast).

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Hydrodynamic wave energy converter models for model-based control design should be validated for control-active scenarios

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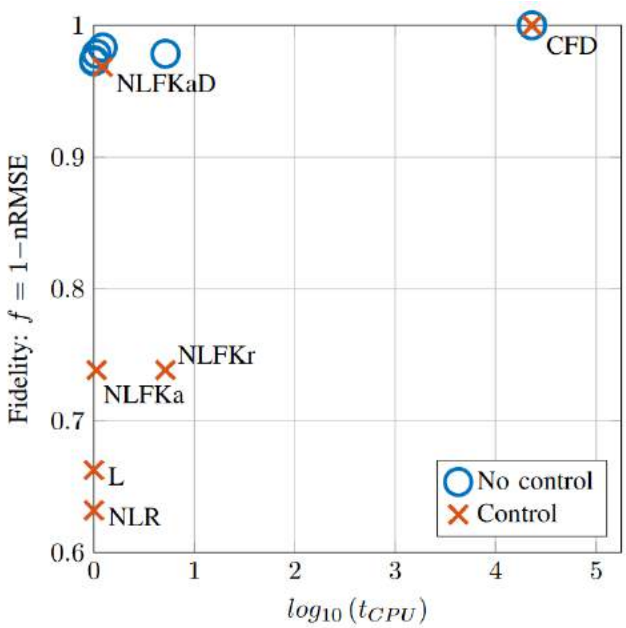
In the bulk of the published literature, the trend is to develop a hydrodynamic model for a wave energy converter (WEC) based purely on wave excitation, with the result that the device is likely to behave predominantly as a wave follower, with relatively low levels of variation in the wetted surface and relative fluid/device velocity. The possible exception to this passive behavior may occur when (typically point absorber) devices are at resonance. Nevertheless, the regime of relatively low levels of variation in the wetted surface and relative fluid/device velocity is convenient, since it accords with many of the assumption of linear hydrodynamic modelling and, unsurprisingly, many hydrodynamic math models validate well under such circumstances.



This is verified, in the accompanying figure, in relation to the 'No control' entries, where the model validation (for a variety of models, see [1] for key) is performed under wave excitation only. However, when control is applied (the red crosses), the vast majority of the models fall away in fidelity.

The impact of this issue may not be major in some applications, or for some device types (which are not strong resonators), but where such models are used to design model-based energy maximizing controllers, there is likely to be a significant mismatch between the model used to derive the control, and they dynamics that the device exhibits under that control.

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Wave Energy assessment in Madeira archipelago

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The present work has the aim to evaluate the wave power resource in Madeira archipelago. For this purpose, a wave prediction system using the SWAN (Simulating WAves Nearshore) model was tested and validated for 1-year (2015).

As input, the SWAN model used the bathymetry from GEBCO (General Bathymetric Chart of the Ocean), interpolated for 0.02°×0.02°, the boundary conditions from WWIII spectral output points, provided by Ifremer, with a temporal resolution of 3h and wind fields from Era5, provided from ECMWF (European Centre for Medium-Range Weather Forecasts), with 0.25°×0.25° of spatial resolution and 6h of temporal resolution.

The results were validated against Ifremer satellite data, using a Matlab toolbox named ALTWAVE (Appendini et al. 2016), that match the data between the model and the satellite in temporal (a limit of 1h:30m) and spatial dimension (a limit of 0.25°). As a result, a five column matrix with latitude, longitude, time, Hs of satellite and Hs of the model was achieved. The statistic parameters RMSE (Root Mean Square Error), Bias, SI (Scatter Index) and r (correlation coefficient) were afterward calculated showing a good agreement between measurements and simulation.

The conclusion was that the local with the highest wave power resource in Madeira archipelago is Porto Santo, with an increase of values up to 35-45kW/m at its north.

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Reproducing significant wave events in experimental facilities and coupled numerical models for multiphysic challenges in FSi.

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The usual method of assessing wave loads on structures is by collecting load statistics in experiments or (more rarely) in coupled 'fast(er) solver' - CFD model calculations employing long random wave sequences. However, these approaches are often prohibitively expensive, and time / CPU demanding. Significant savings and more reliable results can be achieved if a set of representative waves in a stochastic test sequence could be reproduced in a deterministic way. The current work, describes a methodology of producing inputs for experimental or numerical wavemakers to accurately reproduce such representative waves. Two newly developed numerical flumes are also presented.

The new methodology is presented through the example of a real-life application concerning the design of an offshore gravity-based structure. It is emphasised, that the proposed methodology differs considerably from any 'brute-force' approach applied previously, and it can be used to generate, i.e., *. particular sequences from long-term random records of real, *. different versions of a particular realisation of a random wave train, and *. wave sequences of different steepness but with identical other parameters.

In the numerical domain, two-dimensional Lagrangian (structure free) simulations are conducted to obtain fully non-linear free surface elevation and wave kinematics. One-way coupling is performed between the Lagrangian solver and either the OpenFOAM based olaFlow CFD model, or a new Eulerian fluid-structure-interaction solver, which operates without sorting for structure solver and passing the interface jump condition. This way, the use of only the fluid solver (instead of the fluid + the FSI solver) is enabled thereby accelerating the development of efficient models for the complicated multi-phase problems including, e.g., articulated structures. The current work is relevant to WG1 (topics 3 to 5) and to WG2 (topic 2,3 and 5).

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Generation of homogeneous wave field in a numerical basin for modelling WEC (array and farm) interactions and far field effects

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One of the challenges in the field of renewable wave energy is to determine the optimal geometrical layout for wave energy converter (WEC) arrays or farms, targeting the maximum energy production and the correct assessment of the impact of WEC arrays or farms on the surrounding wave field. For this purpose, accurate and detailed numerical modelling of WEC arrays and farms under realistic 3D wave conditions is considered crucial, which is a topic addressed by "Working Group1" of the WECANet COST Action CA17105. This kind of application requires a homogeneous wave field in the entire numerical domain and thus two new wave generation techniques have been developed and implemented in two different phase resolving numerical models at Ghent University, Belgium.

Traditionally, in time-domain models oblique waves are generated along two intersecting L-shaped wave generation lines. In our study, a wave generation layout using periodic lateral boundaries has been developed (Vasarmidis et al., 2019a) in a time dependent mild-slope wave propagation model, MILDwave (Troch and Stratigaki, 2016), in order to accurately generate regular and irregular waves in any direction. With this technique, the information leaving one end of the numerical domain enters the opposite end and thus no lateral wave absorbing sponges are required. In this way, the wave diffraction patterns that appear inside the numerical domain as a result of the intersection of the two wave generation lines and due to the interaction with the lateral sponge layers are avoided. This technique has been used by Verao Fernandez et al. (2019) to study WEC farms under short-crested waves.

In addition, a new internal wave generation method combined with wave absorbing sponge layers has been derived and applied in the non-hydrostatic model SWASH (Zijlema et al., 2011), in order to generate waves in a more accurate way and avoid re-reflections at the boundaries. With this technique, a spatially distributed source term in the form of mass is added to the continuity equation. This source term is a function of a velocity that is called the energy velocity and for the system of SWASH equations has been mathematically derived by Vasarmidis et al. (2019b). The numerical results of water surface elevations, orbital velocities, frequency spectra and wave heights, showed a very good agreement with the analytical solution and the experimental data. This indicates that SWASH with the addition of the proposed internal wave generation technique can be used to study WEC farms even under highly dispersive and directional waves without any spurious reflection from the wave generator.

Both above mentioned techniques are employed at Ghent University and are proposed here for studying WEC (array or farm) effects.

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High-Fidelity Modelling of Wave Energy Converters

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Wave Energy converters (WEC) are often analyzed via potential-flow or empirical-based tools. This is due to gained experience and trust on these type of tools in the past, to the generally lower influence of viscosity in wave-related phenomena and their low computational cost. Nowadays, with the democratization of viscous-flow tools (CFD, or Computational Fluid Dynamic), and HPC (High-Performance Computing) hardware, almost all fields of Maritime problems are seeing an increased use of these higher-fidelity tools. This is true for ships, underwater vehicles, offshore platforms, fixed and floating-wind turbines and several other ocean engineering systems [1,2]. For WECs the use of high-fidelity CFD has been less widespread. At WaVEC-Offshore Renewables Institute, due to our CFD development and application background with community-based open-source multi-phase code ReFRESCO (www.refresco.org) we would like to promote the use of CFD to analyze WECs. And this, in a cooperative environment where different tools could be used, different numerical approaches tested and at the end knowledge gained, published and made open-source available to the community. Therefore, we would like to propose a task within *WEC-"Working Group 1: Numerical hydrodynamic modelling for WECs, WEC arrays/farms and wave energy resources"* dealing with high-fidelity CFD and tackling the following aspects, by order of complexity: 1) Analyzing three different types of WEC and characterize their hydro and aerodynamic behavior, including the quantification of Reynolds scale-effects; 2) Perform couplings between CFD, advanced mooring and PTO modelling tools, which allow to characterize the complete behaviour of the structure; 3) Analyze the devices at extreme conditions and analyze their survivability; 4) Perform elastic deformation Fluid-Structure-Interaction analysis of WEC; 5) For one WEC device, study farm interaction. This implies many calculations, years of work, coordination efforts and large computational resources, which we are willing to apply for within Portuguese and EU organizations. Lastly, in order to increase CFD credibility as engineering tool for WECs, modern Verification and Validation [3] procedures should be considered. This allows to quantify numerical and modelling errors (whenever experiments are available) and identify uncertainties, which can lead to lower safety margins and therefore lower LCOE.

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OpenFOAM Numerical Simulation of the Performance of the Oscillating Water Column Model WEC of the OES TASK 10 (Ocean Energy System – International Energy Agency)

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Oscillating Water Column (OWC) wave energy converters (WECs) have received considerable attention in the field of wave power generation due to their rather high reliability and simplicity. The performance of an OWC WEC is usually investigated by laboratory-scale experiments and field tests, but also, more and more by numerical simulation tools. However, there exist problems regarding the fidelity of these numerical tools, for example, whether the numerical models are accurate enough to reflect the nonlinear phenomena, and whether they can well handle sub-systems such as the Power-take-off (PTO) or the mooring systems. Therefore, it is important to carry out the validation and verification of the numerical models applied for OWC WEC simulation. Ocean Energy Systems (OES) is an Energy Technology Network program under the International Energy Agency (IEA). One of the tasks (Task 10) focuses on numerical modelling of wave energy systems, specifically, an OWC WEC, and investigates the issue of verification and validation of its numerical modelling. Different numerical models, including those based on potential flow theory, viscous flow theory, linear and nonlinear models are be used within the OES Task 10. The results of these numerical models will be compared to discuss the fidelity level of each model.

Within the scope of the OES TASK 10, this abstract proposes to apply nonlinear numerical modelling based on the CFD package, OpenFOAM, in the simulation of the hydrodynamics and aerodynamics of the OWC WEC. The “olaFlow” toolbox will be employed for generating the waves and solving the multi-phase flow. The results will be compared with experimental data obtained from the Korean Research Institute of Ships and Ocean Engineering (KRISO) [1]. This work will contribute to the WECANet Working Group 1.

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Optimised design of wave energy devices for multi-use marine areas and mild sea conditions

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Wave energy installations are still far from being economically feasible, due to a number of challenges: i) low power conversion rates; ii) need to produce in ordinary states but to stand extremes; iii) need to harvest energy in deeper seas, facing the need of a) moorings, whose design is still not reliable enough and of b) energy transfer to shore with high energy losses due to immature conversion technologies and sharing with other economic activities in situ; iv) insufficient practice of device scaling depending on the climate of the installation area. UNIBO research on wave energy would like to address these challenges, by specifically contributing to these 2 following main issues, by means of a combination of prototype data assessment, new experimental activity and numerical modelling with upgraded tools.

1. Investigation of the synergies of installation and operation of wave energy devices in arrays and/or in multi-use marine areas (Working Group 1).

   - Experience gained with case studies of wave energy devices installed at O&G platforms for the purpose of creating a multi-use areas in the national project PLACE "Conversion of off-shore platforms for multiple eco-sustainable uses". The data shared may allow for assessing the weak and strong points of mooring design, the challenges of local use of the power production for other economic activities and the advantages of sharing infrastructures.
   - Numerical modelling of floating bodies installed close to existing platforms with OpenFOAM, by developing appropriate coupled procedures accounting for the effects of the PTO and of the moorings, which are essential for appropriate assessment of the power production and of the space requirements.

2. Innovative wave energy converters for power production also in mild states, including innovative systems for energy conversion and best practices for mooring design (Working Groups 2, 3).

   - Development of an innovative system for energy conversion based on membranes, to be tested in the new UNIBO wave tank in combination with a new floating wave energy converter concept. The aim is to develop and test at small and large scale a low-inertia device, suited to mild seas, with high time-response to waves and high energy conversion efficiency.
   - Optimisation of the mooring design, by the analysis of case studies with the upgraded OpenFOAM model and of the experimental activity on the new WEC.

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Abstracts for Working Group 2:

Experimental hydrodynamic modelling and testing of WECs, WEC arrays/farms, PTO systems, and field data

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Mooring Systems:

design, cost and monitoring

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When the mooring system of a Wave Energy converter is taken into consideration, it is often considered as a secondary element, auxiliary to the prime mover and the PTO system.

But for a significant number of failures on offshore installations the culprit was the mooring system. If only one or two decades ago, the majority of the work on mooring design was taken from oil and gas sector, in recent years it become clearer that the similarities between the two sectors were smaller than foreseen.

Nevertheless, due to the unrealistically given marginal role mooring systems have still a long way to go. Among the others the following areas are of particular impact:

1) Design
2) Monitoring
3) Cost

First of all, in this context the term mooring system includes all the elements from the connection at the device to the connection at the sea bottom, comprehensive of the anchor, piles or similar.

The three main point of discussion are expanded below for clarity.

1) The design of the mooring system as part of the machine system is still questionable: although numerical models to estimate the mooring line behaviour are readily available now a days, their coupling with numerical models are not. There are examples of good matching with experimental data, but those are a result of a lengthy tuning process, which mines the result validity if the conditions changes.
2) Monitoring is another fundamental point to take into consideration and push its development forward. Collect experimental results, at any scale, for a mooring system is not a trivial task, and it might be necessary to develop new techniques and instrumentation.
3) Cost the cost of the mooring system for wave energy is often underestimated. This is often not related to the material cost, which is a small percentage of the project capital cost, but mostly associated with the installation and maintenance costs. Looking in the literature over the subject there is a huge variability on the definition of the mooring system for wave energy converters.

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The LABIMA's proposal for a "Round-Robin" testing program under the WECanet Network

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As highlighted in the WECanet proposal, in order to support the further development of the numerical tools used for wave energy projects there is an acute need for experimental data that can be used for their validation and thus for the assessment of the related uncertainties. Often, measurements taken in laboratory-scale models are used for validation. However, scale-distortion and laboratory-effects affect the quality of these laboratory-scale measurements.

In order to develop a reliable data base for validating numerical models there is not any other alternative then the deepening of the knowledge on scale and laboratory effects. A viable methodology for deepening our knowledge in that respect is the execution of the same test program in different laboratories where the same device is tested according to the same experimental procedure and different model-scales are used.

The aim of the present proposal is to initiate, during the WECanet meeting in Porto, the design of a Round-Robin testing program to be executed in a mid-term perspective, under a voluntary base, within the WECnet network.

The activities already conducted at LABIMA, the Laboratory of maritime Engineering of University of Florence, concerning experimental test in a fixed oscillating water column wave energy converter will constitute the basis for a further development of the experimental activities in the framework of the present proposal of a Round-Robin program.

The data base generated will be fully open for wide-scale adoption as standard benchmark which is currently hard to access freely. The outputs of this activity may also provide recommendations for further coordination of laboratories practices and procedures.

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Systematic errors in wave-tank experimental tests for wave energy converters

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There are two fundamentally different sources of error in wave-tank experimental results for wave energy converter, random errors and systematic errors, which result in uncertainty in the final output of any experimental campaign. The estimation of the random error can be relatively easily achieved by multiple runs and assessment of the variation of the results. There are relatively well-documented procedures for producing the uncertainty that arises for random errors. The estimation of systematic error is more problematic because there is no clear knowledge of the true result, against which the systematic error can be determined.

A potential method of assessing systematic errors is to use multiple campaigns where potential sources for systematic errors have been isolated. For example, if all tests on a wave energy converter are done in the same location in a wave tank then there is the potential for a systematic error in the results due to the presence of standing waves in the wave-tank. The following is an incomplete list of potential sources of systematic error that could exist

- Location in wave-tank
- Choice of wave-tank
- Characteristics of incident waves
- Selection of scaling laws
- Construction of bespoke models
- Bespoke instrumentation set-up

The challenge with this method is that it is likely to require significant investment to produce some estimates of the systematic errors.

It is understood that some benchmarking of the wave-tank testing has been undertaken as part of the Marinet programme; however, if this has been undertaken it has not been widely reported. It is proposed that the current best-practice for wave-tank testing of wave energy converters is reviewed and the potential for investigating the magnitude of systematic errors investigated, where estimates can be produced with an acceptable degree of effort.

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Wave energy research in the new Coastal and Ocean Basin in Ostend, Belgium

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The new Coastal and Ocean Basin (COB) [1] is located at the Greenbridge Science Park in Ostend in Belgium (http://COB.ugent.be). The laboratory will provide a versatile facility that will make a wide range of physical modelling studies possible, including the ability to generate waves in combination with currents and wind at a wide range of model scales.

The facility is designed to serve research and industry needs in the fields of mainly offshore renewable energy and coastal engineering. The wave basin will have state-of-the-art generating and absorbing wave generators, a current generation system and a wind generator. The aim is to generate waves and currents in the same, opposite and oblique directions. The wave basin will be fully operational in 2020.

In the field of renewable energies we aim at a detailed understanding of the optimal geometrical lay-outs of wave energy converter (WEC) arrays and farms under realistic 3D wave-current conditions, as well as of the interactions between the WECs of the farms. This comprises the establishment of a generic dataset to validate the recently developed high precision numerical models ([2] - [4]) used to simulate WEC farm effects. This new dataset will be realised at the COB within the upcoming 'WECfarm' research project, designed to follow-up the completed 'WECwakes' project [5] - [6]. Furthermore, experimental research aiming at numerical model validation of wave slamming on complex floating objects such as (but not limited to) WECs, as well as on WEC mooring effects, is planned.

This research is situated in the topics of "Working Group 2: Experimental hydrodynamic modelling and testing of WECs, WEC arrays/farms, PTO systems, and field data" and "Working Group 1: Numerical hydrodynamic modelling for WECs, WEC arrays/farms and wave energy resources".

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The Influence of Scour Development Around the Suction-Bucket on the behavior of the foundation for Wave Energy Converters (WECs)

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Suction-Bucket presents a significant potential for the foundation of wave energy converters (WECs). Both mooring systems for deep waters and fixed bottom systems for shallow waters can be supported with suction bucket foundation for the designing of WECs. The bucket structure consists of a steel cylinder with a large diameter D, skirt length L and skirt thickness ts, closed by a generally heavily stiffened upper steel lid. The studies on the scour development around the bucket structure and the effect of scouring on the behavior of the bucket foundation system especially for WECs are very limited.

In marine environment, the shear stress caused by the flowing water due to the abrasion of the soil surface by passing current, wave, and flood may exceed the threshold of the critical shear stress of the sediment or erosion resistance of the soil around the foundation of marine structures. When this happens, the soil particles around the offshore can be removed and scour can be developing at the upper soil surface around the foundation. The scour will lead to complete loss of lateral and axial resistance down to the depth of scour below the original seabed. The studies on the scour development are generally concentrated on the scouring around the single pile especially for offshore wind farms. However, the diameter of the suction bucket foundations is quite larger than the monopiles. It is stated in the guide DNV-OS-J101 [1] that the extent of a scour hole will depend not only on the properties of the soil but also on the dimensions of the offshore structure. However, the investigations on the scour development of such large foundation systems are scarce [2]. There are also few studies on the behavior of the soil-bucket interaction as a foundation of WEC [3]. Moreover, the effect of scour development on the response of the bucket foundation for WECs has not been adequately studied yet.

Consequently, the implementation of experimental and numerical studies is required to understand the scour development and WEC-seabed-foundation interaction of suction-bucket.

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Experimental simulation of oil-hydraulic Power Take-Off systems for Wave Energy Converters

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The Centre for Marine Technology and Ocean Engineering (CENTEC) has been dedicated to the development of a generic oil-hydraulic power take off (PTO) for wave energy converters (WECs). More recently, CENTEC has been award funding for the design, construction and testing of a Hardware In the Loop (HIL) simulation test rig, by our Portuguese national funding agency for science, research and technology (FCT).

The short-term objective for this research is to physically test PTO critical components, such as the motor-generator drive, and the numerical models of different WECs. The medium-term objective is to expand the test rig to include more oil-hydraulic components and the long term one is to achieve higher technology readiness levels (TRLs).

However, the Centre doesn't have experience on performing these tests, despite having some experience on a different technology, the electrical PTO at Tecnalia. Moreover, if our researchers are going to work on a real oil-hydraulic test rig they must know how to do it safely.

The participation in the WECANet symposium in the working group 2 and topic dedicated to "wave emulators to perform dry tests for PTO systems" may provide the opportunity to find support from experts on the field of HIL simulation, access to their facilities and staff, and to learn with them how to perform the testing safely. On the other hand, the Centre may provide testing services to entities with activities in the offshore renewable energies, either in person or remotely with the help of information and communication technologies. Thus, contributing for the building up of more competences, knowledge and qualified personnel on WEC and PTO HIL testing, and more opportunities for capturing more and better funding for the WECANEt.

I'm also available to participate in WG3 because I'm involved in research dedicated to WEC arrays.

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Power-Take-Off Damping Scaling Recommendations

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Reproducing the effect of the power-take-off (PTO) system at laboratory scale is a difficult task. In general, in early-stages of wave energy research it is common to reproduce the PTO in a simplified and sometimes inaccurate way. However, since the effect of the PTO often influences the outcome of experimental tests, frequently, results obtained are far from reality and in most cases difficult to interpret. From one side, the dynamic response of the device studied may not be representative of its full-scale counterpart and, most importantly, the power absorbed by the device is often either underestimated or overestimated by a large extent. This issue exists because the power, following the Froude laws, scales with $S^{3.5}$, determining every little uncertainty to be largely amplified when the results are scaled to the target full-scale. In general, the PTO is monitored by a set of sensors and the absorbed power assessed indirectly. In this circumstance, uncertainties from multiple sensors have to be combined and the global uncertainty related to the power estimation further amplifies. Normally, the major causes of errors and large uncertainty are the mechanical friction losses, inappropriate calibration and superficial estimation of measurements errors.

This work aims at inciting a discussion on which procedures can be followed to limit and well quantify the uncertainties related to model-scale PTO damping. The major actions that can be undertaken for scaling and assess PTO damping in a reliable way are of three types. The first type of actions regard collecting series of recommendation on how practically construct miniaturized PTO systems. A series of measures can, in fact, be implemented for reducing mechanical friction within miniaturized PTO systems, which in general are not well known. The second set of actions relate to essential calibration procedures needed at the beginning of experimental tests. In fact, it is essential to well calibrate and characterize the PTO damping with early calibration tests, usually dry tests, before moving to the actual tests in water. In published studies, often initial calibration tests are little reported and, in particular cases, totally skipped. A set of fundamental requirements, regarding initial calibration tests should be listed and publicized. The third type of action regards quantification of uncertainties following recognised guidelines. In particular, in what concern the PTO force and damping values, very limited literature exists on assessing uncertainties related to empirical related measured quantities. For all type of actions proposed it is required at first an extended literature review that summarise recent development on the topic. It is advised that particular focus should be made on recent technologies and methods.

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Numerical Modelling and Tank Testing of Wave Energy Converters for Hybrid Wind-Wave Platforms

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After the signing of treaties such as the Kyoto Protocol and the Paris Agreement, the concern of governments and organizations on behalf of the environment had definitely increased. In the Ocean Engineering field, this concern may be translated to an increase on Research & Development devoted to Offshore Renewable Energies (wind, waves, tidal).

The most mature sector of those is definitely the wind technology, whereas fixed structures for wind energy offshore already constitute considerable parcel of the installed power capacity in Denmark, Germany and UK. In regards to Wave Energy Converters (WECs), some prototypes had already been deployed, and in many configurations, such as wave flaps, overtopping devices, attenuators, etc.; however, the associated Levelized Cost of Energy is too high and their normal operation is affected by the lack of personnel able to perform the rather expensive maintenance. In the theoretical sphere, technology for WECs still present modelling gaps, whereas the response of such devices is highly non-linear in nature.

Thus, some authors have been investigating the use of hybrid wind-wave platforms. Due to the technology gap, WECs are employed to FOWT structures, the main hull being only slightly modified. This approach leads to the global decrease on capital and operational expenditures. In this particular article, point-absorber WECs are employed around a semi-submersible FOWT in concentric configuration. The stability and dynamic behavior of the platform are evaluated both numerically and experimentally. The same is performed for a possible configuration of hybrid concept, with different PTO parameters, which affect the dynamics of the system and are ultimately responsible for wave energy conversion.

Then, a non-linear frequency domain numerical model which is under development will be presented. It will correctly evaluate the RAOs of the hybrid concept, as well as stability parameters, energy efficiencies, and so on. Because the hybrid system is very complex in nature: it possesses many degrees-of-freedom, non-linear geometric constraints, non-linear viscous damping and relevant higher-order effects; the numerical model will encompass all these phenomena. PTOs are included to the model as linear mass-spring-dampers, and are identified as potentially effective on passively controlling the system, for, if optimized, they may reduce the motions and accelerations of the platform, as well as enhance its stability.

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On the duration of test time series for stable and reliable performance indicators derived from experimental testing of WECs

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The subject of this abstract relates to Working Group 2 *Experimental hydrodynamic modelling and testing of WECs, WEC arrays/farms, PTO systems, and field data* under the topic *Experimental model set-up and field device instrumentation: problem identification and guidelines collection and assessment of their effectiveness*.

In IEC TS 62600-103 (2018) guidelines are given with regard to how long individual time series should be used to achieve satisfactory accuracy and reliability of key performance indicators. In here, minimum requirements are naturally dependent on the specific area addressed, i.e. when testing for power performance characterization in irregular long crested waves, minimum duration of 250 waves are prescribed, while for short crested waves the minimum duration is set to 1500 waves. The assessment of power performance are of relevance in operational conditions and here the main interest is at average performance parameters. When addressing survival condtions the key performance indicators if interest are more the extreme value of e.g. motions or forces. This is also reflected in the minimum requirement for duration of tests in these conditions, which are set to 3h storm duration (assumingly in full scale), which typically will translate into approx. 1.000 waves.

While these recommendations seems reasonable, it would be very useful to investigate which levels of variation the set durations gives rise to, for the various KPIs of interest (average power, peak forces etc.), and how this depends on the types of WECs, PTOs, measuring equipment etc.

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Perspective for future activities of Ship Design and Research Centre CTO S.A. in Working Group 2

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As the harvesting of wave energy in Polish area of Baltic Sea is at very early stage of development, not much work is also realized in the field of laboratory scale model testing. The intention of CTO is the to recognize global trends in this area, gain basic knowledge in hydrodynamic testing of wave energy converters and possibly contribute to the development of best practices in model testing of WECs.

Ship Design and Research Centre CTO S.A. is primarily interested in the development of methodology for laboratory scale tests of single WEC devices, as this type of tests are feasible for its Offshore Laboratory. The lab is equipped with a longitudinal tank and the wave making device consisting of paddle-type wavemaker and active damper of the same construction, allowing for generating high quality representations of the wave spectra in wide range of significant height and modal period. This facility is then well suited for benchmark studies of WECs; its applicability for tests of arrays is rather strongly limited. It is also intended to participate in comparison of the performance of different types of facilities, so as to contribute to the review and classification of the facilities employed for WEC testing. Another point of interest is the participation in the development of the approach to WEC optimization based on combined numerical and experimental studies.

CTO's facilities might be also used for cooperative research in specific marine renewable energy topics in various schemes, e.g. next frame programme HORIZON EUROPE, initiatives like MaRINET2, HYDRALAB+ or in ERA-NETs projects.

CTO also intends to contribute to the organisation of a 3-day Training School in year 2021 at the premises of all three Polish organisations taking part in the WG2. The purpose of the mission besides lectures given by industry and academia will be to bring PhD researchers and Early Carrier Investigators whose institutions lack research facilities together and to show hydrodynamic investigation capabilities of three different types of research infrastructures in Poland.

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Hydrodynamic coupling on Gyroscopic-Pendulum device for Wave Energy Converter

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The Delft University of Technology is developing a new concept of Wave Energy Converter (WEC) inside a floating module called the "Gyroscopic-Pendulum (GP)". This concept is a modification of Vertical Axis Pendulum (VAP) by installing a spinning disk at the center rotation of the pendulum. Similar to the VAP, the GP has a free rotating pendulum around the vertical axis of the floater. The electricity is converted using a generator which is connected directly to the pendulum shaft. In addition, the GP device has a controlled flywheel (the spinning disk) that can generate a gyroscopic effect on the pendulum rotation. The rotation axis of the flywheel is parallel with the pendulum axis. Based on the preliminary study, the gyroscopic effect on the GP device can have a positive impact that allows enhancing the average produced power compared to the VAP [1].

In the current stage, the numerical model of the GP device is completed. An 8 Degree-of-Freedom (DoF) model of the GP device was developed which comprises of 6 DoF belong to the floater and 2 DoF belong to the pendulum and disk rotations. The first test setup of the 4 DoF simplified model has been done numerically to evaluate the gyroscopic effect on the pendulum rotation. In the next stage, the implementation of the hydrodynamic coupling in the GP model is planned. The floater shape is decided in this stage to describe hydrodynamic forces due to wave interactions on the floater. In line with the topic of WG 2, an integrated model in the time domain between the device and hydrodynamic models will be developed. During implementation, justifications could be made in order to create a reasonable coupling model such as considering only unidirectional waves acting on a regular finite surface area of the floater. Finally, the coupling GP model which has 6 DoF (i.e. heave, surge, pitch, roll, pendulum and disk rotation motions) will be assessed.

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Emulation of Wave Energy Converter (WEC) in Real-time Simulation: Power Hardware-in-the-loop Simulation

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The focus on renewable energy has gained much attention in wind, solar, hydro and wave power generations. Wave power has great potential due to its high energy density but there are challenges as well. Wave energy which can be harvested through Wave Energy Converter (WECs) Arrays could present their significant impact due to the voltage variation at connection point to the grid/microgrid. Therefore, It is crucial to investigate these impacts to be grid compliant in terms of voltage variations and induced flicker severity at the connection point.

The choice of power system simulators (PSS) is gaining interest due to their capability of assessing the grid impact of WEPs at a lower cost to than testing in real operating parks. The PSS reduce potential threats to the grid stability and the requirement of performing various tests on the real power network. The hardware-in-the-loop (HIL) system is the most common setup due to its flexible implementation, usually combines a physical controller and a virtual plant, executed in real-time (RT) computer simulations. RT simulations within the HIL allow the testers early on to determine the design issues and the impact of the virtual plants in faulty and extreme condition.

The developed hydrodynamic model is integrated with a PHIL system to emulate a real WEC's behaviour. The range of the torque applied, through a conversion of the output parameter from the hydrodynamic model, was 500-2300 rpm. The WEC emulator is interfaced with the microgrid using controlled power converters. The grid short-circuit ratio (SCR) and impedance angle is considered to be a grid compliant at the connection point. Moreover, a fictitious grid study is carried out for different grid impedance angles and different SCR. The WECs are placed in a park in different orientations and studied with their grid impacts at the connection point of the grid. The study investigated the voltage variations and induced flickers and distortion at the connection point in different layouts of the park. The study also investigated the impacts while using the energy storage and presented the grid compliant level in each case.

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CORES / BDCA perspective on the "Experimental model set-up and field device instrumentation: problem identification and guidelines collection and assessment of their effectiveness"

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On the status and problems of WECs experimental model set-up and field device instrumentation

We need experimental hydrodynamic testing in order to (1) validate advanced numerical tools, (2) study something we can't prove on the computer, but on a large scale physical model (e.g. 1:10 or more), and (3) support full-scale validation and monitoring of WECs in working conditions at sea. It can be argued that the modern development of experimental equipment and measuring techniques in experimental basins (offshore, ship hydrodynamics, etc.) is quite sufficient to serve for the study of WECs/WEC farms. This is true in general for the common classical studies (e.g. wave disturbance by the WEC array, wave pressure on the hull, etc.). However, this is not the case with the emerging unconventional types of studies, e.g. modeling of elasticity of mooring lines (Tomasicchio et al., 2014); modeling low pressure valves (Cappietti et al. 2018), etc., where novel approaches are needed. It concerns even more the studies on assessment of the environmental impacts of WECs. There is an acute need of improvement of both laboratory and field instrumentation and methodologies for (A) testing unconventional structures, and (B) evaluating physical changes in the vicinity of WEC arrays: study the near-field risk of sediment mobility; study on impacts on water quality (due to oil/lubricant leakage, biofouling, etc); modeling underwater noise produced by wave energy devices (arrays), electromagnetic fields, and other.

Suggested activities to attack problems and contribute to WECANET WG2 objectives

BDCA have agreements for access to 2 hydraulic test basins (CNILHI-UACEG-Sofia, www.uaceg.bg, and BSHC-Varna (www.bshc.bg), and maintains long year cooperation with NHRI - one of the biggest China's Hydraulic Labs, within the Joint Research Center on Water Science and Engineering, https://jrc.nhri.cn/. CORES possess surface water drones (www.coresbg.eu) which can be re-invented for field observations at WECs arrays (water sampling, noise recording, underwater cameras, etc.). We can contribute to WECANET WG2 by: (1) Exchange of knowledge and experience within WECANET network, and beyond; (2) Hosting of STSMs in Varna, Bulgaria; (3) Organizing training events (*1st WECANET training course, Varna, February 2019*); (4) Participation/presentation at scientific events; (5) Dissemination of WECANECT achievements via web page, social media, and using other publicity tools.

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Polish perspective for hydrodynamic investigation and assessment of marine renewable energy devices with focus on WECs

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As mentioned in the WECANet action description, the marine renewable energy industry and especially wave energy industry is facing a number of challenges which still require research. Poland is unfortunately one of the non-leading countries in wave energy technology and this industry sector is just born. Therefore a lot of work has to be put both by researchers and policy makers to facilitate the growth of this marine renewable energy sector.

More and more work is carried out by Polish R&D institutions in the topic of marine renewable energy. However, there are still challenges both from technological, institutional and legal point of view, that have to faced. Polish parties involved in WG2 of WECANet have capabilities to perform investigations on the hydrodynamic performance and other issues related to marine renewable energy devices including WECs and tidal arrays. Ship Design and Research Centre S.A. owns an offshore lab, equipped with wave making device consisting of paddle-type wavemaker and active damper, allowing for generating high quality waves in wide range of significant height; the Foundation for Safety of Navigation and Environment Protection is in possession of current generator with the ability to produce low-depth water current up to 4 knots in a scale of up to 1:24; Institute of Hydro-Engineering owns wave flume, which is 64.1 m long, 0.6 m wide, and 1.4 m high. A modern data receiving system can work at frequency of sampling up to 300 000 Hz.

The mentioned facilities might be used for cooperative research in specific marine renewable energy topics in various schemes, e.g. next frame programme HORIZON EUROPE, initiatives like MaRINET2, HYDRALAB+ or in ERA-NETs projects.

The idea of Polish participant is to organise a 3-day Training School in year 2021 at the premises of all three Polish organisations taking part in the WG2. The purpose of the mission besides lectures given by industry and academia will be to bring PhD researchers and Early Carrier Investigators whose institutions lack research facilities together and to show hydrodynamic investigation capabilities of three different types of research infrastructures in Poland.

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Grid scale wave energy conversion through the multi-float multi-mode system M4

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Wave energy conversion has an important contribution to make to renewable supply with a global resource similar to wind. While wind turbines have capacities of 5-12 MW most wave energy converters (WECS) typically have capacities of up to 200 kW. This may be increased using multi-float systems where power from the modes associated with each float combine constructively to give capacities similar to offshore wind turbines. M4 is a modular system enabling this philosophy with up to 8 floats investigated to date. Modelling is key to developing complex systems and wave basin validation is essential. Linear diffraction-radiation modelling for this purpose will be outlined and results from the wave basins at Manchester, Plymouth and Cork with EPSRC and Marinet2 funding will be shown. Improvements in energy capture using control are clearly desirable and methods developed with Queen Mary University London will be outlined. Energy capture and approximate costings for various sites worldwide will be presented. Confidence in technology may only result from ocean tests and plans for ocean testing at half scale in Shenzhen, China will be outlined. Further questions associated with design will be addressed.

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Experimental testing and numerical modelling of WEC arrays

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This work refers to PhD research performed at Ghent University, Belgium, within the topic: "Experimental study and numerical modelling of combined near-field interactions and far-field effects of wave energy converter farms". Since the execution of the WECwakes experiments in 2013, which generated a large database to be used for numerical validation purposes, numerical models have progressively advanced [1] - [2]. As a result, a new experimental campaign within the WECfarm project has been initiated to obtain a database to validate these new advanced numerical models for WEC array modelling. The WECfarm experiments will be conducted at the Coastal and Ocean Basin (COB) [3] in Ostend in 2021, as part of the collaboration between Aalborg University, Denmark (Jens Peter Kofoed, Francesco Ferri), Queen's University Belfast, UK (Matt Folley) and The University of Edinburgh, UK (David Forehand). This part of the research is situated in the topics of "Working Group 2: Experimental hydrodynamic modelling and testing of WECs, WEC arrays/farms, PTO systems, and field data".

The SPH software DualSPHysics [4] is used for numerical modelling of the tested WEC arrays, in collaboration with the EPhysLab research group of The University of Vigo, Spain. Finally, a coupled DualSPHysics-OceanWave3D numerical wave basin will be established to model WEC arrays, where the wave propagation model Oceanwave3D will also be employed to model impact of WEC arrays on the surrounding wave field [5]. This part of the research is situated in the topics of "Working Group 1: Numerical hydrodynamic modelling for WECs, WEC arrays/farms and wave energy resources".

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Abstracts for Working Group 3:

Technology of WECs and WEC arrays

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Electrical infrastructure for wave power parks

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Wave power sector is moving from development and testing of a single device to multiple device demonstration. Different solutions exit to connect more than one device to the shore grid. It includes individual direct device connection, radial connection, connection of clusters of devices etc. [1] Though planning of electrical infrastructure for a single WEC is usually limited by deciding of the parameters of one power cable to shore and power cable connectors, the future planning of wave power parks shall be done at earlier stage in order to decide on the optimum installed capacity of each WEC, farm layout and configuration, interconnection between units in the WEC array. Development of a suitable electrical infrastructure when optimization of a WEC is done can increase CapEx and introduce unnecessary complexity to the system.

In the present study, exiting technologies of electrical infrastructure will be reviewed for WECs already that were built so far and tested offshore. The review will be extended to a study of wave power technologies. The study will present technical as well as economical aspects of marine energy electrical architecture. The study will relate different WEC technologies, their installed power capacity, existing technologies available off-shelf and potential need for other solutions. Information for tidal devices and offshore wind power parks will be employed in the study.

This work aligns with the priorities on optimization WECs and WEC arrays and electrical aspects of technology of WEC arrays and therefore fits into the WECANet COST Action and the Grant Period 2 framework.

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Survivability and design optimization of WECs addressing array effects and combined concepts

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Working group: 3 – Technology of WECs and WEC arrays
Working Group Topics: Survivability, design optimization, combined concepts.

Significant opportunities and benefits have been identified in the area of ocean wave energy due to extremely abundant and promising resource of alternative, renewable and clean energy in the world's ocean. Many different types of Wave Energy Converters (WECs) have been inspired and proposed by a great number of researchers and inventors and more than one thousand patents have been registered by 1980.

WECs are designed in order to operate in their resonance limits and in a big number of cyclic dynamic loading; survivability related problems are the basic reasons that after forty-five years WECs are unsuccessful industrialized. Today the technology of ocean wave energy cannot be considered mature enough for large-scale commercial deployment but WECs are in a reconsideration phase as far as design methods, tools and criteria in order to address survivability related issues and to propose efficient survival operating modes. Survivability should be defined and addressed clearly.

At the same time and in order the WEC technologies to recover the lost time, design optimum solutions in terms of cost efficiency and structural integrity efficiency should be targeted for both device level but also array level. Specific optimization methods and tools should be developed and applied for single- or multi- optimization design problems including many design variables and thresholds. The optimization methods should be capable for finding an optimum design within a specific WEC but also within a specific ocean area and an array level.

Commercial wind farms are occupying a large ocean space; it might be beneficial to combine WECs into co-located ocean energy farms or even into one platform. It is therefore of interest to investigate possible combined systems for simultaneous extraction of wind and wave energy to possibly reduce the overall cost as well as to ensure an efficient use of the ocean space. Survivability and design optimization of the combined systems present increasing complexity and require robust computational models and numerical analysis tools.

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The underwater wave energy converter (WEC)

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Working Group 3: Technology of WECs and WEC arrays - WEC design optimization

Power plants that gather wave energy have to be placed near cities and other populated areas. For this reason, the downsides of this technology are that it disturbs commercial and private vessels and may be a nuisance for people who live close (by generating noise pollution and devastating the natural landscape). In addition, surface structures may pose a collision threat to sea birds.

One solution to these potential technology flaws is to place the entire structure underwater. Thus, more consideration should be given to developing solutions enabling similar performance and operating completely underwater.

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A new atlas combining wave climate statistics with wave energy converter survival

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Long-term survivability of wave energy converters (WECs) is recognized as one of the main barriers to the progress of the wave energy sector (Magagna and Uihlein, 2015). To overcome this problem many efforts have been devoted to develop innovative designs and materials, improving the reliability and survivability of the technologies during storms or extreme conditions. On the other hand, several authors have conducted wave energy assessments, which provide both mean and extreme wave statistics useful to design and develop wave energy converters. An additional strategy to face this problem could be the construction of combined WEC-climate atlas, identifying WEC designs with the highest survivability at a given location and, conversely, the best site of deployment of a specific technology in terms of survivability. Similar atlas have already been developed from the perspective of wave electricity production (e.g .Bozzi et al. 2018). They provide the performance of a number of wave energy converters at many worldwide coastal areas and are of great value in determining deployment locations optimizing energy capture and conversion efficiency. Similar atlas could be also constructed from the perspective of WEC survivability. Depending on the principle of operation (pitching, heaving, etc..) each wave energy technology has a typical failure mode, due to either fatigue or extreme loads. For each WEC class a main survivability issue (e.g. power take of system, moorings system, power electronics gearbox) could be identified and then put in relation to wave climate statistics (e.g. mean wave height, wave height with a given return period, mean wave direction, wave steepness, etc..). The rationale is that for a given wave power potential the energy distribution among sea states would favor the survivability of a WEC design more than another. The final aim is to identify optimal deployment locations in terms of overall reliability of each class of WECs.

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Assessing Wave Energy Converters as Viable alternative renewable energy sources for Island States

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The pressure of climate change and the growing energy demand has increased interest in marine renewable energy resources, such as wave energy which can be harvested through Wave Energy Converter (WECs) Arrays.

Following the launch of this WECANET programme, we need to move to the investigative phase to understand where we are. Wave energy, though in abundance, has not been tapped into yet as much as wind and solar. Attempts have been made but small and far between.

Of course, with the advent of the much improved, tried and tested solar, as well as the onshore and offshore success of wind energy, the focus has not been strong on Wave energy converters, even because of the complexities this brings.

Still, Island states like the Maltese Islands, that are densely populated, with limited roofspace and land for solar, as well as difficulty in installing large scale wind farms because of the heavy visual impact this will have on the islands, Wave Energy converters for an Island state will make lots of sense, especially if the technology used is shore tied.

With this in mind, it is therefore important to look into the technology currently deployed worldwide, with data of success and failures, and investigate first where we should pt our focus whether on shore tied or completely offshore. This can be looked at from a technology perspective, from an ease of grid connection perspective, as well as from a price per watt respective.

In this way this can be applicable to all working groups, but mostly WG2, WG3 and WG4, therefore also fulfilling WECANet's main target of equal research, collaboration and funding opportunities for all researchers and professionals, regardless of age, gender and location.

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Development of an oil-hydraulic power take-off system for a oscillating wave surge converter

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Working Group 3 – WEC design optimization

This study presents the performance of a Wave Energy Converter (WEC) attached to a generic oil-hydraulic power take-off system (PTO) [1]. This WEC is made of a flap hinged at the sea floor and operating in pitching mode [1, 2]. The PTO consists of two single-rod cylinders attached on each side of the flap, which oscillations around the hinge moves the two cylinders in opposite directions. Then a hydraulic motor receives the oil-power and drives an electrical generator. The study simulations take into consideration different sea states conditions, cylinder dimensions and power take-off layout configurations. A comparative analysis between the flap type and point absorber WEC is performed as regards to PTO efficiencies, average and peak power ratios.

The study reveals that WEC wave excitation moments, rather than resonance [3], and a less constrained design optimization of the PTO mechanical interface allow a more effective and efficient PTO.

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A perspective on wave energy conversion at seaports

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Despite the sizeable theoretical resource that exists around the world and the advantages over alternative energy sources, wave energy remains an untapped source of renewable energy. This can be attributed, in part, to challenges faced by WEC developers, namely design, performance optimization and survivability at sea. Nevertheless, some devices are being considered for particular applications, including integration into harbor breakwaters. As port authorities search for new and environmentally friendly energy sources to complement their energy mix, wave energy becomes increasingly appealing, given the high exposure of breakwaters to wave action and the additional benefits of such an integration (*e.g.*, cost-sharing and onshore grid connectivity). Under the scope of WG 3, recent experience with the study of WEC integration into breakwaters denoted the importance of further developing applicable WECs, namely through hybrid approaches [1] where individual concepts are combined. This allows for the mitigation of weaknesses inherent to each concept and bolster overall performance and energy production. Such a task is achievable by a composite modelling methodology, where numerical models are applied to assess geometry configurations and predefine control strategies for the power take-off system and physical modelling studies are carried out to validate the numerical models and assess the potential damage to the structure and the effectiveness of the control strategies, as well as obtaining estimates on the energy production. The research done revealed the importance of analyzing the survivability of both the hybrid WEC and the breakwater and also of assessing the impact of the WEC on the functional performance of the breakwater, e.g., in terms of overtopping flow rates and behavior with respect to wave reflection.

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Challenges in the distribution grid from wave energy integration

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"The hosting capacity is defined as the maximum distributed generation (DG) penetration for which the distribution network still operates according to design criteria and network planning practices based on the European standard EN50160". The hosting capacity varies a lot between different locations in the grid.

Adding new generation or consumption in a distribution grid affects the power flow, voltage quality, short circuit currents and other operational parameters of the grid [1, 2]. Depending on the local properties of the distribution system, the properties of the energy source and the kind of interface used DG integration at the distribution level can cause: overload of feeders and transformers due to large amounts of generation during periods of low consumption; increased risk of overvoltages due to generation at remote parts of a distribution feeder; increased level of power-quality disturbances beyond what is acceptable for other customers; incorrect operation of the protection.

Wave and tidal energy converters are specific DG as they generate intermittent power. It is therefore of great importance to balance the power before connecting it to the grid. Energy storage systems should be used to minimize the power fluctuations and deliver a steady power to the grid.

Our work will give examples on calculation of hosting capacity of distribution gird for small scale generators. Voltage rise, rapid voltage changes and voltage unbalance are the performance indicators that will be used to calculate the hosting capacity of low voltage networks for wave generators. Another problem that will be studied is smart control algorithms for hybrid systems with wave generators and battery storage that minimize the fluctuation of the power delivered to the grid.

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Emerging wave energy technologies from Finland

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Due to the climate change and local industry demands for reliable and environmentally friendly solutions is growing. In Finland, there are good engineering skills and resource available for development of wave energy business. Currently, there are two main industry actors with two totally different technologies.

AW-Energy Ltd.'s (http://aw-energy.com/) flagship product, WaveRoller®, is a submerged wave energy converter based on a hinged panel that is attached to the sea bed in the near shore area. It generates electricity from the movement of the waves (surge phenomenon) and is connected to the electric grid on shore. Wello Ltd. (http://wello.eu/) uses the rotational movement of a Penguin device is derived directly from wave motion, and it's captured by the hull shape. The Penguin has no hydraulics or joints, and all moving components never come into contact with sea water. Both devices can be manufactured by any shipyard and transported to the site. They are planned to be easily connected to moorings and electricity grid. Electrical connections, grid connection points and grid capacities with national regulations are setting threats for commercially profitable site.

Industry is still quite young and testing of different technologies in challenging environments is still fragile. Weather conditions and seasonal changes are different than used in Finland. In ice and snow, Finns manage but for example tide levels can be challenging. Weather conditions and seasonal changes can differ much from Bay of Bothnia. Stormy waves, salty sea water, sand storms and unforgiven sun shine can test the devices over their limits. Bathymetric data, including sea bottom type (e.g. sand, rock and clay) and seabed geology can be challenging at promising wave energy areas due to lack of reliable information. Environmental aspects have to be taken into account protected ecological/wildlife, archaeological or other special interest areas.

Opportunities are as several coastally situated industries has shown interest to invest to reliable local energy source. In addition, the demand of the industry to reduce the cost of energy and especially at the coastal areas are increasing in marine renewable energy resources.

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Hydrodynamic Performance Evaluation of Arrays of Wave Energy Converters

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Ocean wave energy conversion by exploiting the interaction of a single or multiple Wave Energy Converters (WECs) with sea waves has been the subject of many research efforts during the last decades. Converters based on the oscillating water column concept (i.e. Oscillating Water Column device – OWC) or on the heaving-oscillation principle (Point absorber device – PA) are widely regarded as the most promising WECs. In order to increase the performance of a WEC or an array of WECs, several structural parameters related to the device and the array configuration have been up to date examined. Representative examples are: (a) the geometrical characteristics of the wave converter (i.e. diameter, draught, shape of the chamber, etc.) which affect the hydrodynamic characteristics of the device; b) the type and the characteristics of the mechanical system that transforms the wave motion into mechanical power (i.e. air turbine for an OWC; gear box for a PA); and c) the array configuration of WECs (i.e. distance between the devices; place of the devices concerning the incoming waves etc.) [1].

Another way to increase the efficiency of a WEC system is to integrate it into other maritime structures such as a breakwater or a harbor, so as to supply wave power to shore and to reduce the intensity of wave action inshore. The integration of WECs with other maritime facilities is triggered by better economic viability through cost sharing on construction, installation, operation and maintenance.

The content of this abstract is in line with the 3rd Working Group topic "*Technology of WECs and WEC arrays*" since the present analysis is focusing on the three-dimensional wave diffraction, pressure– and motion– radiation problems of an array of WECs, free floating or placed in front of a vertical breakwater, by applying: a) the image theory, for the vertical wall simulation [2]; b) the multiple scattering approach, for the determination of the interaction phenomena between the converters [3]; and c) the matched axisymmetric eigenfunction expansions formulations, for deriving the velocity potential representations around each device of the array [4]. The aim of this analysis is to examine the efficiency of an array of WECs placed in front of a vertical breakwater and the effect of the breakwater on the absorbed wave power range.

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Control of wave energy converts and connection to grid or desalination systems

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My name is Jennifer and I am a PhD student at the Division of Electricity at Uppsala University, Sweden, focusing on wave powered desalination for freshwater production. Different aspects on wave power, for example modelling, control systems, economic and environmental aspects and grid integration is highly interesting for me. I would be happy to take part of the discussions on the WECANet meeting and I hope to learn from other researchers in the field.

My research interest in Working Group 3 is related to the electrical aspects of wave energy converters (WECs). For example related to different types control of specific WECs (e.g. latching and declutching), if this is beneficial or not for the specific purpose of the system with respect to system survivability and cost. The goal to investigate grid integration of WECs is highly interesting, as well as connection to specific functions in society, such as water services (e.g. desalination). Furthermore, it is interesting to investigate full systems, including several WECs connected in a wave power park and their control. In the case of wave powered desalination, the desalination plant and local salinity of seawater etc. may put different and varying requirements on the driving intermittent wave power output. This would affect control and demand system analysis. Therefore, I look forward to participate in the activities of WECANet and specifically Working Group 3. I have been involved in several studies regarding WEC modeling, design, control and connection to grid or specific functions, such as water systems (desalination). The wave power research on Uppsala University dates back several years, and all publications are available on https://www.teknik.uu.se/electricity/publications/ .

I hope to meet you all on WECANet!

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A review of contemporary regulations for ship-like objects with respect to wave energy converter structural design

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The regulations with respect to structural design of wave energy converters (WECs) are often neglected in assessment of these objects. WECs have no fully developed rules, regulations or practical guidance for the design of their unit structure, i.e. stiffened plating and its response to hydrostatic and hydrodynamic loadings. This is a noticeable gap of such novel industry that could lead to neglecting issues in structural risk assessment and later - insurance level determination. One could use an experience of naval architecture approach to the ship-like objects in which a structural engineer's starting design point is: rule, regulation and classification procedure [1, 2, 3]. These structural regulations could present a considerable help since their semi empirical procedures are based on decades of marine experiments, theoretical research and incidents gathered for ships, ship-like structures, floating docks or marine objects of unusual design. This might provide structural integrity transfer to WECs. In other words, the raising question should be: how to determine the thickness and arrangement of the WEC bottom plating stiffened panels since there are no proven procedures? Will such panel sustain structural loads in extreme conditions? Direct calculations (for example – finite element or buckling analyses) are not sufficient for structure determination since the phenomena related to the long term service exploitations are very hard to be included (corrosion, long term wave conditions).

Shipping structural regulatory practice might have some answers and guidance. All floating structures, WECs and ship-like, experience the same input thought complex wave conditions and different weight – buoyancy distributions. Therefore, a review of contemporary ship structure regulations related to the structural design and loading with respect to the WECs are to be carried out especially considering that such authorities already propose the procedures for structural assessment of floating objects of "an unusual or unconventional" design.

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What is the way forward for wave energy?

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Since Stephen Salter [1] published on wave power in 1974, many scientists and engineers have tried to make a contribution to the development of wave energy. Different ways of capturing the energy from waves have been proposed and tested. Different power take off systems have been investigated. EMEC lists over 8 different types of wave energy converters and over 200 wave developers. This makes clear that the idea of harvesting energy from waves has sparked the imagination of many, and for good reasons, because wave energy is renewable, and the resource is huge.

However, in spite of all these efforts, the commercial success of wave energy has been very limited until now. Scaled versions of many devices have been tested in wave tanks, some full scale devices have been tested in the ocean, but this has not yet led to commercial success. The main reason is probably the very harsh environment in which devices have to survive, an environment with extremely large forces, and with salt and humidity. While wave energy converters need to be sensitive to waves in order to capture energy in moderate wave conditions, they also need to survive in extreme wave conditions. However, also the fact that the large effort that is put into developing wave energy is scattered over so many different devices and developers impedes progress.

Therefore, I hope WECANet could contribute to answering questions like:

- What is the way forward for wave energy?
- Is there a way to converge the research and development effort going into wave energy in such a way that it makes progress possible?

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Improving the Hydrodynamic Efficiency of Coastal Oscillating Water Column Devices

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The extensive research activities were carried out in recent years in the Centre for Marine Technology and Ocean Engineering (CENTEC) to improve the hydrodynamic efficiency of the Oscillating Water Column (OWC) devices. The main motivation of the group which focused on this topic was the high cost of energy production of Wave Energy Converter (WEC) devices as improving the efficiency can directly influence on reducing the costs. In this context, the group has significant achievements to promote a solution to enhance the efficiency of OWC devices by adding a properly designed step next to the OWC chamber. This idea was initially proposed in the paper published by Rezanejad et al. (2013) in which they proved the beneficial aspects of the application of the stepped sea bottom concept by employing solely the numerical approach. In the next step, the comprehensive experimental investigations were carried out and it was proven that the efficiency of the OWC device can be improved by more than 80 percent in the broad range of wave periods by the application of the stepped sea bottom concept.

The mechanism caused the aforementioned improvements on the performance was extensively described by employing analytical, numerical and experimental approaches by Rezanejad and Guedes Soares (2018). The achievements in terms of improving the efficiency can also be applied in other types of WEC devices by imposing the equivalent mechanism. Hence, the main goal for participating in the next WECANET meeting is to promote this idea as well as motivate other participating groups to establish international collaborations to approach toward the goal of the practical application of this idea. Furthermore, the same groups are currently also focusing on the new floating OWC type WEC device with enhanced efficiency and it’s on their scope of work to promote this concept as well.

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Wave energy control: The WECCCOMP competition

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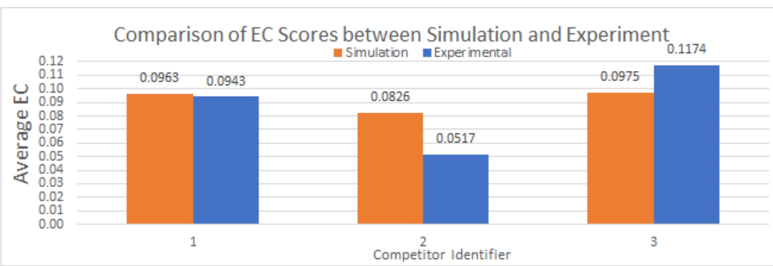
A wide variety of energy-maximising control algorithms for wave energy converters have been proposed [1,2,3]. Most are evaluated in simulation, often with linear simulation models, and there is rarely a basis for comparison, given the variety of wave energy converter (WEC) platforms upon which the control studies are based, and the variety of sea states used for evaluation. Over the past 18 months, the Wave Energy Control Competition (WECCCOMP) [4] has endeavoured to compare a range of energy-maximising control strategies on a level playing field, but providing a standard simulation model on an open-source platform (WEC-Sim) and specifying a specific range of 6 sea states. The entries were evaluated, and validated by the organizing committee and competitors were also invited to implement their controller in an experimental setting at Aalborg University, with the support of a MARINET 2 grant.



One of the encouraging outcomes of the competition is that the ranking of controller solutions were consistent between simulation and experiment, with little drop-off in performance. One question now is now the momentum of WECCCOMP can be maintained to provide further recommendations with regard to real controller designs for wave energy systems, perhaps through release of the WECCCOMP study as a benchmark system, or the development of new control benchmark problems. Perhaps this is an area where WECANet can play a role?

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Electrical and Cost-benefit Aspects of Integration of Wave Energy Converters Distributed Generation to Power System

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Within the WG3 my focus would be in electrical and cost-benefit aspects of high-level integration (penetration) of WECs distributed generation (DG) to power systems both on coast lines and on islands. Due to the variable nature of wave energy and resulting generated electricity, there are many technical aspects of WEC DG integration to consider, such as [1]: influence on voltage rises, changes in power flows and losses, short-circuit currents and protection schemes, power quality in terms of EN 50160 norm including voltage variations, flickers injection, harmonic distortion, mostly on the grid connection point and close surrounding as well as general influence of increasing level of WEC DG integration on overall power system supply reliability and stability. In order to ensure high(er) level of integration of WECs all these aspects need to be considered based on cost-benefit analysis of possible technical measures to overcome these problems on both WECs and power system (usually distribution grid) side.

It is therefore necessary to determine the cost-benefit trade-off between measures on WECs side to ensure smaller impact on power quality, mostly on smart active and reactive output power control, back-to-back converter measures and smart (micro)grid operation including other RES DG (mostly PV and wind) and/or energy storage compared to measures on power system (distribution grid) side such as usage of automated load tap changers, smart grid demand (load) side management, strengthening the grid by building new lines or connecting to higher voltage etc. In my opinion this could be done only in strong co-ordination between primary energy hydraulic side (WG1 and WG2), machine, electrical and other engineering measures of transformed energy (WG3) and cost-benefit and environmental impact (WG4).

Finally, coming from 'a non-leading country in wave energy technology' my specific interest is in possible deployment of WECs in smart PV/Wind/WECs based microgrids with(out) energy storage on Adriatic Sea (applicable to other Mediterranean) coastline and particularly islands with high distribution grid investment, operation and maintenance costs as well as a strong increase of electricity demand during the tourist season that could play a major role in faster commercialization of WECs.

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Improving wave energy prospects by focusing more research on the goal of reducing the maintenance costs

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This is a proposal for a subject of discussion under the topic of WEC design optimization in the Working Group 3: Technology of WECs and WEC arrays.

The main concern regarding the production of electrical energy by WECs is the issue of profitability of this technology. Various studies have analyzed this problem. The main concern is the levelized cost of energy which is few times higher than for other competitive technologies in renewable energy industry. The main expenses responsible for this difference are the device and the operational costs.

The high device cost is connected to the fact that there is great versatility of devices as the technology is still in the under development phase. This expense should go down with time, thanks to technological advancements and efforts to standardize the technology.

Second biggest source of expenses, the operational costs have better prospects to decrease in the nearest future. In this category the biggest expenses are generated by the unplanned maintenance and repairs of the devices. In the industry facing the most similar obstacles — the offshore wind farms industry, much of the current research is directed towards reducing the unscheduled corrective maintenance costs. The wave energy industry should follow that approach.

From technological standpoint this objective can be achieved either by devising more durable components or by various efforts dedicated to allow more of the unplanned maintenance to be anticipated, as this allows to lower the costs significantly. To identify the technological areas promising the most progress, initial research should be directed towards a throughout and detailed analysis of the maintenance issues of the past wave energy projects and prototypes. Formulated conclusions and recommendations would constitute a basis for further research.

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Wave energy technologies selection based on comparison in Adriatic Sea by different variable input data and optimal electric connection

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There are several wave energy converter (WEC) technologies interesting to use in practice for optimal design, for example oscillating water column, point absorber buoy, overtopping device etc. Each WEC technology has its development potential based on further research and improvement. It is hard to say which WEC technology is optimal solution for application at exact location that differs from the other by amplitude, wave velocity distribution and wave direction distribution. It is normally for scientists and investors to focus on sites with better energy potentials for example in Atlantic Ocean. An important part of the investment in WEC is connection cost to electric grid. However - from our point of view, it is very interesting also to focus on Adriatic Sea as our wave energy resource for coastline application. Republic of Croatia has 78 islands with surface greater than 1 km^2 (44 island inhabited by more than 15 people, 35 islands inhabited by more than 100 people, 17 islands inhabited by more than 1000 people), 525 small islands with surface between 0,1 – 1 km^2 and 389 small rock islands with surface lower than 0,1 km^2. Great length of the coastline means that there are many potential sites to install wave plant with low costs for connection between WEC plant and electric distribution grid. It would be of great importance to improve reliability of power supply for island's society, their institutions and households. Our role in WEC technology development could be in control & electrical aspects, system of controlling and data acquisition (SCADA), operation and undersea cabling between plants (interconnection) and from plants to island or mainland (connection to electric grid) with inverter and transformer station on the land. Also, planning, design, control and manage hybrid system as optimal solutions combining WEC with wind and solar renewable power sources are in our research field.

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Fault tolerant electrical generators for wave energy converters

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Working group: 3 – Technology of WECs and WEC
Working Group Topic: WEC / WEC arrays electrical aspects, grid integration

The electrical generators are the "heart" of most of the WECs, as they are converting the mechanical energy captured from the waves to electrical one to be delivered to the consumers [1]. Its global performances are profoundly influencing the overall WEC operation. A great variety of generator types were proposed and implemented in WECs, as synchronous permanent magnet, transverse flux, switched reluctance, etc., both rotational and direct driven linear ones [2], [3]. As these devices are operated in remote places and in very harsh (salty) environments their faults are impending. Their smallest fault can stop them, or to bring their characteristics much below of that designed. These certainly negatively affect the overall WEC performances, and are hard and costly to repair.

Therefore, the fault tolerance increase of the generators used in WECs is a critical issue, and is of real interest for all involved in this field [4]. My research interests are and will cover in the near future identifying new concepts leading to this purpose. These concern not only construction changes in generators (modularisation, improved winding arrangement, applying better quality materials, etc.), but also power converter and control related issues [5].

I am opened for collaborations in this field in the frame, and also outside the WECANet programme, inclusively hosting in our laboratories young researcher fellows (Ph.D. students, postdocs, etc.).

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Improve the Feasibility of WECs by Size Optimization

Working Group 3: Technology of WECs and WEC arrays -WEC design optimization

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Basically, one important obstacle in the development of wave energy is that the LCoE of WECs is not competitive with offshore wind and some other renewable technologies. Another is that there exist so many different types of WECs, which make it hard to converge the attention and investment. Therefore, it is of high significance to find a fair way to evaluate WECs and compare them with other renewable technologies. However, the sizes of devices are rarely considered during the evaluation of LCoE of WECs. Literally, the LCoE is a size independent indicator, in which the sizes of devices are not expected to make difference. But the performance of WECs is highly related to the coupling of wave resource and devices' size. So it would be fairer to take size optimization into account during the evaluation of various WECs.

Regarding optimal power-volume ratio, Falnes[1] proposed a famous view "Small is Beautiful" as for floating point absorbers. But referred to wind turbine industry, the increasing size of individual device could be helpful for decreasing the cost of maintenance and operation. Obviously, the optimal size of WECs is highly objective-dependent in practice. The linear scaling law (Froude Law) is widely adopted to investigate the relation between performance and sizes of WECs. Based on the relation, the optimal size could be determined according to different economic objectives. However, the nonlinear effects, such as viscous drag and non-linear F-K force, will also bring some uncertainties on the performance estimation, especially in small devices and relatively steep waves. So it is necessary to establish the nonlinear model to investigate the relation between performance and size.

Our future activities are mainly about: 1) establishing the size optimization model for WECs based on linear model; 2) using CFD technology to quantify the scale effects during size optimization; 3) analyzing the influence of non-linear effects on the performance prediction of WECs and modify the optimization model. These works are expected to reduce the uncertainties of size optimization of WECs and make WECs comparable.

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Integration issues of Wave Energy into Power Distribution Grid

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Working Group 3: Technology of WECs and WEC arrays – electrical aspects

Grid integration of renewable energy extensive deployment is being become complex task, in recent years. Intermittent and unpredictable production from renewable sources imposes new challenges to Transmission System Operators/Distribution System Operators (TSOs)/ (DSOs) to keep power system in stable operation mode. Significant participation of renewable sources in a power system jeopardize power production/consumption balance, i.e. power system stability. An electric power need to be injected into distribution/transmission grid in the most efficient way to fulfil technical, economic and environmental requirements.

Electrical connection solution for wind offshore and wave energy converters are very similar. Produced energy from wind and wave energy converters need to be collected at one point by submarine cables, offshore power transformer station platform, usually. From such platform, submarine cable(s) are required to make connection with onshore grid, at higher voltage level in most cases. An optimal grid integration solution is very case dependent, so each project has to be evaluated individually.

Selected electrical connection solution has to be analyzed in both steady state and during disturbances in power system. There are requirements, prescribed by TSOs/DSOs, for each generation unit in power system to support power system stability. Certain tests have to be performed to simulate real operating conditions and confirm required stability capabilities. Most of National Grid Codes requirements for renewable generators, in order to be competitive with conventional generators nowadays, are almost the same like for conventional ones, to be capable to break through the fault and support voltage during faults.

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Optimal design of wave energy converters subject to physical constraints and power take-off control

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Wave energy converters are used to capture the energy carried by ocean surface waves. In order to maximize the energy extraction of wave energy converters from incident waves, several strategies can be employed [1]–[3]. Among them, two well-known approaches propose optimizing the geometry of the primary capture system and employing advanced control strategies for the power take-off system. However, most endeavor so far have been limited to carrying geometric optimization or power take-off control independently. Recent results [4] have shown that, power-take-off control informed geometric optimization can significantly improve the energy production of a three-body hinge-barge wave energy converter. In [5], results indicate that, for a 1-DOF point-absorber type wave energy converter, the optimal radius and draft of the floating buoy can be obtained depending on the type of control strategies. Furthermore, a successful WEC requires the consideration of physical constraints in the design stage, to improve its survivability in real-sea operation.

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Abstracts for Working Group 4:

Impacts and economics of wave energy and how they affect decision- and policy-making

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Unlocking the wave energy potential through interdisciplinary methods within Working Group 4 in the WECANet COST Action

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I would like to express my interest to participate at the 2nd General Assembly of WECANet at Porto contributing in Work Package 4, both as the Work Package 4 (WG4) Leader and as a researcher in the field with an active interest in addressing non-technological barriers of wave energy.

At the Assembly I will present the subjects for WG4, disseminated from the 1st General Assembly and will steer the participants in setting up goals and potential deliverables. I also want to participate as a researcher in addressing some of the economic barriers, especially with issues related to innovation funding, CApEX reduction and socio-economic barriers.

I am currently active in the field on wave energy, and I work on several techno-economic issues. I am exploring the explore market potential of wave energy converters (WECs) in current (and future) mix of renewables, and niche markets/applications where WECs can contribute. I also work on innovation and financing potential, and the definition a helpful metric for WECs convergence aiming to reduce CApEX by 30-60% .(Lavidas, 2019, 2018; Lavidas and Polinder, 2019; Lavidas and Venugopal, 2018)

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Investments Influencing Factors Influencing for Marine Renewable Energy Mix Achievements

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Energy systems relying on variable renewable energy sources suppose production of energy from wind turbines, photovoltaics, solar thermal, wave energy converters, etc., is the main source of energy in system. This creates a large amount of the energy renewables mix, especially in the form of electricity that has to be utilised in the energy system to supply demands that to a large extent. Electricity generated from marine renewable resources (tide, wave, ocean current and offshore wind) reached 42,619 GWh in 2016, with a total installed capacity of 19,252 MW. Offshore wind was the main contributor of course and still quite ahead from the wave energy, with 41,596 GWh generated and 18,726MW installed.

Among the possible main economic criteria and subcriteria with the important effects on the development of W&T renewable energies most authors identify five main categories: incentives, profitability factors, preoperation costs, operational costs and revenue (C4) and externalities (C5). Incentives are here referred to those policy-based tools accomplished by the governments to encourage the potential investors to invest in marine renewable energy or to expand their existing activity in this area. Ownership right, feed-in tariffs, quotas, tenders, tax incentives, and public financial supports might be regarded as sub-criteria identified for the incentives in this survey which seem to have important roles in pushing the investments on the W&T energy technology

Speaking of the investors' involvement in energy technologies have the potential to play a role in the cost reduction strategies of larger companies. Although wave energy converter technology development is in its early stages, advancements are accelerating at a rapid pace and scaled versions of commercial devices are currently being tested at dedicated oceanic test sites such as the Hawaii Wave Energy Test Site, the United Kingdom Wave Hub, and the Pacific Marine Energy Center Test Sites. Prior to full commercial-scale deployment of WEC arrays or farms, it is necessary to demonstrate competitive economic performance of these WEC technologies relative to other energy generation technologies.

Involving a variety of companies as the business expands reduces risks to investors. It also triggers diversification amongst different types of ventures (tidal, solar, wind, etc.) and maximises market opportunities. On the other hand, this strategy requires cooperation among local companies many in the scale of small companies to promote incremental innovation and micro-innovation. Clusters can provide

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platforms for cooperation among SMEs. Clustering should enable possible synergies amongst different businesses to be identified and promoted, and help to attract investment.

The main innovation topics in the field are supposed to be the multi-use platforms for offshore wind, wave and aquaculture and the floating foundations. Thus an energy mix might be achieved with involvement of point absorbers, attenuators, and oscillating wave surge converters. Predominantly the investors are hesitant and waiting for majour subsidised funding to upgrade the infrastructure that will provide the technology development. In most of the advanced technological countries spatial spillover and omitted common factor bias, provide robust evidence that the financial market developments significantly promotes cleaner energy in the long run. Still a challenge is the lack of adequate suppliers available and a lack of convergence in terms of design of wave energy converters. The direction ahead is related to the public monitoring of the development phases and some certain governmental policies for appropriate pull and push mechanisms.

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Identification of innovation potential of sea and ocean wave energy sector

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Working Group 4: Impacts and economics of wave energy and how they affect decision- and policy-making
Topic: identification of innovation potential and exploration of wave energy market potential

It is necessary to first assess the potential for innovative technical solutions in the field of renewable energy production (wave and ocean energy). This is an interdisciplinary task that will require reviewing existing research and previously identified technical solutions.
Reviewing the actual state of renewable energy production requires the use of methods and tools applied in this and other economic sectors, which will require a holistic approach. Scientific publications and databases are the main sources of information on the actual state of innovation of technologies used to generate marine renewable energy from sea and ocean waves. The following databases are proposed to be included in the analysis:

1) WoS Core Collection, Google Scholar, ScienceDirect – these would be used to analyse recent scientific publications, help evaluate the state of the science concerning sea and ocean wave energy, and identify experts in this field [1, 2, 3];
2) Available patent databases such as WoS Derwent Innovations Index, Espacenet, WIPO Patentscope, Google Patents or Patent Innovation – these would help identify technical solutions and determine their innovativeness and market potential [1, 4, 5, 6].

The information obtained will allow for the assessment of the potential for technology development in the industry and may be used to create industry development standards.

Acknowledgments
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Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) of Wave Energy Converters (WECs)

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LCA is a valuable tool for providing quantitative data related to environmental consequences of wave energy devices both at design and installation stages. I wish to contribute to 'WG4-Impacts and economics of wave energy and how they affect decision- and policy-making', which aims to clarify uncertainties on non-technical aspects (cost, environmental impacts, legal issues, policy, etc.) of wave energy systems, using my previous experience (Elginoz & Bas, 2017a, 2017b, 2016) of LCA of marine renewable energy systems (offshore wind turbines & WECs) in the context of MERMAID project (FP7).

There are numerous studies related to environmental impacts of WECs considering various aspects in a wide spectrum (change in habitats & biodiversity, change in currents & hydrography, noise, etc.). Currently, I am preparing a review paper on environmental impacts of WECs including LCA studies. Due to this reason, T4.1 and T4.4 are the first actions that I can effectively contribute. Besides, LCA of WECs has limited number of examples compared to other ocean energy technologies. I think establishing a database of previous EIA & LCA studies aiming to develop a systematic database specific to WECs developed in various countries and close the gap of efficient networking of researchers on this area will be very fruitful for future sectoral studies. This is one of the research topics that I want to develop projects. Besides, depending on my background of physical modelling, I can contribute to integrated optimization of WECs in T4.5.

I have a new position that provides me the opportunity of starting to establish a small hydraulics laboratory & my research group, which will combine my studies in coastal engineering, LCA and EIA. As an ECI, I wish to expand my existing network for future collaborations and realizing my aim of beinga well-known woman scientist. WECANet will be a very good opportunity for this.

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Renewable marine energy generators and integration in commercial ports' infrastructure

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Many researchers from all over the world are trying to find the best suitable solutions to fight climate change by exploiting on a sustainable way the ocean renewable energy resources. Particularly, recent assessments have been done already in very particular places to evaluate the wave energy resources, however, the results obtained are not yet attractive enough for potential investors.
Considering the particular case of the ports, which are great energy consumers, a focus should be put in the future increase of energy demand and the ways to cover it in a sustainable and renewable way. Ocean energies should play an essential role in solving this issue.
The ITF (International Transport Forum) predicts that ships will carry out more than three-quarters of all goods movements by 2050 and the current demand pathway projects that maritime freight transport will grow at a compound annual growth rate of 3.6 percent through 2050. This will lead to a near tripling of maritime trade volumes by 2050 compared to 2016 figures [1]. Ports should play their role in this growth by adapting their infrastructures to an increase on the automation and electrification of the terminals. The on-shore power supply technology should also be considered in that adaptation.
Ports should be able to supply as much clean energy as possible to become "zero emissions" ports, and this can only be achieved by the use of renewable energies. Wave energy is a promising candidate.
However, the criteria for the evaluation of the feasibility of port wave energy plants should not be the same as other existing projects as the expected outcomes are different. Climate change adaptation issues should also be taken into account as well as environmental impact assessment.
My contribution to the WG4 would be focused on the non-technological assessments that should be considered on the design of wave energy arrays. This contribution is in line with the aim of the WG, "*going beyond the scope on technological barriers and incorporating non-technological assessments*". My ports' management experience and knowledge can provide the WG this point of view more focused on the commercial use of energy and the climate change requirements for the adaptation of the infrastructures.

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Identification of wave energy frameworks by an analysis of results of European projects

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Working Group 4: Impacts and economics of wave energy and how they affect decision- and policy-making
Topic: Identification of resource and environmental and legal frameworks that support and/or hinderwave energy in MS and the EU.

Marine energy has been the subject of EU research and analyses from different perspectives. Information on this subject can be sourced from ongoing and completed projects, such as MaRVEN [1], RiCore [2], SEA WAVE [3], MUSES [4], Opera [5], SI Ocean [6], WESE [7], SOWFIA [8], and SETITAN [9]. These projects analyzed issues such as the environmental impact of marine energy converters, risk analysis and standardisation [2], strategic risk analysis [3], cooperative use of the oceans [4], reduction of the costs of obtaining energy from waves [5], methodology for energy resource assessment [7], environmental, risk, and sustainability analysis [9], and the development of new technical solutions for wave energy converters (WECs) [10]. Reviewing the results of European projects will primarily allow for the organization of data on current achievements and progress in this area. Additionally, resources and environmental and legal frameworks can be identified which support and/or hinder wave energy in the EU. Information on the sources of project financing will provide added value. In order to achieve this goal, it is proposed to use databases of projects carried out in the EU.

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A spatial multi-criteria decision-making method for wave farms site selection in the European coasts

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The continuous increase in energy demand and the related negative impact on the environment through fossil fuels has raised severe challenges. The renewable energy sources (RES) are increasingly considered as a potential solution for sustainable energy production and reduction of negative environmental impact. In the European Union, the exploration and of wave energy potentials and the implementation of wave energy converters is underdeveloped and requires more active research. Furthermore, the European continent is one of the largest emitter of CO_2 since the predominant share of energy production is generated from fossil fuels. The main barriers for the deployment of the wave energy industry in the region are the lack of political, legislative and regulatory support, low prices for electricity and heat generated from fossil fuels, lack of information for decision-makers (e.g. data from research projects) as well as the preference for centralized energy supply schemes. These barriers are contributing to an inadequate investment climate for the implementation of this RES facilities. Nevertheless, in some countries of Europe with a potential of RES and a comparatively low degree of economic centralization, the situation is different.

In the present research involved in all points of WG4, the initial conditions for the development of wave energy potentials for the production of energy in the European coasts (Baltic Sea, North Sea, Atlantic Ocean, Mediterranean Sea and Black Sea) will be examined using a multi-criteria assessment methodology. For the assessment of the wave potential at a regional scale, a multi-criteria method based on the geographic information systems (GIS) and complete with techno-economic and socio-legislative data will be conducted to identify feasibility wave farms locations. An innovative element of the proposed multi-criteria methodology will be the combined assessment of the maximum available factors relevant for the economically feasible exploration of wave energy potentials. These factors will include the energy status with the specific features of the energy infrastructure, the energy policy-relevant for wave energy production along with the market and economic conditions of the region. The results of this research will support the potential role of energy planners and national authorities.

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Renewable energy sources, carbon emissions, and economic growth: A Granger-causality in quantiles analysis

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Energy is fundamental to development, but as economies evolve, rising incomes and growing populations demand more energy (Tabary and Purdie, 2016). The most common energy-related product consumed worldwide has been the fossil fuel energy. Sebri and Ben-Salha (2014) emphasise that the expansion of energy-consuming activities around the globe has led to two major concerns: the exhaustion of non-renewable energy resources (mainly oil) and respectively, the problem of global warming caused by the increasing amount of carbon dioxide (CO2) and methane into Earth's atmosphere and oceans. Particularly, the global emissions have been seen to rapidly increase of around 3% per year between 2000 and 2013 (Oliver et al., 2016). This global nature of energy challenges requires that renewable energy resources be appropriately managed and used to alleviate global warming (Zhang and Cheng, 2009).

Renewable energy is commonly defined as energy generated from renewable resources, which are naturally replenished on a human timescale, such as solar, wind, geothermal, tide, wave, wood, waste and biomass (Sebri and Ben-Salha, 2014). Contrarily to conventional energy, renewable energy sources are clean, safe and inexhaustible (Lehmann et al., 2017). As a future consequence, many conventional (non-renewable) energy sources are expected to step back their leading position in the overall share of energy consumption.

The International Energy Agency (IEA) predicts that renewable energy will be the fastest growing component of global energy demand (Sadorsky, 2012). According to their Alternative scenario, global demand for renewable energy is expected to grow by 10.4% per year between 2007 and 2030 (Conti et al., 2016). Over this same period, world primary energy demand is expected to grow by 0.8% per year. This signifies that the renewable energy sector is expected to double in approximately 7 years (Sadorsky, 2012).

Recently, the Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) reached a milestone agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future (United Nations, 2015; Lavidas and Venugopal, 2018). This agreement poses a significant opportunity for integration of renewable energy into economies' current power production mix, aiming to achieve higher renewable energy contributions and maintain grid stability (Lavidas, 2019).

Wave energy offers a renewable resource with the advantage of being foreseeable ahead in time and expressively higher energy density compared to wind and solar energies (Lehmann et al., 2017). In fact, European Commission published a list of 45 Wave Energy Converter (WEC) developers that have reached

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open-sea deployment by 2015; 7 are the US based, 26 are the EU based, 6 are Australian, and 6 are from the rest of the world (Magagna and Uihlein, 2015). Particularly, in Europe, wave and tidal energy capacity is expected to reach 2250 MW or about 0.5% of the total installed electricity capacity in the EU by 2020. The sector aims to install 100 GW of wave and tidal energy capacity by 2050 (Badcock-Broe et al., 2014).

The relationship between renewable energy consumption, carbon emissions and economic growth is a subject of intense debate. However, the current literature shows a limited empirical evidence for such a link. Sadorsky (2012) claims that if there is causality from renewable energy consumption to economic growth, then reductions in energy availability have significant welfare implications. At the same time, the 2016 report of International Energy Outlook highlights that economic growth has a substantial influence on world energy consumption (International Energy Agency, 2016). Hence, as countries develop and industry grows, energy demand increases rapidly. Therefore, renewable energy has emerged as an energy source that may alleviate the growing concerns over carbon emissions, high and volatile fuel energy prices, and the dependency on external energy sources (Sadorsky, 2012).

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Opportunities to increase the usere of WECs in the context of current requirements for the energy sector

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The need to provide economic growth to meet the needs of the constantly growing world population, ensuring return on investment in innovative technologies, resource provision for the transition to a carbon-free economy require a qualitatively new approach in the formulation of a strategy for the development of the energy sector worldwide.

Additional factors that have a significant impact on global energy markets are issues of restoring environmental balance and restrictions on the entire fossil fuel industry related to the requirements of IMO 2020. All of these factors have the potential to dramatically change the world's energy map and to direct governments, private investors and funds to alternative energy production and distribution especially in those parts of the globe that do not have their own energy sources and rely on imports of liquid and gaseous fuels for energy production. WECs is the one of the main alternative technologies for energy production and distribution especially in island countries that do not have their own sources.

The development of modern information technologies can also have a positive impact on the implementation and use of WECs specifically advanced analytics, artificial intelligence and advance robotics using which to create and predict new climate models that allow the WECs to be used more efficiently, to reduce production and commissioning costs, to develop more efficient technologies, materials and logistics.

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The economics of wave energy, barriers to investor decision-making, and policies that can move the industry forward

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My name is Olof Lindahl, PhD and I am a researcher at the Department of Business Studies at Uppsala University, Sweden. My research has for the last five years to a large extent focused on the economics and business of critically important, but currently commercially struggling, industries and technologies. Specifically, policy incentives may have important influence on such industries and technologies in the form of subsidies, regulatory change, innovation prizes and other interventions that affect investor confidence. A previous focus of my research has been on how policy changes may allow for the development of new technologies in the pharmaceutical and medical technologies fields. More recently, I have started to become interested in and to work with wave power and the wave energy converter (WEC) designed at Uppsala University (see e.g. www.teknik.uu.se/electricity/publications/). Specifically, I have been involved in recent studies on the economics and environmental aspects of the materials in use of WECs, such as permanent magnet material for the linear generator of the Uppsala WEC. Moreover, I am currently co-authoring a paper discussing lithium extraction from wave powered desalination.

I am highly interested in participating in WECANet and especially Working Group 4, discussing the economic and environmental aspects of wave power. Moreover, in this context, issues relating to the economics of wave power and how this affects investment decisions as well as how it can be affected by policy-making is of interest. With this in mind, I would very much like to get the chance to take part of the discussions at the WECANet meeting and I hope to both get to know, and to learn from, other researchers in this important field. My research interest in Working Group 4 is related to the influence that non-technological barriers exert on the wave power sector and its development. I am particularly interested in bottlenecks critically affecting decision-making by introducing uncertainties related to markets, regulations, etc. for wave energy investments. Regulatory frameworks and policy interventions wield important influence on the economics of wave power and the barriers to investment. In this sense, wave power seem to have at least some similarities (such as the important of industry and investor perceptions of barriers), but also some unique characteristics such as the particular socio-economic; environmental impacts, compared to other industries I have previously studied.

I hope to get the opportunity to participate in the WECANet Porto meeting, and in particular that of Working Group 4.

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Wave energy exploration potential in the EU under spatial, economic and technical constraints

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In a context of climate change and global growing energy demand, continuous innovation in energy strategies and policies is crucial to inspire coastal EU Regions to fulfil the upcoming climate and energy targets. Being Europe a continent highly constituted by coastal countries, efforts should be focused on taking advantage of the marine resource and lead the strategies towards different ways of the blue economy.

The offshore wind energy resource in the EU is already been widely explored. It is currently in an established commercial-stage, in contrast with the less developed wave energy sector. Consequently, more attention needs to be put now into providing policy-makers and investors with meaningful information about current technical, spatial and economic constraints of wave energy exploration and its possible contributions to the different nation's energy systems.

Considering the aforementioned and in the framework of the WG4 topic, a relevant research project would consist of evaluating wave exploration potential in coastal Europe as a combination of wave resources, technical projections of WECs, economic costs and spatial constraints of offshore wave farms in a continuous space, using Geographic Information System (GIS) methodologies. Also, the spatial distribution of the levelized cost of energy (LCE) is to be developed, in order to provide information on the suitable geographical locations for developing wave farms which would deliver energy at or below a given competitive cost.

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Wave Energy Converters – environmental and legal frameworks

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The growing energy demands in EU and MS, especially for green energy production, result in interest in wave energy production. It is rather obvious that WECs will have the effect on environment. According to existing regulations, for any engineering construction (inland or marine) preparation of the Environmental Impact Assessment is requires. At the moment we are at the testing stage of WEC installations. However, bulk production and installation of WEC will require legal framework.

Based on experience gained with the test installations, it should be possible to working on recommendations/guidelines for preparation of EIA for WECs. Such guidelines should cover different WEC types, as well as varying environmental conditions (e.g. regional approach). It is necessary to identify factors which are/can be harmful for the environment, and search mitigation measures. In the same time environmental conditions can hinder (e.g. bio-fouling) proper work of WECs. In recommendations for EIP preparation we should focus on the construction and exploitation stage. In addition, guidelines should cover monitoring issues, both at the pre-investment and exploitation stage.

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Environmental impact analysis of the wave energy convertors within WG3 and WG4

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The Environmental impact analysis (EIA) requires developers to supply comprehensive environmental data relating to baseline conditions and device installation and operation. Since wave energy convertors (WECs) represent a new energy production system in deployment, there is a gap in knowledge and information available to all participants – from regulatory authorities to developers. Potential impact on the environment can vary depending on type of system installed (Greaves D. at all, 2016). Wave energy extraction system are generally classified according to working principle (attenuator, point absorber, and terminator) and location (shoreline, near-shore, and offshore), and EIA should cover every aspect of the installed system (Chen Z. et al, 2013; Falcaode A. F. O., 2010). The main conserns are impact on the benthic community, species-specific response to habitat change (leading to abandoning the habitat but the area could be re-colonized , if substrate and habitats are restored to similar state), the entanglement of marine mammals, turtles, larger fish and seabirds. Research in the area of environmental impacts should be focused on localized environmental impacts including e.g. electromagnetic field effects of subsea cables, flow alteration, sedimentation and habitat change of near generation devices (Beyene A., et al., 2015; Boehlert et al., 2008; Uihlein A., Magagna D., 2016). Changes to wave parameters are considered in conjunction with hydrodynamic forces, such as current velocities and resultant bed shear stress (Roberts, J. D., et all., 2017). Chemical effects of WECs such as spills (low probability but high impact) and continuous release (fouling paints) can cause water quality interference (Michel et al. 2007). Noise disturbance – throughout all stages of construction, operation and decommission is evident that these structures produce sounds that may disturb or even cause physical damage to wildlife in the vicinity but also disturb local communities (Beyene A., et al., 2015; Copping, A., et al., 2014; Margheritini, L., et al, 2012). Interference with marine animal movements and migrations – construction of large scale system could disrupt breeding or feeding areas or interrupt with migration routes (Margheritini, L., et al, 2012) and also lead to collision with moving parts of the devices, particularly turbine blades (Copping, A., et al., 2014).

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Wave energy converters standards as an easy way to go from prototype to implementation

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The introduction of appropriate standards to improve the implementation of proposed technologies for obtaining energy from sea waves should be one of the basic elements of discussion in thematic group No. 4: Impacts and economics of wave energy and how they affect decision- and policy-making.

Two-thirds of the Earth's surface is covered by seas and oceans. It is estimated that conversion of kinetic energy of sea waves into electric energy can be very efficient. For example, the use of ocean wave energy in the US Coast of North America could generate around 20 times more electricity than using wind farms in this area. The energy resources of the sea in the regions off the coast of Great Britain could be viewed similarly. Wave energy is one of a few sources of renewable energy that is less sensitive to the rapidly changing environmental and climate factors. Unfortunately, so far the technology of obtaining electricity from sea waves, unlike traditional hydropower, has rarely gone beyond the phase of experiments. The reasons for this can be, among others, due to the absence of standards that could significantly improve the implementation of the proposed technologies. For this type of investment, implementation is a complex business process, since it requires the involvement of large interdisciplinary teams of specialists, including scientists developing the theoretical foundations of the production process and designers. Improving technology implementations is also an element of a state policy. Therefore, in order to be able to use wave energy more effectively, it is worth improving this process. Standards or procedures can become powerful tools that can help overcome the chaos, speed up the process of technology implementation, and help manage costs.

As the current literature shows, the most important element in the process of implementing wave power plant projects are high investment outlays for research and a long process of conducting preliminary economic and technological analyzes. The introduction of appropriate norms and standards applied to the projects of wave power plants will significantly reduce the costs of implementation, facilitate access to processes related to the implementation of this type of investment and indicate economic, social and ecological benefits. It will also allow to develop suitable methods for avoiding conflicts related to environment protection and predisposing suitable locations.

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Resource Assessment and Site Selection for Turkey

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Ocean Engineering Research Center (OERC) of Civil Engineering Department of Middle East Technical University (METU) is part of the consortium that is updating the existing Wind Energy Atlas and developing the Wave Energy Atlas of Turkey for the Ministry of Energy and Natural Resources, Turkey. OERC is responsible for the resource assessment of wave energy and site selection for high capacity WEC applications. In Turkey, there is no framework considering the resource and environmental assessment regarding wave energy and no legal framework for implementation of WECs. As we are working on providing the wave energy atlas, the considerations related to such frameworks are being discussed with the Ministry. These meetings are setting the initial frameworks for the government related to these topics. Therefore, identification of resource, environmental and legal frameworks that support and/or hinder wave energy in MS and the EU, uncertainties-influence of resource, device and legal frameworks in the evaluation of WEC(s) of Working Group 4 of WECANet is a subject that we can contribute to and learn from experiences of other participants.

At the moment, we have completed an initial assessment of possible WEC sites (Bozgeyik, 2019), but the study does not consider the WEC types inclusively. This initial assessment uses wave energy potential calculated by several researchers for the surrounding seas (Black Sea, Mediterranean, and Aegean). However, we have seen that different researchers provided significantly different annual mean wave energy potentials for the surrounding seas because of input data; the model used and limited measurements. Also, our site selection assessment uses parameters commonly used in the literature, but we had to make some unique assumptions due to national strategies and issues. In Turkey, for wind energy, the government determines the sites to be licensed according to their technical assessment method; we expect a similar approach for wave energy. Therefore, a solid resource assessment, site and WEC selection guideline could be one outcome of WECANet that can be an incentive for the government(s) to invest in wave energy, especially for those locations of lower wave energy potential. We can also establish stronger links with the Maritime Spatial Plans (eg. European MSP Platform) and Blue Growth (Blue Economy).

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A unified framework for wave energy investment appraisal

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The last decade has seen an unprecedented progress in assessing global wave energy (WE) resources and their power generation potential. Despite the growing research interest in this area, the commercialization of WE gener-ation technologies is still slow and obscured by technological and environmental considerations. Most important, little is yet known about how well wave energy integrates with onshore renewable resources, such as wind and solar, and more mature clean generation technologies already in operation.

We propose the formation of a research team aimed at developing industry guidelines for evaluating the investment potential of WE generation technologies. The agenda of this team will be related to the activities of WG4 and the two subtopics: “investigate the awareness and acceptance of WECs…”, “identification of innovation and financ-ing potential…”. The group will collaborate with other members of the WECANET Action in translating weather pre-dictions and experimental models for WEC arrays into decision aid and risk analytic tools, tailormade to the needs of investment and insurance companies.

Key to the economic analysis of WE technologies is the understanding of the spatial dependence structure of the production profiles of WEC arrays and how they fit to the existing national portfolios of (conventional and renewa-ble) power generation units. Our conjecture is that the efficient harvesting of wave energy will require a careful mixture of dispersed locations and diverse (onshore) renewable resources. The experience gained from other studies involving mixed types of renewable resources at various geographical scales (see e.g. [1]-[4]) makes us to believe that a portfolio approach to wave energy investments will likely lead to less capital-intensive and more environment-friendly WE deployment grids, which will integrate more smoothly with existing power infrastructure.

To fulfil its objectives, the team is planning a combination of research, networking and training activities:
• Creation of a WE project/site database to be used as reference for case studies
• Development of user deporting and graphical tools supporting the quantification of the economic value and the investment risk of wave power plants
• Preparation of online courses related to the economics of WE

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• Organization of workshops/training schools/special sessions in conferences and STSMs

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Facilitating the commercialization process of wave energy technologies using support tools for innovative projects

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Working Group 4: Impacts and economics of wave energy and how they affect decision- and policy-making
Topic 4: Explore market potential of wave energy in current (and future) mix of renewables

There are several dozen different technological solutions enabling obtaining energy from sea waves. We can classify them into various categories [1, 2]: number of patent applications, number of research projects, the number and size of business entities involved in the projects, WEC technological principle (location, orientations, mode of working surface, reference frame, power take-off). The wave energy projects are at various levels of development in terms of implementation on the market of renewable energy production, mostly measured by TRL level [3]. Each of this technological solutions should be treated as a separate innovative project. Each of them is associated with several challenges not only of technical and technological nature, but also regarding the management of the process of commercialization of research results. Confronting the managerial challenges, this support can take various organisational forms: coaching, mentoring, consulting or managerial training. The type and method of support tools used are more important than the profile of the entity that offers them. Therefore, the key question can be formulated: *What support tools will be best for specific projects developing innovative technologies for obtaining energy from sea waves?*

It is possible to select and afterwards test available support tools that are used to solve problems encountered by both technology start-ups and mature companies. We can distinguish three basic product development phases that determine the type of available support tools used and the intensity of the support process [4]: Ideas to Product, Product to Market, Finance Strategies. An analysis is needed to adapt existing or new support tools to innovative products such as WEC, a wave energy sea farm or a new renewable energy supply system.

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Abstracts for
WECANet Short Term Scientific Missions

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Employment of a swapped-signal band-pass filter for wave energy grid integration

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Wave energy has become one of the most promising energy sources, due to its potential has been estimated in 92 PWh/year [1], which represents 0.24% of the energy mix worldwide [2]. Besides, the devices in charge of exploiting this resource for electricity consumption purposes can work 90% of the yearly hours, which triplicates the production of other renewable energy generation technologies, such as solar and wind [3].

However, these indicators are not enough to declare its complete viability. In that sense, many challenges must yet be overcome in order to make the wave energy more competitive in the near future, being one the most important the grid integration which, in spite of being already achieved [1], is not based yet in taking any advantage of the purely harmonic and uncertain nature of the waves to gain power at the point of power delivery.

In this contribution, a swapped-signal band-pass filter for wave energy grid integration purposes is proposed. With this arrangement, losses associated to the usage of a high-speed flywheel as a high-pass filter are accounted in 7.25%, whereas a gain of 1.72% is obtained by means of integrating a capacitor-based amplifier before reaching the point of power delivery.

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The Use of the *isoAdvector* Geometric VOF Method in Numerical Investigations of Wave Energy Conversion

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OpenFOAM is one of the most used frameworks for numerical investigations of Wave Energy Convertors (WECs). Multiphase CFD solvers of OpenFOAM originally use the MULES algebraic Volume-Of-Fluid (VOF) method to capture the water-air interface, which might suffer from smearing and numerical instabilities. The *isoAdvector* toolbox (e.g. Roenby et al., 2016) provides a geometrical method for water-air interface advection. This algorithm provides more stability and speed to the simulation and eliminates the need for artificial compression of the interface to reduce its smearing.

A numerical wave tank with the *isoAdvector* method is utilized to study point absorber WECs by coupling to the native 6-DoF solver of OpenFOAM. The numerical tank is used to simulate wave loading on the WEC and investigate its survivability. The model will contribute to the objectives of Working Group 1 of the WECANet Action, especially to enhancing multiphysics modeling focused on fluid-structure interaction.

Additionally, the *isoAdvector* method is used to numerically investigate the innovative concept of *SeashellBreakwater*, which is a composite breakwater with artificial units shaped like seashells that can focus the wave energy for more efficient conversion.

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Numerical investigation of the CECO wave energy converter at FEUP

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As the world strives to remove its reliance on fossil fuels, wave energy presents itself as a reliable source of renewable energy with a very high potential. Numerical simulations offer an inexpensive alternative, in comparison to physical modelling, for the initial development of novel devices, in this case a wave energy converter. During the short term scientific mission, computational fluid dynamics was used to model the CECO wave energy converter [1]. The model has been developed using the commercial software, ANSYS CFX [2,3]. In order to reduce on computational resources required, a 2-dimensional model of CECO has been developed in order to investigate the non-linear effects on the device. The dynamic response of CECO, which was calculated within the model, has been compared to the results of the experimental testing of the device carried out at the wave tank at FEUP, in order to validate the accuracy of the model. The results obtained from this model, will not only aid in the development of CECO but, also, can be used to model similar wave energy devices. Therefore, having a greater impact on the development of wave energy worldwide.

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WECANet-LABIMA Open Access Data Base for Numerical Models Benchmarking

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Due to wave-energy dissipation while propagating towards the shore, fixed Oscillating Water Column (OWC) Wave Energy Converters (WECs) mounted on coastal structures exploit a wave-energy resource that can be substantially lower than the offshore counterpart. Indeed, focusing mechanisms triggered by the wave bottom interaction may lead to the formation of coastal hotspots but it a rare case thus most of the time the offshore resource is greater. In order to exploit the offshore wave-energy resource the Floating OWC devices might represent a feasible alternative and the best cost-benefit compromise.

The performance of floating OWC WECs has been widely studied using both numerical and experimental methods. However, due to the complexity of fluid-structure interaction of floating OWC WECs, most of the available studies focus on 2D problems with WEC models of limited Degrees-Of-Freedom (DOF) of motion, while 3D mooring effects and multiple-DOF OWC WECs have not been extensively investigated yet. Therefore, in order to gain a deeper insight into these problems, the present study focuses on wave flume experiments to investigate the wave-OWC interaction and mooring performance of a laboratory-scale floating OWC-WEC model. A series of flume experiments were already done in the MaRINET2 EsfLOWC project completed at the end of 2017 and a new laboratory-scale experimental campaign is under conduction under the LABIMA-UNIFI and STMS-WECanet support. The data already obtained and new data comprises multiple-DOF OWC WEC motions, mooring line tensions, change in the air pressure inside the OWC WEC chamber and free surface elevations throughout: wave flume, close to and inside the OWC-WEC. The tested wave conditions include regular and irregular waves. The obtained data will provide a database for numerical validation of research on floating OWC-WECs and, on floating OWC-WEC farms or arrays used by researchers worldwide.

These measurements will be: i) deeply described in a detailed report in order to be used by third parties, ii) organized in an online open-access database for easy downloading and use. The developed database, comprising OWC, will constitute the reference database for benchmarking numerical models. Worth to mention that the new experimental campaign comprises also laboratory-scale tests on a model of Overtopping-Devices, but the presentation of these tests is planned for a subsequent WECnet meeting.

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Short Term Scientific Mission: 'Development of the Assembly Book of Abstracts, Annual progress report, website and Action book of the WECANet COST Action CA17105'

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This Short Term Scientific Mission (STSM) will be carried out from 17/02/2020 to 15/03/2020 at the Civil Engineering Department of Ghent University, Belgium. The work will contribute to the objectives of the COD (COST Action Coordination and Dissemination) activities of the WECANet COST Action CA17105. As part of the present STSM, the abstracts presented by the participants of the WECANet Assembly of 28-29 November (Porto, Portugal) will be processed in the 'Book of Abstracts of the Assembly', which will become publically available on the WECANet website (www.wecanet.eu).

Based on the outcomes of the workshops organised during the WECANet Assembly in Porto an overview of the work progress of the different Working Groups will be generated, including opportunities for future work, collaborations, training, research synergies and publications. We will encourage and assist on publication of output from the Action's Working Groups in the technical literature. These publications refer mainly to "Special Issues" of well-known journals included in the Web of Science focussing on topics of the WECANet Action, in order to achieve a wider dissemination of the WECANet results.

Furthermore, we will start the development of the annual progress report. This report gives an overview of all past activities (CG/MC/WG meetings, annual assemblies, training schools, workshops, conducted STSMs, publications, special issues and awarded conference grants).

In addition, we will start to develop the WECANet COST Action Book, which will document and reflect on the most important findings, guidelines, practices, etc. We will initiate the definition of the framework of the WECANet COST Action Book, in close collaboration with the WECANet Core Group and the Working Group leaders and Vice-leaders to obtain a state of the art of the work carried out within the scope of the WECANet Working Groups. The goal is to invite members of WECANet to contribute to the book, based on the publications published in well-known journals along progression of our Action.

Finally, we will optimize the intra- and inter communication of the different Working Groups by extending the WECANet website with an exclusive user area for communication between the WECANet members. This user area allows WECANet members to form groups focussing on specific topics.

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Optimization of Buoy Parameters for C-Gen Wave Energy Converter

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Marine waves are promising but challenging resource of renewable energy. Over 150 designs of the wave energy converters exist nowadays, and in Europe over 50% of them are focused on the point absorber technology [1]. Wave energy converters at Uppsala University (UU WEC) and University of Edinburgh (C-Gen) are based on the concept of a point absorber. It also involves a direct drive linear generator power take off. C-Gen currently undergoes tests in open water and it is adapted to be tested without hydrodynamic floater, through a motor, driving the linear generator. Modular system is developed, so that the generator can be adjusted to a particular wave climate of the deployment location [2]. UU WEC concept is represented by a buoy connected to linear generator via tight rope. Generator is placed on the bottom of the sea bed on a concrete foundation, while buoy is floating on the surface [3].

A numerical modelling was performed to calculate power output of C-Gen, taking into account various floaters. The buoyancy force limit was calculated for floaters of various height and diameter, then the average power was calculated. Evaluation of the floater parameters was done on the basis of the maximum of average power output.

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Short Term Scientific Mission on WEC modelling in DualSPHysics

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This Short Term Scientific Mission was carried out by two applicants from Ghent University (Belgium) Nicolas Quartier and Timothy Vervaet from 25/02/2019 to 17/03/2019 at the EPhysLab in Ourense and fits in the objectives of 'Working Group 1: Numerical hydrodynamic modelling for WECs, WEC arrays/farms and wave energy resources'. The main objectives of the STSM were to acquire the skills to perform basic simulations of Wave Energy Converters (WECs) in DualSPHysics [1] as well as more advanced simulations using the coupling techniques with Project Chrono [2] for the modelling of mechanical constraints, MoorDyn [3] for the modelling of mooring tensions and the wave propagation model OceanWave3D [4] for modelling WEC array/farm effects. The STSM started with the basis of the Smoothed Particle Hydrodynamics (SPH) method by looking into the governing equations, their numerically treatment and (dis)advantages of SPH. The workflow of DualSPHysics, the input and output files and the pre- and post-processing tools were treated.

Firstly, basic simulations were carried out with DesignSPHysics, which is the Graphical User Interface (GUI) allowing the design of simple DualSPHysics cases. The GUI was specifically useful for visualization of the considered cases and importing ".stl"-files of objects into the DualSPHysics domain. Special attention was given to wave generation, propagation, reflection and passive and active absorption. Post-processing tools for the representation of motion data of floating objects, data of water surface elevation and data of acting forces were used. Results were visualized in Paraview.

The recently developed coupling between DualSPHysics and Project Chrono [2] allowed the addition of mechanical constraints (hinges, springs, joints, etc.) to the domain, which can be used to study Power Take-Off systems of WECs. After the introduction with the DualSPHysics-Chrono coupling, the basics of the DualSPHysics-MoorDyn coupling were explained and trained by solving cases involving moored floating objects [3]. This STSM provided the applicants an intensive training in DualSPHysics, which allows them to apply this numerical tool on their own wave energy converter research cases.

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CFD analysis of Flap-type Wave Energy Converters

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Over the years, different configurations of flap-type Wave Energy Converters (WECs) have been developed, considering various characteristics (e.g. geometry of the flaps, location of the rotation axis, installation depth). Flaps have been investigated as standalone devices or combined in multi-body systems.

In this context, a new multi-body floating system with multiple flap-type WECs has been proposed in [1]. In that study, the hydrodynamic response and the power performance of the proposed system were investigated in the frequency domain using the potential flow theory. The generalized modes' concept was introduced for describing the flaps' rotation relatively to the platform, while emphasis was given on the interactions between the system's flaps. The results of this investigation indicated extreme values in the response of the WECs, attributed probably to viscous damping effects.

Motivated by this, a Short Scientific Mission (STSM) in the framework of the COST Action CA17105, has been granted to the first author of this abstract aiming at assessing and quantifying viscous damping effects on the response of the aforementioned system by conducting a Computational Fluid Dynamics (CFD) analysis. Considering the flaps of [1], the CFD analysis is implemented for an elliptical, fully-submerged rotating flap, hinged at the bottom with two rigid arms. A series of simulations is conducted for the examined WEC using the CDF toolbox OpenFOAM. The results of the present CFD analysis can be utilized for enhancing the numerical modelling of the proposed system and for optimizing its design.

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A decision support system to evaluate wave energy farms sitting

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The implementation of wave energy converters (WECs) in the EU is barely developed yet and requires more active research. The main barriers for the deployment of the wave energy industry in the region are the lack of political, legislative and regulatory support, low prices for electricity and heat generated from fossil fuels, lack of information for decision-makers as well as the preference for centralized energy supply schemes. These barriers are contributing to the inadequate investment for the implementation of new RES facilities.

Being Europe, a continent highly constituted by coastal countries, efforts should be focused on taking advantage of the marine resource and lead the strategies towards different ways of marine energy. Especial attention should also be put on small insular states. Islands have vast ocean resources at their disposal in comparison with their landmass and are distant from the big continental energy networks; thus, they constitute excellent opportunities for boosting marine energy exploration. This would help to reduce energy dependence and guarantee competitiveness, employment, and quality of life.

Consequently, more attention needs to be put now into providing policy-makers and investors with meaningful information about current technical, spatial and economic constraints of wave energy exploration and its possible contributions to the different nation's energy systems.

In the proposed research, different regions across the European coasts (Baltic Sea, North Sea, Atlantic Ocean, and the Mediterranean Sea) will be examined to identify the most suitable areas for the potential exploration of wave energy. For this purpose, a multi-criteria (MC) methodology will be implemented based on Geographic Information Systems (GIS). This methodology allows the combined assessment of the wave resource, together with technical requirements of WECs, economic cost, environmental impacts, inland energy demand and different spatial and socio-legislative constraints in a continuous space (see Figure 1). Further, resulting in suitable sitting alternatives will be ranked in terms of adequation for the sitting of a wave energy farm through a Multi-criteria decision method (MCDM).

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To include the energy demand and economic feasibility as ponderable factors in the MC and MCDM analyses, previous in-depth analysis is required for these factors. Moreover, the current energetic framework in the different EU inland territories is characterized in order to justify the relevance of implementing wave farms as new sources of renewable energy. On the other hand, the ranking of WECs by location is calculated to trough an equation that combines techno-economic parameters. This equation provides information about where the wave energy converters would deliver power at or below a given competitive cost. In this way, the best WEC could be identified for each location previously selected.

The study will be carried out for different case scenarios considering different kinds of WEC technologies. The results of this research constitute a prerequisite at early-stage research towards the installation of offshore wave farms across the European marine territory.

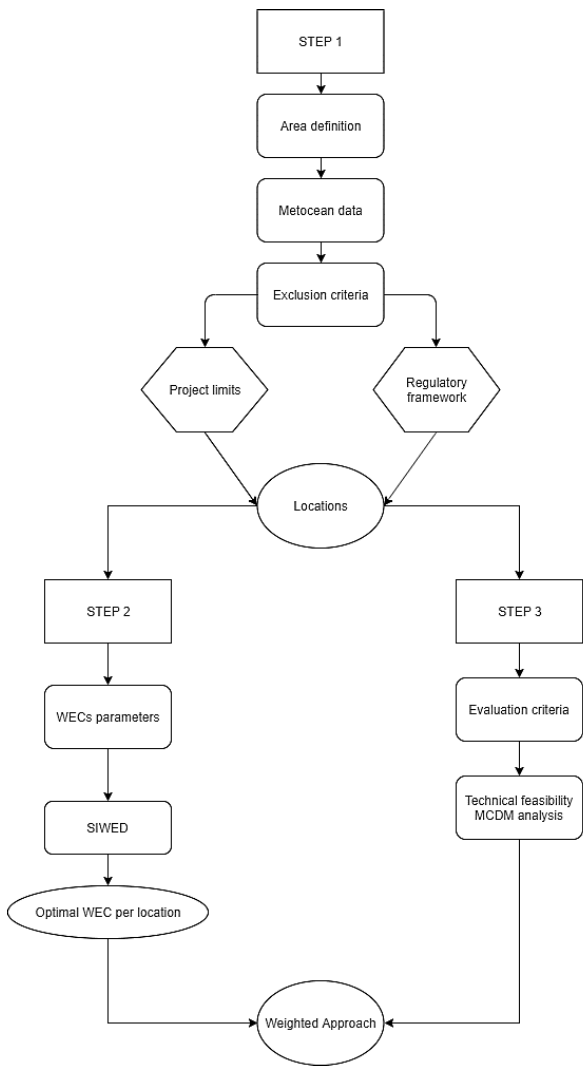

Figure 1. Methodology flowchart.

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