# LiftWEC

## DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

## Deliverable D2.3

## Review of Current Lift-Based WEC Concepts and Specification of Preliminary Configurations

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# EXECUTIVE SUMMARY

This document constitutes Deliverable D2.3 'Review of Current Lift-Based WEC Concepts and Specification of Preliminary Configurations' of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885. It is the intention of the project consortium that the LiftWEC project culminates in the identification of one or more promising configurations of a Wave Energy Converter operating through the use of one or more rotating hydrofoils that generate lift as the primary interaction with the incident waves. This report compiles information on pre-existing lift-based Wave Energy Converters, reports on the development of Preliminary LiftWEC Configurations and provides direction to research efforts during the second phase of the LiftWEC project.

In this document a literature survey is presented. This literature survey outlines information in the public domain relating to pre-existing lift-based Wave Energy Converters, as well as a small number of other devices which may be of interest to the consortium. As there are very few lift-based Wave Energy Converter concepts only a small number of devices are discussed. Furthermore, as there has historically been little interest in lift-based wave energy conversion, there is typically very little published literature even on those concepts. The notable exception to this is the CycWEC device, which has been the focus of study for a single research group for over 10 years and has been the focus of approximately 15-20 different publications. The CycWEC device is under development by the Atargis Energy Corporation and is a lift-based wave energy converter consisting of a pair of rotating hydrofoils that exploit lift to generate rotational shaft torque and ultimately, generate useful electrical output.

The learning obtained from the literature review was both directly and indirectly fed into the first LiftWEC project workshop. The aim of this workshop was to generate a suite of Preliminary LiftWEC Configurations that would form the basis for further research conducted during the second phase of the LiftWEC project. This report outlines the methods used in developing both individual elements of design/operational principles and complete LiftWEC configurations. The outcomes from these exist in the form of '*ideas*' and '*Preliminary LiftWEC Configurations*' respectively and are included in the appendices of this document. A discussion on the outcomes from collaborative consortium assessment of the range of configurations generated is included in Section 4, noting the identification of significant modularity/commonality across many of the configurations developed. It was found that the various elements of design consideration can be separated into six distinct areas including; hydrodynamics, control strategy, structural design, operations & maintenance, cost of energy and social & environmental impact. The completion of further work is therefore directed to addressing key design questions identified within these areas.

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# 1 INTRODUCTION

This document constitutes Deliverable *'D2.3 Review of Current Lift-Based WEC Concepts and Specification of Preliminary Configurations'* of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885.

## 1.1 PROJECT OUTLINE

The LiftWEC project focuses on the development of a novel type of Wave Energy Converter (WEC), called LiftWEC, which is intended to utilise hydrodynamic lift forces to incite device motion and extract wave energy using one or more rotating hydrofoils, as opposed to the more traditional approach of exploiting buoyancy and diffraction force regimes. This radically different approach to the design of wave energy converters offers the opportunity of making a step-change in the potential of wave energy, and thus lead the way for its commercialisation, where no commercially viable wave energy system currently exists.

## 1.2 PURPOSE OF DELIVERABLE

The fundamental purpose of this deliverable is to outline the proposed direction of research efforts during the second phase of the LiftWEC project. These directions were agreed by the consortium at the first LiftWEC project workshop, which was held in Project Month 06 (May 2020). Specifically, this is achieved through; (1) reporting on the outcomes of the first LiftWEC project workshop, (2) presentation of a suite of *'Preliminary LiftWEC Configurations'* which were developed by the consortium at that workshop and (3) the identification of key design considerations relevant for investigation by specific project work packages.

In order to ensure the LiftWEC project makes use of currently available knowledge and understanding, a literature review has been conducted and relevant learning obtained compiled within this deliverable. In order to maximise the usefulness of this work, findings from the literature review were directly and indirectly fed into the first LiftWEC project workshop previously mentioned.

Consequently, this deliverable has 2 main aims:

1. To provide an overview of all known, pre-existing Wave Energy Converter concepts which seek to operate either through the generation of lift forces, or some other potentially similar process, and
2. To report on the preliminary LiftWEC configurations developed at the workshop and provide direction for further research efforts.

## 1.3 DEVIATION OF DELIVERABLE

The content of this deliverable deviates slightly from its description in the LiftWEC proposal text. In the proposal, outcomes from the first project workshop were to be reported in Deliverable D2.2.

However, due to timing issues surrounding COVID 19, reporting on the first project workshop (Section 3 and Section 4) is now included here, in Deliverable D2.3.

## 1.4 STRUCTURE OF THE DOCUMENT

This document is divided into 4 main sections, including this introductory section. Section 2 presents a literature survey of pre-existing device concepts which seek to extract ocean wave energy by means of the generation or exploitation of lift forces. Where appropriate, this literature survey also includes elements of review on other devices which may be of interest to the consortium. Section 3 details the methods employed in the LiftWEC project workshop to encourage collaborative development of both particular elements of design (termed 'ideas') and entire potential LiftWEC configurations. Section 4 discusses the development of potential LiftWEC configurations and subsequently outlines key design considerations which should be further investigated during the second phase of the LiftWEC project.

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# 2 REVIEW OF LIFT-BASED WAVE ENERGY CONVERTER CONCEPTS

## 2.1 OUTLINE OF REVIEW

In order to ensure the greatest potential for successful development of the LiftWEC concept it is important that the LiftWEC project exploits pre-existing knowledge and understanding relating to the design and operation of lift-based Wave Energy Converters (WECs). As part of that knowledge capture, a literature search has been conducted on the most prominent lift-based wave energy conversion systems identified. This section provides a brief overview of those devices which have been identified as most relevant to the LiftWEC project. Note that there is only one lift-based Wave Energy Converter which has been the focus of a significant body of published work; the Atargis CycWEC [1]. Consequently, there is much more information available regarding this device than others. Rather fortunately, the design approach taken by the Atargis team in developing the CycWEC is probably the closest to the design brief for the LiftWEC of all the lift-based systems identified. In order to best present the information available, this review is separated into two sections. The first section gives a significant, however not exhaustive overview of the literature relating to development of the CycWEC device. As a result of the wealth of information available, this section is further sub-divided into meaningful sub-sections, each detailing research conducted on particular aspects of device design, hydrodynamics, etc. The second section comprises a series of much shorter reviews of each of the remaining device concepts that have been identified. As a result of the smaller volume of literature, these reviews are typically much less informed and shorter than the review of the Atargis CycWEC. Furthermore, in many cases, the information available on other devices is much less relevant to the LiftWEC project overall.

## 2.2 ATARGIS CYCWEC

From consideration of the available literature it is evident that of all lift-based Wave Energy Converters, the device concept which has undergone the greatest level of development is the Atargis CycWEC. While the majority of lift-based Wave Energy Converters have been only briefly considered, the CycWEC has been the focus of investigation for the Atargis company and its personnel for in excess of ten years, and whilst the research team consists of only a small number people, a significant body of work has been completed. This has included the development of a variety of numerical models and methods and at least three separate physical test campaigns, including two sets of wave basin tests conducted at 1:10 scale. The work of the team has led to the filing of a number of international patents and the formation of the Atargis Energy Corporation, which now acts as the conduit for further development and exploitation of the CycWEC concept. The remainder of this section is dedicated to outlining the nature and development of the CycWEC device, including details on the numerical and physical modelling reported in the literature. Note that the details presented here are far from exhaustive and much more information can be obtained from reader inspection of the literature mentioned. In particular much of Siegel, 2012 [2] and details from many other earlier works have been omitted for brevity.

### 2.2.1 Device Overview

From a fundamental perspective, the CycWEC device is not dissimilar to the outline design brief for the LiftWEC concept, consisting of a number of hydrofoils intended to exploit the generation of lift

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forces to drive their rotation around an axis aligned orthogonal to the incident wave direction (i.e. parallel to an incident wave crest).

The most recent iteration of the CycWEC design comprises two hydrofoils attached to a central shaft which generate lift in order to extract ocean wave energy and convert it to rotational shaft energy [1]. This rotational energy is converted to electricity by means of two direct drive permanent magnet generators. Both hydrofoils are set at a fixed radius from the central shaft and are intended to remain fully submerged beneath the free water surface at all times. Lift is generated through direct interaction between the hydrofoils and the wave-induced velocity flow-field. Hydrofoil pitch control is used to control the angle of attack experienced by the hydrofoil in an attempt to maximise hydrodynamic performance of the system. A 'mooring' system is employed to counteract the forces generated by the hydrofoils as well as the shaft torque at the generator. It is noted that previously, in 2015, the CycWEC system was described by the same author as "*one or more hydrofoils attached eccentrically to a main shaft*" [3] indicating that the developers may have considered operation with more, or less, than 2 hydrofoils, however all published literature considers systems comprised of two opposing hydrofoils set 180° apart.

A 3-dimensional CAD rendering of the most recently proposed full-scale prototype of the CycWEC system (taken from Siegel, 2019 [1]) is presented in Figure 1.

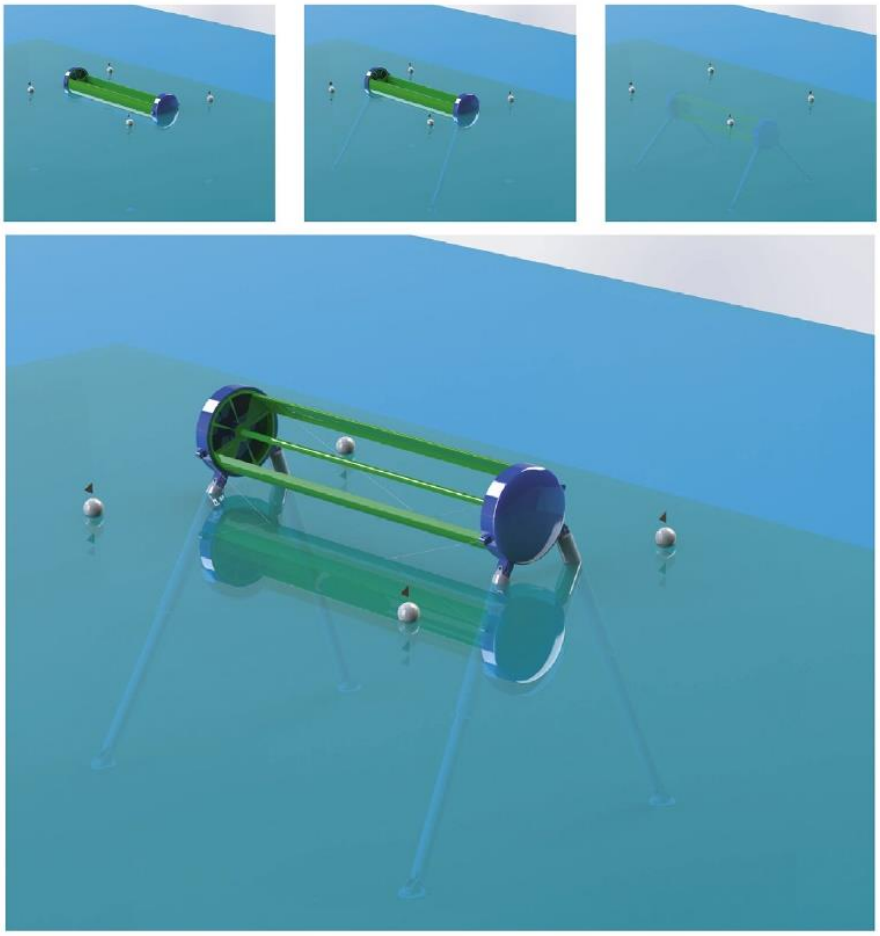

*Figure 1: 3-Dimensional CAD rendering of the most recently proposed full-scale CycWEC prototype. Taken from Siegel, 2019 [1].*

The top portion of Figure 1 shows the full-scale CycWEC prototype at three different levels of submergence. Note that this image does not correspond in any way to various tidal levels but rather demonstrates the 'jack-up' element of the support structure design which permits the rising and lowering of the prime mover and its associated components for installation, decommissioning and maintenance. The lower portion of Figure 1 presents a fully 'jacked-up' image, allowing reader inspection of the primary components of the CycWEC system above the free water surface.

In general terms, the CycWEC system can be assumed to consist of; (1) the rotor assembly, (2) the nacelles, (3) the jack-up struts and (4) the mooring system. The rotor assembly, shown as green in Figure 1, comprises the two main hydrofoils, a central shaft orientated along the rotational axis of the hydrofoils and the permanent magnet rotor elements of a pair of direct-drive permanent magnet generators. The rotor section also houses blade pitch control actuators along with their associated electromechanical components. In operation the entire rotor section is free to rotate about the rotational axis along which the central shaft is located. The two nacelles, shown in blue, house the stator components of the direct-drive generators, the main shaft bearings as well as the power and control system electronics. Each nacelle is held in position by two telescoping jack-up struts which are length adjustable through the use of a series of rack-and-pinion gear systems. The struts are attached to four mooring points installed on the ocean floor. It is noted that the mooring points can be located using suction caissons, driven piles, drilled rock anchors or any other suitable technology depending on the requirements as determined by the local ocean floor bathymetry. In addition, the struts are hinged at the supported nacelle such that they can be folded parallel to the main shaft for transportation and installation. This folding is achieved through the use of winches mounted on the opposing nacelle. Cables connecting the struts to the opposing side winches provide stability along the main shaft direction during deployment and operation and can be observed with careful inspection of Figure 1.

To provide an indication of the approximate device size, Siegel, 2019, also provides the dimensioned drawing reproduced here as Figure 2.

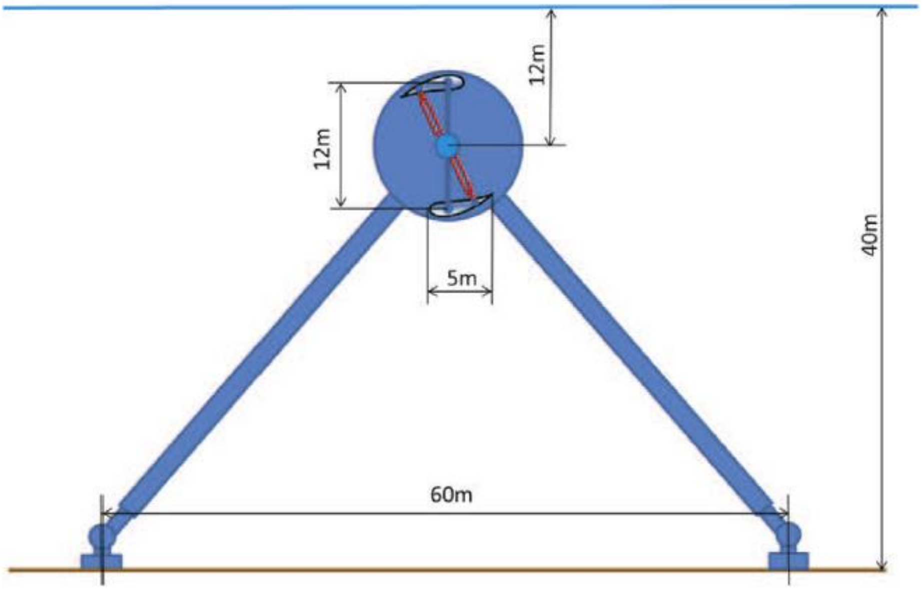

*Figure 2: Dimensioned drawing of the most recent full-scale prototype CycWEC device. Taken from Siegel, 2019 [1].*

While explicit dimensions are given, including the hydrofoil ‘span’ (also referred to as width, or length along the hydrofoil section) of 60m as shown in Table 1, it is noted that individual CycWEC systems should be sized according to the local wave climate for a given installation site.

*Table 1: Prototype CycWEC Dimensions and Characteristics*

| Property | Value | Unit | Operational State |
|---|---|---|---|
| Rotor Diameter | 12 | m | All |
| Hydrofoil Span | 60 | m | All |
| Hydrofoil Chord | 5 | m | All |
| Number of Foils | 2 | | All |
| Displacement | 375 | $m^3$ | Operational and Survival |
| Characteristic Mass | 420 | tons | All |
| Surface Area | 2883 | $m^2$ | Operational |
| Submergence | 12 | m | Operational |
| Submergence | 21 | m | Survival |
| Submergence | $-8$ | m | Maintenance |
| Nominal Generator Power | 2.5 | MW | All |
| Water Depth | 40+ | m | All |

It is noted by the author that this most recent iteration of the proposed CycWEC system is intended specifically for use in intermediate water depths of 40m – 80m. Brief details on alternative design concepts suggested for other water depths can be found in Section 2.2.8.4.

### 2.2.2 Numerical Modelling (Potential Flow Code Hydrodynamic Modelling)

Whilst the continued development numerical methods for assessing CycWEC performance have been outlined in the literature, for brevity, only the culmination of these will be reported. Where appropriate, notes may be added to indicate model or method beginnings or outline development pathways where this information is thought to be beneficial.

Primarily, the hydrodynamic performance investigations are conducted considering the conservation of energy using a control volume approach [1]. Naturally, within a defined numerical control volume, the inflow wave energy is known. Then, it is assumed that the hydrodynamic performance of the CycWEC system is suitably modelled by considering the modification of the incident wave train due to the device’s radiated wave field. Thus, the fundamental hydrodynamics of the system are represented through the application of a numerically generated radiated waveform to the control volume. This radiated waveform is constructed using a bespoke, inviscid 2-dimensional potential flow code which is adjusted to include corrections for 3-dimensional wave radiation effects. The balance of the control volume inflow wave energy and the control volume outflow wave energy (as adjusted by the user-generated radiated wave field of the CycWEC device) is therefore assumed to represent the energy extracted by the device. Subsequently, energy corrections are applied to account for viscous losses, as well as those experienced by non-hydrodynamic elements of device performance such as generator losses and control system actuator power losses. Consequently, the overall electric power is typically modelled by an equation similar to Equation 1.

$$P_E = \left( \underbrace{P_{W2D} + P_{W3D} - P_{DW} - P_H}_{\text{Wave Radiation}} - \underbrace{P_{D2D} - P_{DI}}_{\text{Viscous Losses}} \right) \eta_{GEN} - P_A.$$

*Equation 1: Wave-to-electric power equation used to estimate CycWEC efficiency. Taken from Siegel, 2019 [1].*

In this equation $P_E$ represents the overall electric power generated by the CycWEC system, $P_{W2D}$ represents the incident wave power entering the control volume and $P_{W3D}$ 'corrects' this value to account for the three-dimensional radiation effects of the CycWEC system. Naturally, the system will typically not be able to extract all incident wave energy and thus, $P_{DW}$ represents the outflow of remaining incident wave energy exiting the control volume down-wave of the CycWEC system. In a similar fashion, $P_H$ represents wave energy leaving the control volume however this time due to 'harmonic waves' radiated by the system. The balance of $P_{W2D}$, $P_{W3D}$, $P_{DW}$, and $P_H$ represent the radiation-based wave power absorbed by the CycWEC. This is then corrected by viscous drag terms $P_{D2D}$ which represents the 2-dimensional hydrofoil drag and $P_{DI}$ which represents drag due to the 'finite span' of the system. The net balance of all these terms is assumed to represent the mechanical rotational power available at the shaft which is further affected by the generator efficiency, $\eta_{GEN}$, and power extracted in activation of the hydrofoil pitch control mechanisms, $P_A$. It is noted that other losses such as bearing friction and radiation and drag losses due to structural elements are neglected.

Thus in outline, the hydrodynamic model can therefore be assumed to consist of; (1) the primary, inviscid, 2-dimensional potential flow code which uses a conservation of energy approach to estimate 2-dimensional wave cancellation efficiency, (2) a 3-dimensional radiation correction, and (3) a first principles viscous loss estimate based on published hydrofoil data.

#### *2.2.2.1 2-D Potential Flow Model*

The fundamental core of the CycWEC hydrodynamic performance assessment is based on a 2-dimensional linear potential flow code which is used to determine the interaction of a pair of rotating hydrofoils with the free water surface [1]. It is stated that in taking this approach it is assumed that the device hydrodynamics are suitably modelled using linear potential flow theory, and that the flow field around the CycWEC device is largely two-dimensional owing to the large span-to-chord ratio of the device design (see Section 2.2.1).

The numerical methods employed for the hydrodynamic performance assessment are based on earlier work by Marburg [4] where they were used to investigate the interaction of a single hydrofoil with the free water surface. The method was later extended by Siegel to incorporate the influence of a second hydrofoil [5]. Results from the numerical methods presented by Siegel were compared to results obtained from a series of physical experiments conducted at 1:300 scale [6] where it was stated that agreement was '*very good*' but discrepancies were observed, particularly during operation close to the surface. Specifically it is noted that the potential flow code simulations suggest a continually increasing radiated wave height as the submergence depth of the system is decreased, whereas the experiments suggest a reduction for very small submergence depths. It is assumed by the author that the deviations occur due to non-linear interactions between the hydrofoil and the free water surface however no further detail is given. Another discrepancy is noted in terms of reduced wave heights for higher frequency 'harmonic' components of radiated wave forms is attributed to effects of scale, owing to the particularly small 1:300 scale nature of the tests.

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For a complete description of the linear, two-dimensional potential flow methods the reader is referred to Marburg, 1994 [4] and Siegel, 2011 [5] however, the approach is also outlined in many later publications including; (1) Siegel, 2019 [1] where it is used to conduct a comparison of the CycWEC device with a series of traditional Wave Energy Converters, and (2) Siegel, 2014 [7] where the method is used to investigate the influence of device design parameters on hydrodynamic performance. In essence, the numerical method may be summarised as follows:

1. Each hydrofoil is represented as a single moving point-vortex with a strength equal to the hydrofoil circulation. A closed numerical solution for the complex flow potential of such a vortex in infinitely deep water was derived by Wehausen and Laitone [8] and was found to satisfy both the kinematic and dynamic free surface boundary conditions at the free water surface.
2. It is noted that in order to achieve meaningful results, the circulation was given a maximum bound according to a given hydrofoil section. In most works, the authors employ hydrofoil characteristics for a NACA0015 profile. In addition, the system is modelled such that operation is only permitted with hydrofoil characteristics representing an angle of attack which is below the critical angle of attack beyond which cavitation is expected to occur. These characteristics are stated to have been taken from published data.
3. Upon implementation, the circulation is held constant with the author claiming earlier work identified constant circulation as the most efficient mode of operation. It is noted that the circulation of each foil was equal in magnitude but of opposite direction, thus representing the opposing pitch of the two hydrofoils.
4. The location of each foil in time is driven according to the parametric form of the equation of a circle, thus representing the circular motion of the hydrofoils. The phase of the parametric equations is adjusted to achieve optimal cancellation through the opposition of radiated wave phase relative to that of the incident water wave.
5. Both kinematic and dynamic boundary conditions were then set. Derivations of a linearized kinematic free surface condition were taken from Newman [9] to ensure consistency of vertical velocity of the free water surface. A dynamic boundary condition ensuring atmospheric pressure at the free surface was derived from Bernoulli's equation.
6. Incoming waves were represented as '*a linear Airy wave*' with the velocity potential also taken from Newman [9].
7. The model then used linear superposition to generate a model of the hydrodynamic flow field through summation of the incident surface water wave potential and the potential of each hydrofoil system. The model used discrete numerical integration with time and wave number to solve for the flow potential induced by the point-vortex source terms representing the moving foils. Numerical convergence of the method for the range of conditions considered was shown in Siegel, 2011 [5].
8. Flow potentials are then used to recreate the free water surface and calculate power spectral densities up- and down-wave of the CycWEC device. The influence of radiated harmonics was observed and accounted for in the assessment of power extracted from the system. It is stated that as a result of the linear approach taken to the modelling the method can readily be adopted for investigation of both regular and irregular sea states.

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#### *2.2.2.2 3-D Wave Radiation Correction*

Early work conducted on the CycWEC device, such as that reported in Siegel, 2010 [10], Siegel, 2011 [5], Seidel, 2012 [11] and Siegel, 2012 [6], focused exclusively on methods developed and assessments completed in two-dimensional physical and numerical environments. During the first physical experiments conducted in a three-dimensional environment however, significant three-dimensional '*diffraction effects*' and '*wave focusing*' were observed. These are discussed in various sources including both Fagley, 2012 [12] and Siegel, 2012 [2]. In response to these findings, work began on development and validation of a numerical method capable of correcting the two-dimensional hydrodynamic model to account for the observed three-dimensional effects. Development of the method begins in Fagley, 2012 [12] and is further refined in Fagley, 2013 [13] and Siegel, 2015 [3]. The method has been employed in a number of investigations since and is outlined in a variety of works, including that given most recently in Siegel 2019 [1].

In brief, the resultant method attempts to 'correct' the previously determined two-dimensional radiation-based power capture (see Section 2.2.2.1) by adding power capture based on an additional three-dimensional element of the radiated wave field which had not been observed when the two-dimensional numerical method was developed. In CycWEC literature this has been described as representing the *'focusing'* of wave energy towards the device where the numerical scheme adopted for its representation allows it to extract energy from a span of the incident water wave front which is greater than the span of the device itself.

Essentially the approach first develops a representative three-dimensional radiated wave field consisting of the linear summation of a series of azimuthally cosine-modulated semi-circular wave fields. This series of wave fields is spaced along the span of the CycWEC device and superimposed atop the incident wave field. Then, as with the two-dimensional method a control volume approach is used to estimate the power capture as the balance of wave energy entering and leaving the control volume.

#### *2.2.2.3 Viscous Losses*

As the fundamental hydrodynamic models developed for assessment of the CycWEC are based on inviscid potential flow methods, there is no consideration of the potential impact of viscous losses on device performance. However, it was noted in Siegel, 2011 [5] that these losses could be as large as 30% of the extracted ocean wave energy at the 'design point' of the device – referring to the primary wave climate a specific CycWEC device is designed for. Consequently, post-model corrections intended to account for viscous losses have been developed by the CycWEC team and are outlined in Siegel, 2019 [1].

The work states that viscous losses experienced by the CycWEC hydrofoils are due to "*skin friction and foil pressure drag, since the flow at the hydrofoils remains attached throughout the entire operational range*" and that it is therefore possible to estimate these losses accurately using basic hydrofoil theory and data published from physical experiments. Two separate viscous loss elements are then considered namely; (1) viscous losses due to two-dimensional hydrofoil drag and (2) viscous losses due to the three-dimensional nature and finite span of the hydrofoil.

In short, viscous losses due to two-dimensional hydrofoil drag are estimated by first considering the relative flow field on the hydrofoil, taken as the vector composition of both a function of the body self-velocity and the wave-induced fluid velocity. Then, lift and drag forces experienced by the CycWEC hydrofoils (assumed as NACA0015 profiles) are calculated based on experimental data published by

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Sheldahl and Klimas, 1981 [14]. It is noted that the experimental data was "*interpolated in Reynolds number to match the operating conditions of the CycWEC hydrofoils*". This estimate of drag force is then combined with the tangential body velocity to estimate performance reduction due to two-dimensional hydrofoil drag.

Viscous losses due to "*the finite span of the hydrofoils*", or, "*the induced drag*", was estimated using basic hydrofoil theory as described in Glauert, 1947 [15]. Siegel sates that this is an additional drag force which increases with the square of the coefficient of lift and equations are given in the text of Siegel, 2019 [1].

#### *2.2.2.4 Generator and Pitch Actuator Power Loss Models*

Note that two non-hydrodynamic model power loss terms are also contained within Equation 1. These are the generator efficiency $\eta_{GEN}$ and power extracted in activation of the hydrofoil pitch control mechanisms $P_A$. As these are not hydrodynamic modelling elements they have been omitted from this review for brevity, however their existence is noted for completeness. Should the reader wish to learn more they are directed to Siegel, 2019 [1].

### 2.2.3 Numerical Modelling (RANS Hydrodynamic Modelling)

Further hydrodynamic modelling of the CycWEC device has also been completed by Caskey, 2014, [16] using a high-fidelity Computational Fluid Dynamics approach. In particular the work seeks to develop an Unsteady Reynolds Averaged Navier-Stokes model of the CycWEC system. However, it does not appear that this work has been subsequently published under peer-review. Whilst the details of this work are not detailed here its existence is noted for the benefit of the reader's curiosity.

### 2.2.4 Numerical Modelling (Mechanical/Structural)

In comparison to hydrodynamic modelling, considerably less has been reported on the structural or mechanical modelling of the CycWEC system. The most comprehensive, and recent, report on modelling of the CycWEC system from a mechanical or structural perspective was reported in Siegel, 2019 [1]. In this work, Siegel sought to benchmark a CycWEC system against a variety of traditional Wave Energy Converter device concepts. These traditional device types had been previously modelled and benchmarked in work by Babarit et al. in 2012 [17], who developed a series of device comparison metrics that included items such as hydrodynamic performance, structural efficiency and the Levelized Cost of Energy. In order to benchmark the CycWEC system against those systems required consideration of the range of metrics employed by Babarit et al and thus, also required the development of some understanding of the structural requirements/characteristics of a prototype CycWEC device.

In short, Siegel, 2019 [1] notes the development of a complete, conceptual CAD model of a given CycWEC device, including foundation details. For ease of reference, a rendered image of the CAD model is reproduced below in Figure 3. For outline details on sizing the reader is referred back to Figure 2 in Section 2.2.1 of this report. Siegel, 2019 notes that all dimensions in the system are to scale and are designed according to estimation of structural loads, however without detailed design of bolt patterns, stiffeners or fittings etc.

Siegel states that all structural loads culminating in the mechanical design of the CycWEC system were estimated based on hydrofoil lift, drag and pitching moment coefficients of blade profiles taken from published literature found in Sheldahl and Kilmas, 1981 [14]. Relative flow on the foils were taken as the vector sum of the body self- and wave induced velocities, with the latter estimated using Airy wave

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theory. Using this approach, the span-wise loads experienced by the foils (assuming an elliptical span-wise lift distribution) were integrated across the span of the CycWEC device for a given '*design*', '*storm*' and '*short*' sea state. It is noted that the simple, well established understanding of the fluid dynamics of fully submerged hydrofoils allowed for "*very accurate estimation of the structural loads*" using simple hand calculations to propagate design loads from the hydrofoils through the nacelles and into the jack-up struts. For hydrofoil assessment, both bending due to lift distribution and torque due to pitching moments were considered. These loads were propagated through the structure, along with other loads such as hydrostatic loading of the nacelles in order to size the primary structural components. It is noted that slam loads were not considered due to the submerged nature of the device.

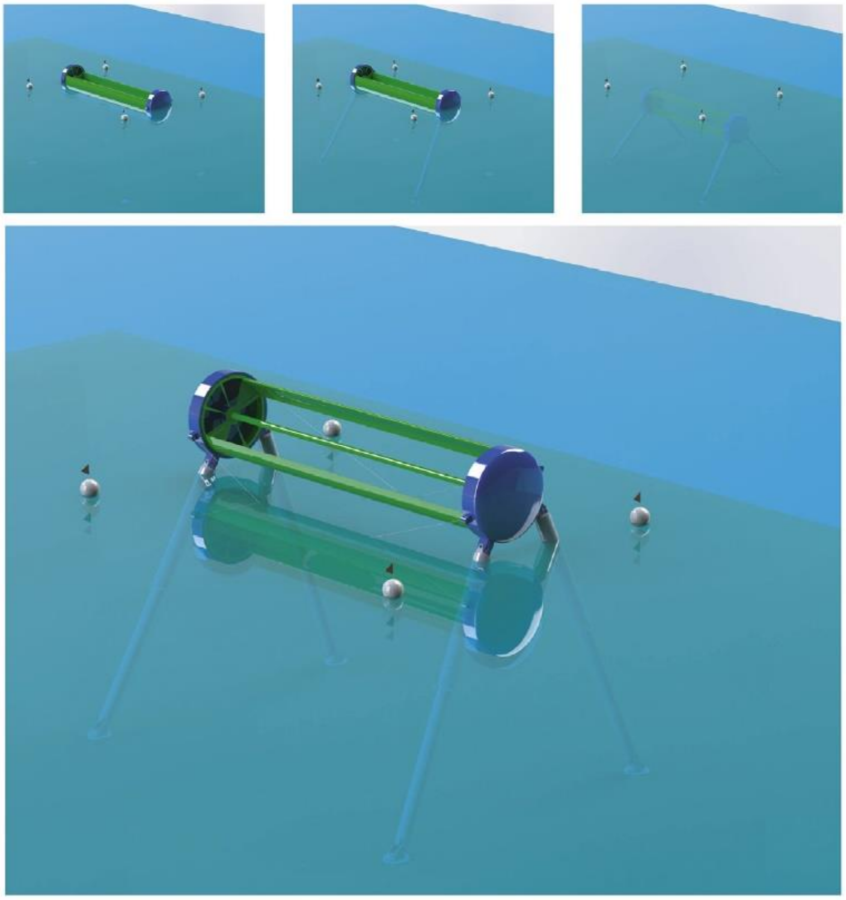

*Figure 3: 3-Dimensional CAD rendering of the most recently proposed full-scale CycWEC prototype. Taken from Siegel, 2019 [1].*

### 2.2.5 Physical Modelling

From inspection of the literature it would appear that two primary sets of physical tests have been conducted on the CycWEC system. The first set of tests was conducted at 1:300 scale, where a small-scale model was tested in a two-dimensional environment with the model spanning the entire width of the wave flume. Details on these tests are can be found in Siegel, 2011 [18] and Siegel, 2012 [19]. The second, and latter, set of tests were conducted at 1:10 scale, with a significantly larger and more complex model tested in a fully three-dimensional environment with results and details reported in Fagley, 2012 [12] and Siegel, 2012 [2].

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### 2.2.6 Hydrodynamic Performance

In Siegel, 2019 [1] it is noted that the fundamental hydrodynamics of the CycWEC system are significantly different than those of more conventional Wave Energy Converters which typical rely on the hydrostatic force, or buoyancy, for their means of interaction with incident water waves. In the same reference the CycWEC device is stated to belong to the terminator category of Wave Energy Converters as a result of its primary dimension aligning perpendicular to the direction of wave travel. The work notes that the underlying principle of the CycWEC device, and thus the key driver on its development pathway, is the extraction of wave energy by means of cancellation, where the down-wave radiated wave entirely cancels the incident wave by means of linear superposition. This is reflected heavily in the approach taken to hydrodynamic modelling where the typical approach is not to model the device itself but rather to attempt numerical representation of its expected radiated wave field (see Section 2.2.2), thus allowing a control volume approach to estimate the power extracted as a function of the difference between the wave energy entering and leaving the control volume. Thus the ideal would be that if only down-wave device-based radiation occurs, and that radiated wave is equal to the incident wave however propagated in anti-phase, the result would be complete cancellation of the incident wave and thus the possible extraction of all incident wave energy (see Figure 4 reproduced from Siegel, 2019 [1]).

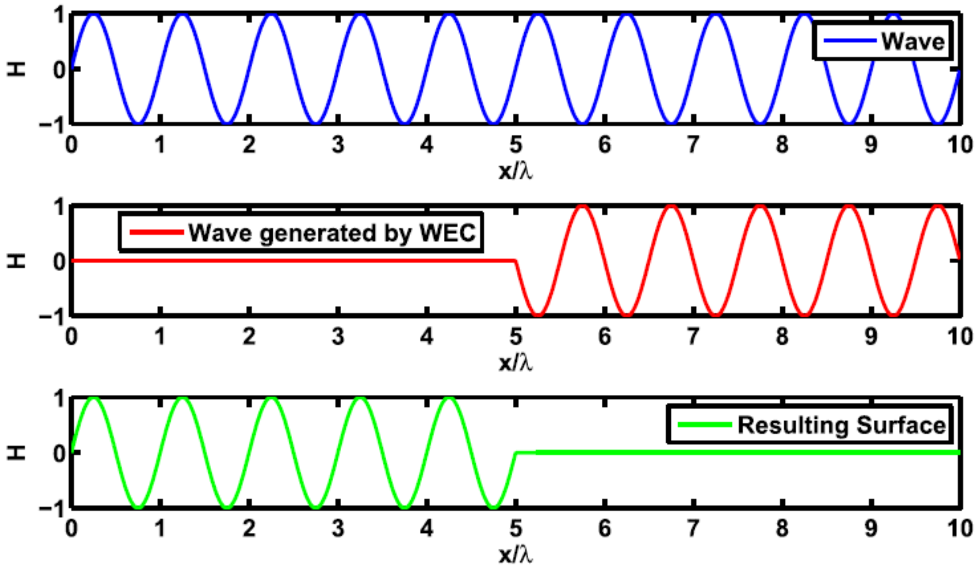

*Figure 4: Representation of Wave Energy Extraction by Radiated Wave Cancellation of the Incident Wave [1]*

Siegel notes that in taking this approach, it is important that the radiated wave profile is modelled accurately, as if the Wave Energy Converter generates additional waves in other directions, or if the amplitude or phase of radiated waves is not correctly modelled then the system performance could be significantly misrepresented. Furthermore, this highlights the importance of control in this approach to wave energy extraction where the wave height, length and phase must all be controlled precisely to optimise the potential for cancellation of the incoming wave.

As with any system, it is important that the hydrodynamic findings presented in the remainder of this section are considered in parallel with the numerical methods used to generate those findings. Whilst this is true of any system, the point is emphasized due to the unique nature of the approach taken compared with more traditional numerical methods commonly employed in the wave energy industry.

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#### *2.2.6.1 Outline Hydrodynamic Performance*

Early work by the CycWEC research team built on the work of Hermans et al, 1990 [20] and Marburg, 1994 [4] who both worked on the development of a lift-based Wave Energy Converter consisting of a single rotating hydrofoil. It is noted by Siegel, 2019 [1] that this research was discontinued due to physical and numerical findings of poor conversion performance which was typically only a few percent of the incident wave energy. Over a decade later, this work was expanded by Siegel et al, 2011 [5] to include a second hydrofoil as well as "*feed forward control of the hydrofoil circulation*" which was based on measurements of the incoming wave. This work involved two-dimensional hydrodynamic modelling of the system using an inviscid potential flow approach where each hydrofoil was represented as either a point vortex source or discrete panel vortex. In this work the system's performance as both a wave generator and a Wave Energy Converter operating in regular, Airy waves is demonstrated. Most notably it is found that the system is capable of extracting greater than 99% of the incident wave energy, however it is recognized that this requires "*optimal parameter choices*" and feedback control to "*synchronize the rotational rate, blade pitch angle, and phase*" of the system. The work also finds that the wave height of the radiated wave (i.e. the wave generated by the hydrofoil) varies linearly with the hydrofoil circulation and that the optimal device radius was determined to be $2R/\lambda_{Airy} = 1/\pi$ where $R$ is the radius at which the hydrofoil rotates and $\lambda_{Airy}$ is the wavelength of the incident regular wave. Thus, whilst the work indicates that the rate of rotation, blade pitch angle, and phase relative the wave should all be controlled, this finding would suggest that some form of varying the operational radius is also useful for real world applications. Upon completion the work concluded that the use of two opposing hydrofoils with opposing circulation greatly improved the wave-making capabilities of the device and, thus, its potential hydrodynamic performance. It was stated that for the modelled system, complete termination of incident waves is possible, with the balance of energy not extracted being lost due to harmonic waves radiated in the up- and down-wave directions.

Despite the numerical simplifications employed, the majority of these findings were largely confirmed by the same authors using small scale physical testing undertaken at 1:300 scale in a two-dimensional testing environment where extraction efficiencies of up to 95% were observed [21].

Following the promising findings obtained for two-dimensional performance assessment in regular waves, the authors continued on to investigate the system's promise for irregular waves [22]. In this work it was found that the use of a dual-hydrofoil system coupled with the feed-forward control not only enabled numerical wave cancellation in regular waves, but also in irregular waves governed by a typical Bretschneider spectrum. Wave flume experiments conducted by Siegel et al, 2012 [19] confirmed these findings and further improvements to the feed-forward control algorithm which included adjusting shaft rotation as well as blade pitch angle increased irregular wave energy extraction efficiencies such that they were stated to be similar to those obtained in regular sea states [23].

Up to this point, all simulations and experiments had been two-dimensional in nature. Consequently the potential influence of three-dimensional effects on device performance were unknown. Furthermore, all wave energy extraction efficiencies were estimated based on wave measurements made on the up- and down-wave sides of the device using a control volume approach as neither the numerical nor physical experiments could determine shaft power by design.

The influence of three-dimensional effects on the performance of the system were not considered until a series of three-dimensional physical experiments were conducted at 1:10 scale. During these three-dimensional tests extraction efficiencies were found to be significantly lower than expected [12]. Further numerical work was therefore conducted to determine the influence of operation in a three-dimensional environment on the performance of the CycWEC system [7], [13], [24].

Results obtained from the three-dimensional numerical simulations are stated to agree well with experimental results and a number of conclusions are drawn. Firstly, a potential increase in power extraction beyond that obtained in two-dimensional operation is noted as a result of '*wave focusing'* where small CycWEC spans are employed [13]. As the span is increased, this potential increase in performance is found to diminish as the system approaches a 2D limit for very large spans. This led to an investigation of the deign space, culminating in the finding that the optimal device performance is found at a much smaller radius of approximately $2R/\lambda_{Airy} = 0.1$ [3]. This suggests an approximate three-fold reduction in the optimal operational radius when three-dimensional effects are considered. The authors state that this occurs due to a trade-off between wave radiation efficiency, which favours larger diameters and viscous losses, which favour smaller diameters.

As an example of the hydrodynamic efficiency of the CycWEC device operating in irregular sea states, Siegel, 2012 [2] presents a timeseries of wave surface elevation both up- and down-wave of the CycWEC device. Evidently there is a significant reduction in the wave induced free surface undulation on the lee-side of the device indicating the extraction of wave energy.

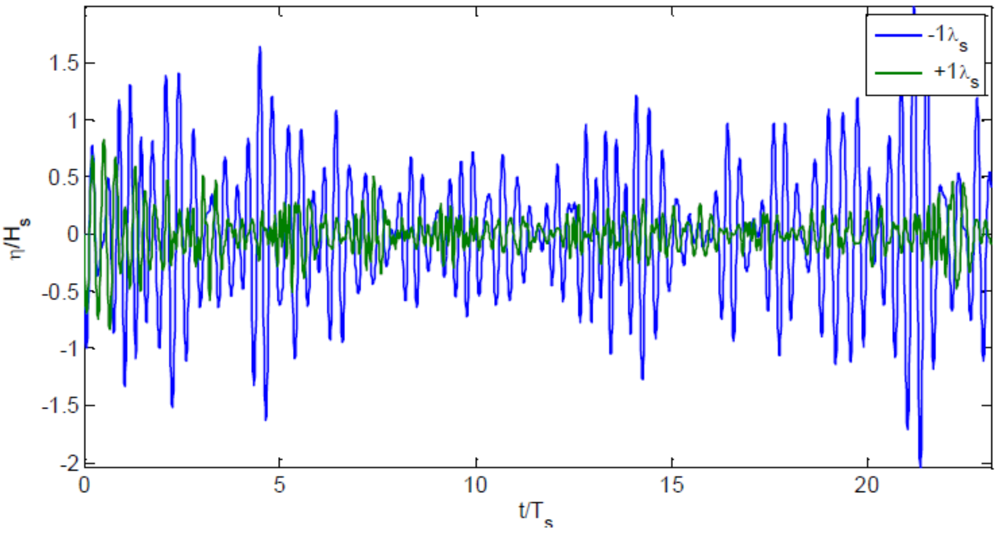

*Figure 5: Example of CycWEC irregular wave energy extraction shown as the reduction in free water surface elevation due to incident wave action up-wave (blue) and down-wave (green) of the CycWEC device [2]*

#### *2.2.6.2 Wave Focussing*

As noted in Section 2.2.6.1, early work on the CycWEC device consisted of physical and numerical assessments conducted in fully two-dimensional environments. The influence of three-dimensional hydrodynamics on system performance were not considered until after a series of physical experiments conducted in a three-dimensional testing facility produced significantly lower performance values that initially expected [12]. As part of this work, the three-dimensional radiated wave pattern of the CycWEC device was observed and quantified for the first time. This led to the development of a new, three-dimensional radiation correction model which was subsequently applied as a correction during use of the two-dimensional potential flow model which was typically used to undertake CycWEC performance assessments. This model was then used to investigate the hydrodynamics of three-dimensional CycWEC systems of finite span (see Fagley et al, 2013 [13], Siegel et al, 2013 [24], Siegel, 2014 [7] and Siegel, 2015 [3]). It was noted that under particular circumstances, CycWEC-like systems of short span could interaction with a greater extent of the incident water wave than the systems own width (or span). This was reported to increase the available wave power that could be extracted by the CycWEC system to more than that physically encountered by the device. An example of the outcome from these investigations is given in Figure 6 which presents the device efficiency for a variety of span to wavelength ratios. Note that the efficiency is plotted against the height of the radiated wave generated at the centre of the device normalised by the height of the incident water wave. Further discussion on the relevance of this presentation and further figures are presented in Siegel, 2015 [3].

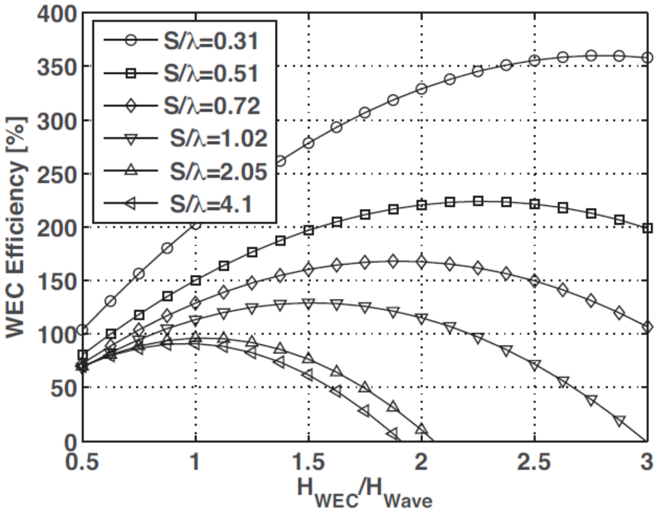

*Figure 6: Wave cancellation efficiency and WEC wave height as a function of the ratio between incoming wave height and centre height of the WEC generated wave for different span to wavelength ratios. T = 2.5 s. Taken from Siegel, 2015* [3].

### *2.2.6.3 Scatter Matrix Performance*

The power matrix presented in Figure 7 is taken from Siegel, 2019 [1] and outlines the performance of the particular CycWEC system detailed in Section 2.2.1 in a variety of sea states.

Figure 7 demonstrates a distinct wave height below which no power generation occurs. This wave height increases significantly with shorter wave periods and is noted to be due to a steep increase in drag induced losses experienced at shorter wave periods. The authors note this 'cut-in' wave height to be analogous to the cut-in wind speed for wind turbines and is caused by the dominance of hydrofoil drag over the potential lift. It is stated that this could be overcome by either; (1) reducing the chord length and thus reducing the drag force due to a reduced surface area, or (2) decreasing the operational radius and thus reducing the drag induced shaft torque. It is stated that the rationale behind the CycWEC's approach in not implementing either of these 'corrections' is due to the would-

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be reduction in performance in larger sea states. This has led the CycWEC team to suggesting a ‘per wave climate’ approach to the design of a bespoke CycWEC system in terms of operational radius, chord length and device span, for any particular deployment location. These suggestions appear to be based on a design space investigation conducted in Siegel, 2014 [7] and supported by similar elements of design space investigation conducted in Fagley, 2013 [13], Siegel, 2013 [24] and Siegel, 2015 [3].

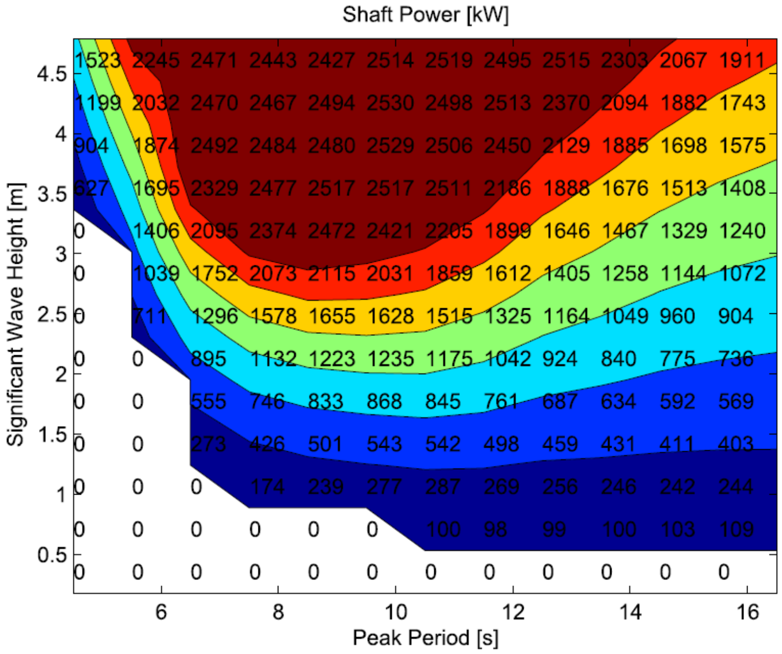

**Fig. 11.** Power matrix for a WEC with $R = 6m$, $C = 5m$, $S = 60m$ and $P_{gen} = 2.5MW$.

*Figure 7: Power Matrix for a CycWEC with 6m Radius, 5m Chord Length and 60m Device Span [1]. Note that the influence of a generator with rated power 2.5MW is incorporated in the modelling.*

### *2.2.6.4 Design Space Investigation*

During attempts to tailor the CycWEC system to optimise power capture in a given wave climate, Siegel, 2014 [7] considered the impact of device radius, chord length and span on the overall hydrodynamic performance. Specifically, the author considered the impact of these design variables on; (1) the average annual shaft energy yield, (2) capacity factor and (3) power production time fraction. The average annual shaft energy yield is simply the amount of energy extracted from the incident wave climate that is made available at the shaft of the device; that is, the total hydrodynamic energy extracted from the sea. The capacity factor is defined as the portion of energy extracted, or the efficiency. Finally, the power production time fraction gives the percentage of time the WEC operates such that it is actively converting incident wave energy into a useful output. As an additional point of interest, the author also briefly investigates the influence of variation in the blade profile adopted.

In this work the author used the traditional means by which the CycWEC system’s hydrodynamic performance has been assessed. This method is outlined in Section 2.2.2 but may be summarised as a control volume approach where the balance of wave energy entering and exiting a control volume encompassing the WEC is assumed to represent the portion of energy extracted by the device. The device hydrodynamics are represented by means of the application of the influence of its radiated wave profile on the incident wave train where this radiated wave profile has been modelled using a two-dimensional potential flow method where each hydrofoil is represented as a point-vortex source with constant circulation. The model is corrected to account for three-dimensional effects viscous loss estimates based on published hydrofoil data.

To begin, Siegel presents the Cancelled Wave Power, $P_{cancel}$, Harmonic Power Losses, $P_{harmonic}$, Drag Power, $P_{drag}$, and overall Performance Efficiency, $\eta$, as a function of wave height and period[1]. Often these are normalised against the Incident Wave Power, $P_w$. These results are reproduced here in Figure 8 and it is noted that the results appear to be for operation of a WEC with design characteristics tailored to be optimum for a specific wave climate. Furthermore, it would appear that these simulations represent performance in irregular sea states however this does not appear to be stated explicitly. It is noted however that system performance is approximately equal in either regular or irregular waves for comparative sea states when ideal feed-forward control is implemented.

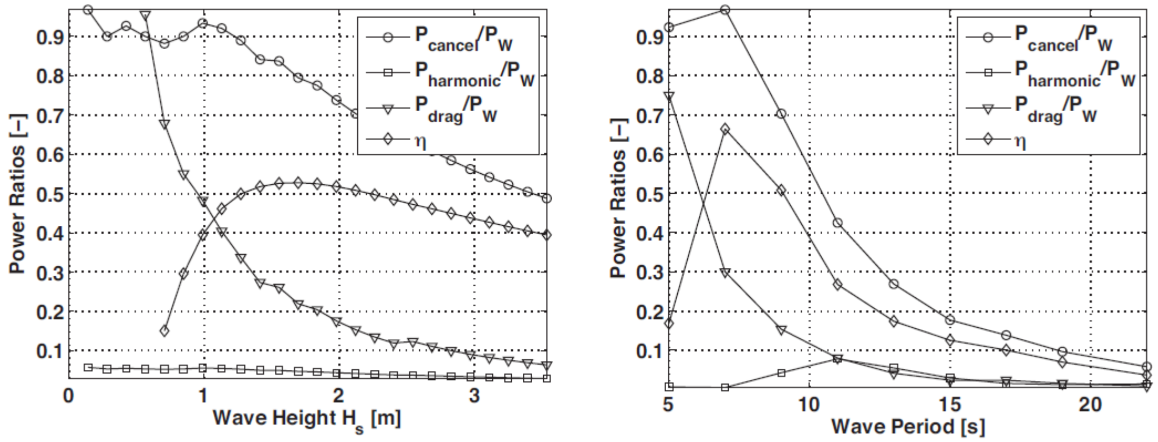

*Figure 8: Cancelled wave power, harmonic power losses, drag power and overall efficiency for a WEC with R=5m and c = 5m. Left, period T=9s. Right, wave height $H_S$ = 2.1m. (Taken from Siegel, 2014 [7])*

Note that the device radius was set to R=5m and the chord length set to c=5m for these simulations. Evidently, where the drag power exceeds the cancelled power, no motion will occur. The authors refer to this as the 'cut-in' point of the device. The peak efficiency encountered by the system is noted to be $\eta = 0.68$ for operation at T = 7s. This is subsequently referred to as the 'design-point' for the system and, in overly simple terms, forms the basis of how the CycWEC research team seek to tailor device parameters for operation in a given wave climate. For a significantly deeper discussion of the author's perceived reasonings behind the nature of the figures presented and the approach taken to tailoring device design to a given wave climate, the reader is referred to Siegel, 2014 [7].

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[1] For clarity, in reading the work it appears that Cancelled Wave Power is essentially the power extracted from the wave as estimated by the radiated wave superposition, Harmonic Power Losses are those due to radiated waves which are harmonics of the operational frequency of the system (often referred to as the Fundamental frequency in CycWEC literature) and Drag Power is the influence of the drag force on the hydrofoil generating a resistive torque at the shaft.

***Chord Length***

The performance of a CycWEC device with a variety of chord lengths is presented in Figure 9, which has been taken from Siegel, 2014 [7]. The figures show performance with both wave height and period. In all cases, the radius is held constant at 5m and thus the influence of chord length on performance can be considered with the variation in results presented. As previous, a commentary on the author's discussion is not presented here for brevity. For further information the reader is referred to the original work. Note that the results are presented for the two-dimensional case of infinite device span.

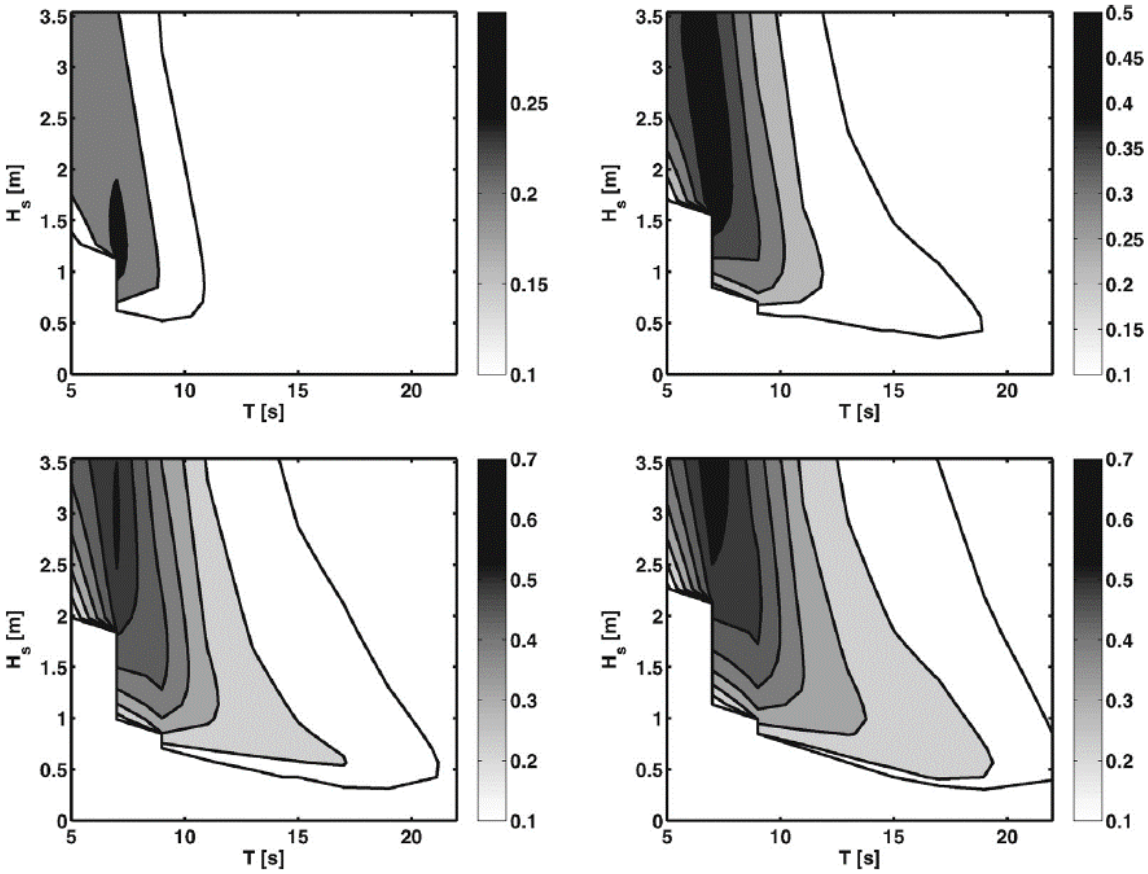

*Figure 9: Impact of chord length on two dimensional WEC efficiency. The hydrofoil chord was varied from c = 1 m (top left) to c = 3 m (top right) to c = 5 m (bottom left) and c = 7.5 m (bottom right), while the WEC radius was kept constant at R = 5 m. (Taken from [7])*

***Device Radius***

The performance of a CycWEC device for two different operational radii is presented in Figure 10, which has also been taken from Siegel, 2014 [7]. It appears a similar investigation to that conducted for chord length was undertaken however in this instance, the chord length was also varied to maintain the non-dimensional chord length $c\colon R = 1$. Thus, not only was the device radius varied, so too was the chord length such that in both instances shown below (Figure 10) the chord length of the CycWEC hydrofoils was set equal to the device radius. As previous, only a portion of the results are presented here, and the reader is referred to the original works for the author's commentary and discussion of further investigation. Note that the results are presented for the two-dimensional case of infinite device span.

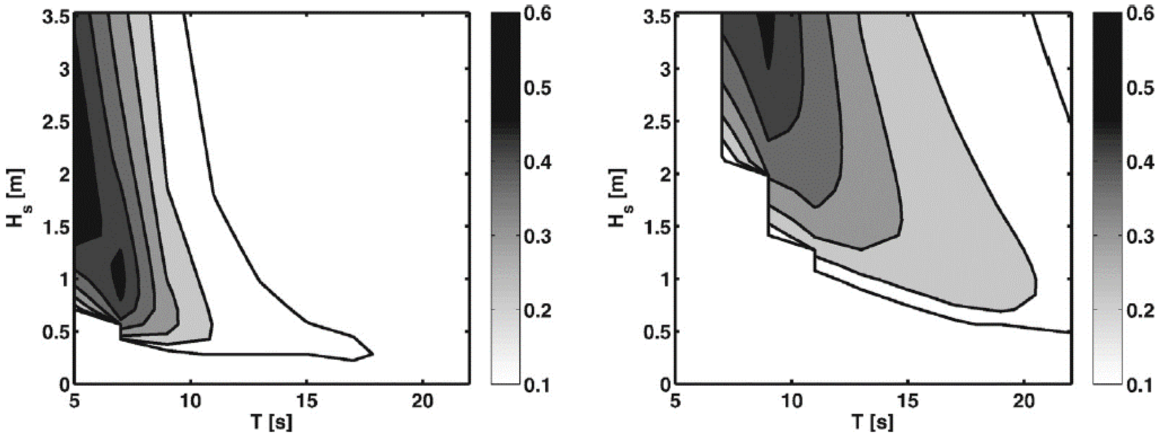

*Figure 10: Impact of WEC radius on two dimensional WEC efficiency. The WEC radius was R = 3 m (left) and R = 7.5 m (right), with the same non-dimensional chord length of c/R = 1 for both cases. (Taken from Siegel, 2014* [7]*)*

***Device Span***

The influence of CycWEC span on system performance is presented in Figure 11, which has been taken from Siegel, 2014 [7]. The figure presents both the efficiency of the average annual power production for a given wave climate and the non-dimensional shaft power for operation of the WEC in a given wave climate. It is not explicitly stated how the shaft power is non-dimensionalized however it is noted in the work that the optimal efficiency of 40% occurs at a span of 40m. Beyond this span the system efficiency is found to decrease and plateau at approximately 35% however the non-dimensional shaft power is found to increase approximately linearly with span. Thus, the decrease in efficiency is stated to be "*more than compensated*" for by the larger amount of incoming wave energy available.

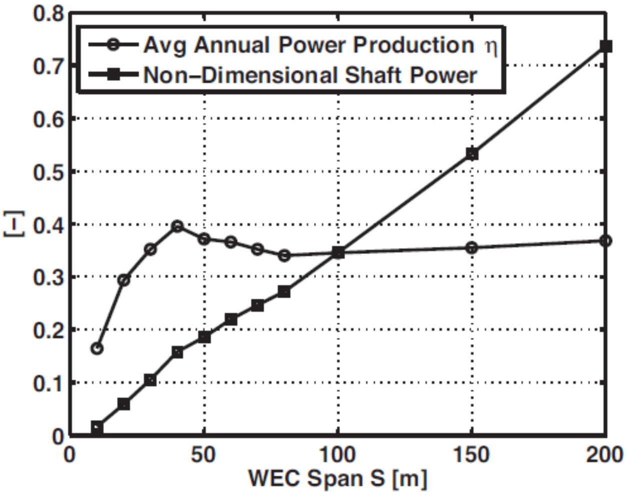

*Figure 11: Annual average shaft power and annual efficiency as a function of WEC span. Three dimensional WEC radius R = 5 m and chord c = 5 m. Data shown is based on unlimited generator power, and specific for the Mokapu wave climate. (Taken from Siegel, 2014,* [7]*)*

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***Hydrofoil Profile***

In the vast majority of CycWEC literature spanning the duration of ongoing investigations, the authors have employed a NACA 0015 profile hydrofoil. In the work presented by Siegel, 2014 [7] it is noted that this profile is “well established” as a basic, symmetric hydrofoil, but that it does not yield optimal performance in term of either lift-to-drag ratio or high lift generation capability. Whilst the author does not go on to investigate the influence of profile design space, the potential for improvement is noted by means of comparison between results obtained for the traditional NACA 0015, and the NACA 63-815 which is offered as a generic cambered hydrofoil. Results are reproduced here as Figure 12 and it is evident that the NACA 63-815 typically appears to outperform the traditional NACA 0015. However, without an improved understanding of the requirements of a hydrofoil section for ideal operation of such a device, it could be argued that it is hard to draw any definite conclusion on superiority. In this particular instance however, clearly the NACA 63-815 has improved the exampled performance.

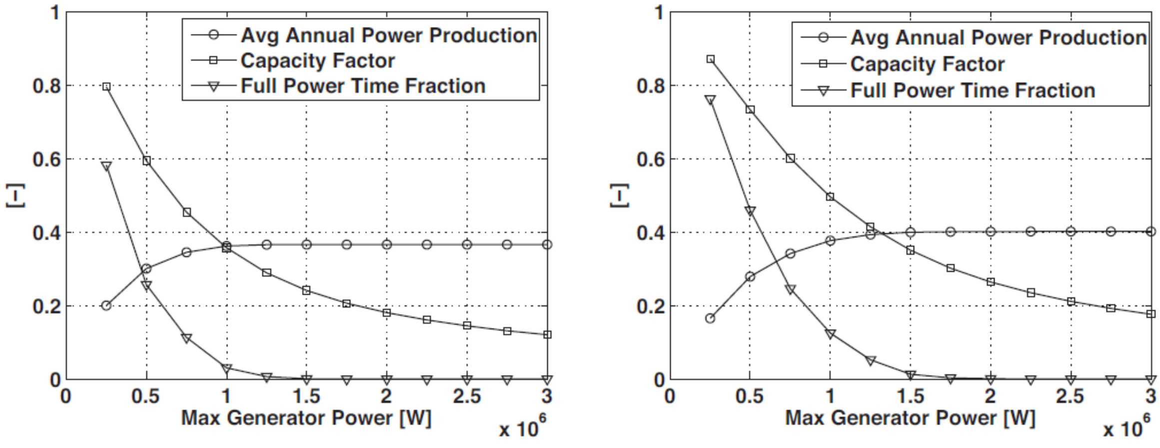

*Figure 12: Impact of hydrofoil shape on WEC performance. Left, NACA 0015. Right, NACA63815.WEC geometry R = 5 m, c = 5 m and S = 60 m. Taken from Siegel, 2014* [7].

### *2.2.6.5 Operation with Variable Submergence Depth*

During the 1:10 scale physical testing described in Section 2.2.5, the influence of submergence depth on the operation of the CycWEC device as a wave generator was investigated. Findings are reported in Siegel, 2012 [2]. Results from the testing which show the power required to spin the CycWEC in still water as a function of submergence depth are presented in Figure 13. Note that the device was driven with constant blade pitch angle and period of rotation across all submergence depths. The results show that greater power is required to spin the CycWEC device as the submergence depth is reduced. The authors state that while the drag induced portion of the shaft power required remains the same regardless of submergence depth, operation closer to the free-water surface results in the generation of larger waves which in turn requires greater input of shaft power. The authors make no note of the perceived significance of their observation in relation to operation of the system as Wave Energy Converter.

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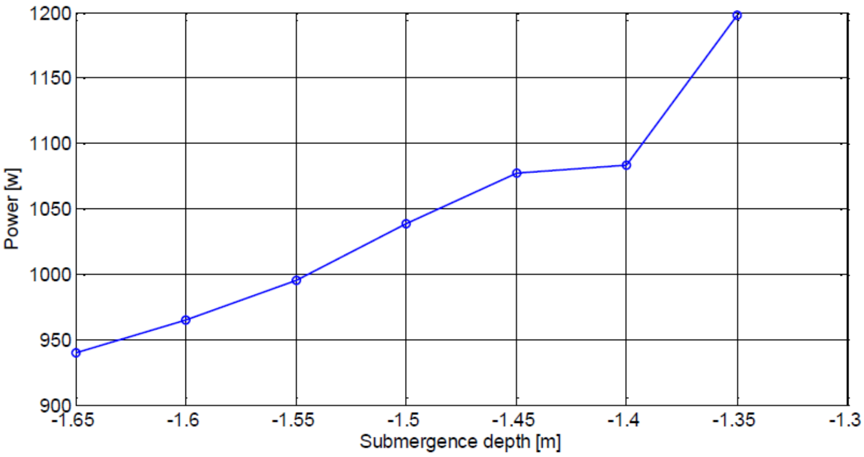

*Figure 13: Power versus submergence depth for fixed angle of attack and rotational period. At larger depths less power is needed to spin the WEC due to less losses with surface interactions (taken from Siegel, 2012 [2])*

### 2.2.6.6 Operation with Oblique Wave Angles

The influence of directionality of the incident water wave train on the efficiency of a CycWEC device was first considered in work by Fagley et al, 2013 [13] and then further presented in Siegel et al, 2015 [3]. This work was conducted using numerical methods outlined in Section 2.2.2, however without the inclusion of the accountancy for viscous losses. The modelling methodology may therefore be described as a control volume approach balancing the known incident wave energy entering the control volume with that leaving the control volume where the CycWEC device is modelled by the influence of a numerically generated radiated wave field. The mismatch between the wave energy entering and leaving the control volume was assumed to be representative of the energy extracted by the CycWEC system. The radiated wave pattern was established based on a two-dimensional potential flow model representing the hydrofoils as point-vortex sources coupled with a three-dimensional wave radiation correction. An example of the influence of device orientation on the radiated wave field is presented in Figure 14 and was taken from Fagley et al, 2013 [13].

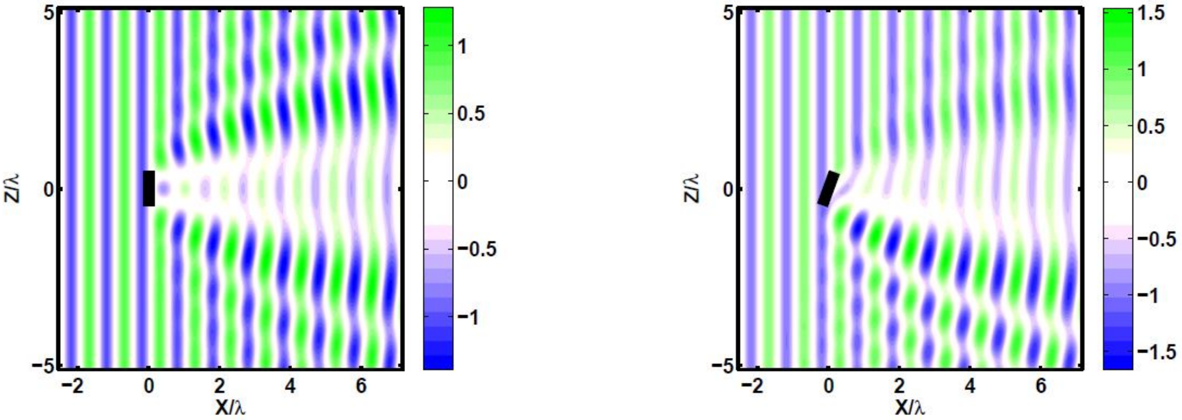

*Figure 14: Surface elevation around a representative CycWEC device with span equal to the incident wavelength at 0° (left) and 20° (right) wave angle (taken from Fagley et al, 2013 [13])*

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The authors note that perfect alignment of incoming long-crested waves is obviously the preferred configuration for the device and present results from a parameter study where both the device span and orientation were varied. The results are summarised in Figure 15 which is also taken from Fagley et al, 2013 [13]. In short, the authors note that an increase in misalignment between the WEC and wave crest results in a decrease in the performance. Also, the severity of the decrease in performance intensifies with WEC span, such that larger devices suffer significantly greater reductions in performance as a result of the mismatched phase of lift generated across the extent of the hydrofoil.

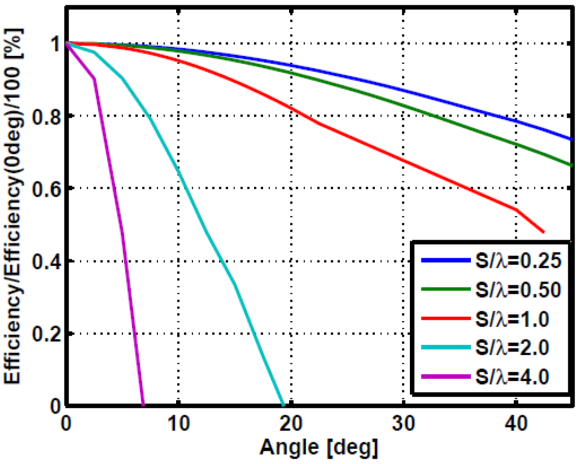

*Figure 15: Wave cancellation efficiency as a function of angle between WEC and wave crest for a variety of WEC spans (taken from Fagley et al, 2013 [13])*

#### 2.2.6.7 Device/Array Spacing

The influence of spacing between multiple device deployed in close proximity to one another was the subject of an investigation conducted by Siegel, 2015 [3]. The rationale behind the investigation stems from the CycWEC team's consideration of potential deployment of CycWEC devices in pairs where each device would be installed on either side of a monopile-type support structure as exampled in Figure 16.

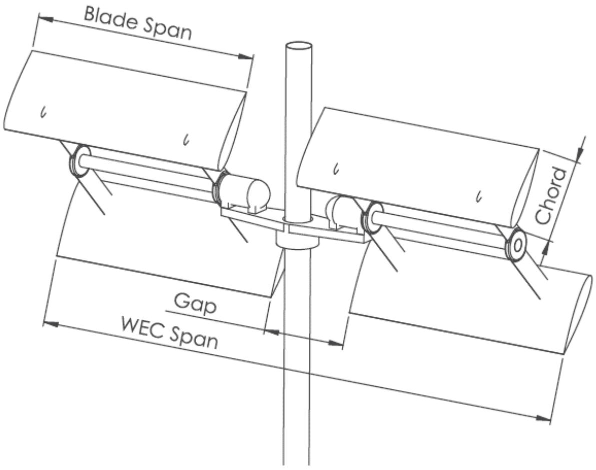

*Figure 16: Example of potential installation of the CycWEC system in coupled pairs via the support of a single monopile system (taken from Siegel, 2015 [3])*

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The influence of gap size on hydrodynamic performance of the system was considered in the work. As with the majority of CycWEC investigations, the approach taken was similar to that presented in Section 2.2.2, which may be summarised as a control volume approach where the influence of the CycWEC radiated wave field on the incident wave field was used to estimate the expected power capture of the device. The fundamental hydrodynamics, and thus the radiated wave field, of the CycWEC device were represented by a two-dimensional potential flow method which modelled the hydrofoils as point-vortex sources and included corrections for three-dimensional wave radiation effects. The model seems to assume ideal rotational and blade pitch control through feed-forward control associated with wave prediction. It is not known if the model accounted for the influence of viscous or other losses.

Results from a parameter study showing the impact of gap size and device span, taken from Siegel, 2015 [3], are presented in Figure 17 for ease of reader inspection.

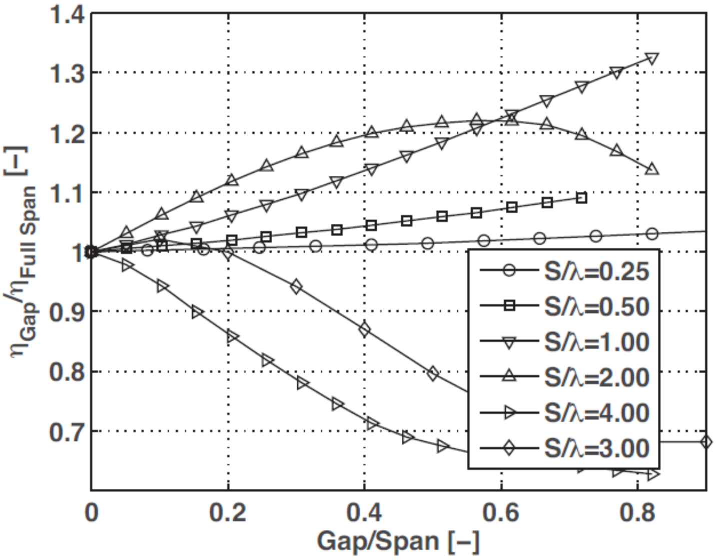

*Figure 17: Wave cancellation efficiency as a function of non-dimensional gap size for different WEC spans (taken from Siegel, 2015* [3]*)*

The results presented in Figure 17 were normalised against results for the efficiency of a single device with a particular span/wavelength ratio however the specific ratio is not given in the text. More discussion on the influence of gap size on performance can be found in the referenced work, including details on the requirement for generation of increased radiated wave heights in order to realise the potential increase in performance. Essentially, the authors warn that the realisation of an increase in performance for a dual-CycWEC system requires an increase in the radiated wave height of the individual units in order to compensate for the radiated wave lost across the extent of the gap. In conclusion the authors suggest that the potential modification is “*relatively minor”* based on the analysis completed.

#### *2.2.6.8 Benchmarking with Traditional WEC Concepts*

A given CycWEC system was benchmarked against a number of traditional Wave Energy Converters was presented in Siegel, 2019 [1] where the CycWEC system was modelled using the approach outlined in Section 2.2.2 including the team’s corrections for three-dimensional wave radiation and viscous losses. In this work, a given CycWEC system is compared against a variety of traditional Wave Energy Converters in terms of Mean Annual Power Production, Absorbed Energy per unit Mass, Absorbed Energy per unit Surface Area, and Absorbed Energy per unit Power Take Off (PTO) Force. Results for the traditional Wave Energy Converters were taken from work conducted by Babarit et al, 2012 [17] which is a widely accepted piece of independent work in the industry.

In the vast majority of cases the CycWEC was noted to significantly outperform the traditional WEC concepts and is suggested as a superior device concept. For brevity, only the primary comparisons are presented here in Figure 18, Figure 19, Figure 20 and Figure 21.

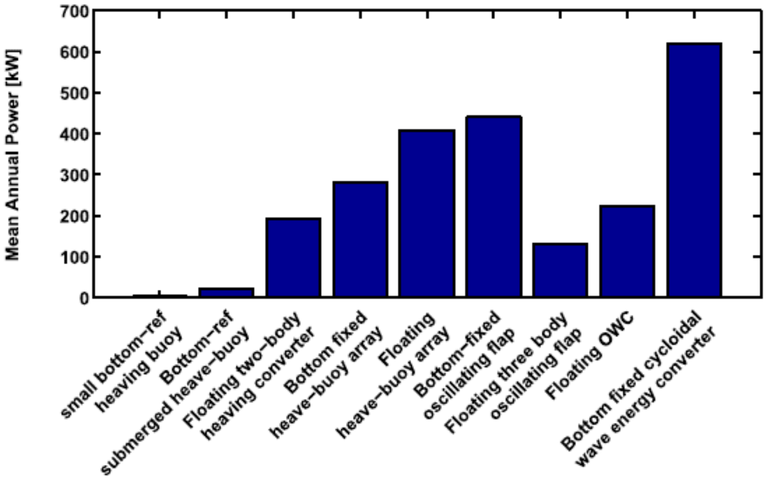

*Figure 18: Benchmarking of CycWEC Mean Annual Power Capture Against Traditional WECs [1]*

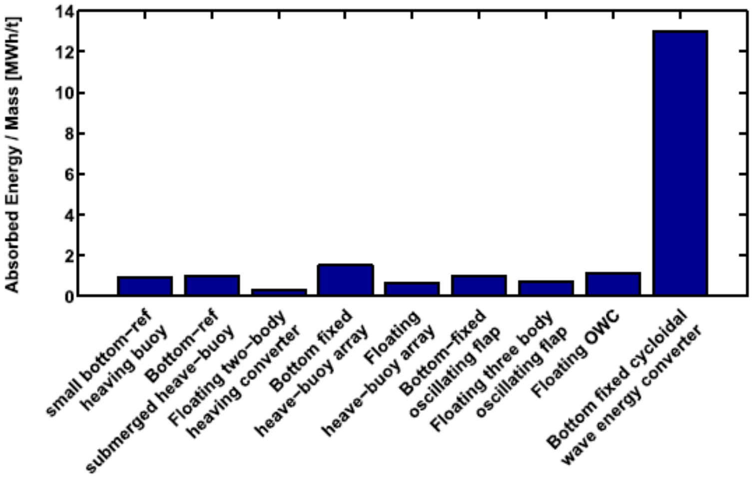

*Figure 19: Benchmarking of CycWEC Absorbed Energy/Mass Against Traditional WECs [1]*

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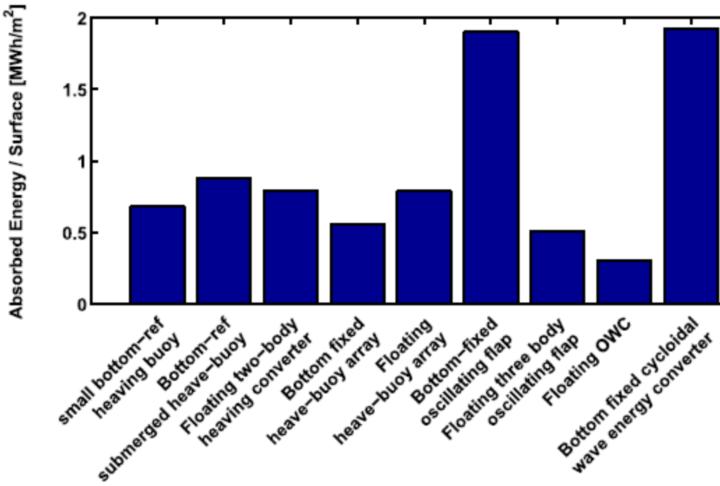

*Figure 20: Benchmarking of CycWEC Absorbed Energy/Surface Against Traditional WECs [1]*

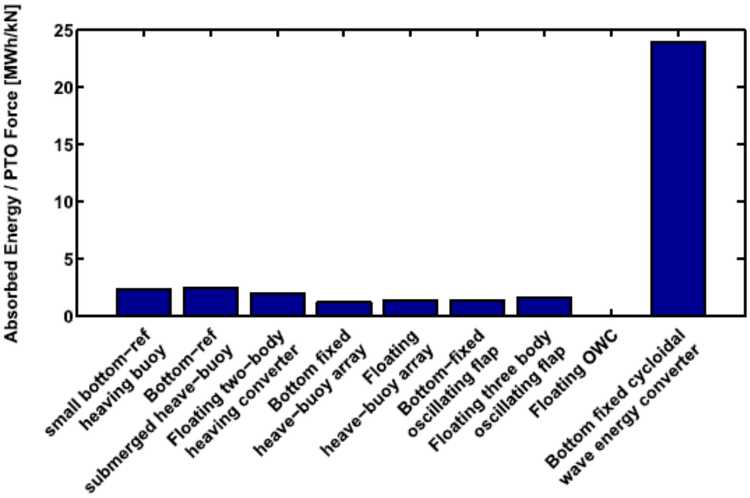

*Figure 21: Benchmarking of CycWEC Absorbed Energy/PTO Force Against Traditional WECs [1]*

For more discussion on the perceived reasons behind the greater performance of the CycWEC over more traditional device types the reader is referred to the original work presented in Siegel, 2019 [1]. Whilst a significant improvement over traditional device concepts is shown, it is noted that the numerical methods employed are significantly different. Furthermore, the CycWEC system's physical characteristics were tailored to maximise power production in a given wave climate whereas this was not undertaken for the variety of traditional Wave Energy Converters reported on by Babarit et al in their original work.

### 2.2.7 Control

Early in the development of CycWEC, the Atargis team noted that efficient conversion of incident wave energy was possible through precise control of the system's operational parameters [10] [5]. Specifically, the team implemented control of the rotor's rate of rotation, blade pitch angle and phase.

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At this time, it was found that synchronization of the device's rotational frequency to that of the incident wave, when coupled with an appropriate blade pitch angle and wave-body phase, allowed extraction of greater than 99% of the available wave energy. Note that these findings were for 2-dimensional simulations conducted in regular sea states where wave prediction and feed-forward was employed.

In subsequent experimental work [19] a model was tested where the pitch angle of each blade was adjustable in real-time using computer control. This was achieved by means of two digital model aircraft servos and allowed the system to produce the desired level of circulation. As with the simulations, foresight of the incident wave characteristics was required to implement the desired control. The signal from an up-wave wave gage was used to generate the feedback control and was processed by the state estimator. The results of the state estimation algorithm were the instantaneous wave height, wave period and wave phase. These quantities were then used by the controller to prescribe the desired instantaneous rotor shaft angle as well as the pitch of the blades.

In [23] the ability of the CycWEC system to cancel irregular deep ocean waves in real time was investigated using an inviscid potential flow simulation. A linear control scheme which proportionally controlled hydrofoil pitch and compensated for phase delays was adopted. The primary objective was to increase the device efficiency by operating at significantly higher blade speeds than the wave-induced velocity. This required intelligent feedback control to specify the most productive hydrofoil orientation and position based on the incident wave field. In this work, an up-wave sensor relayed the incident wave signal to the estimator which determined the wave height, phase and period. The controller then determined the rotational position and blade angle required to generate an opposing wave that effectively cancelled the incident wave field in real time. Using this approach, experimental modelling [12] has indicated that while the CycWEC avoided the losses due to up wave radiated waves suffered by typical symmetric point absorbers, it could nonetheless leverage the benefits of diffraction induced wave focusing at small span to wavelength ratios.

### 2.2.8 Structural Design & Implementation

#### *2.2.8.1 Hydrofoil Profile*

From the literature available in the public domain, it would seem that comparatively little effort has been spent publishing investigations into the influence of hydrofoil properties on device performance. In terms of hydrodynamic performance, the reader is referred back to Section 2.2.6.4 where some consideration of the influence of chord length and hydrofoil profile on hydrodynamic efficiency is presented. In terms of further details there is not a significant amount available however it is noted that CycWEC systems have almost invariably employed two curved NACA 0015 profile hydrofoils. Furthermore, a brief yet interesting investigation into the pressure distributions obtained on these profiles have been described in Siegel, 2012 [2].

#### *2.2.8.2 Power Take Off*

Whilst there is generally little discussion of the implementation of a power take off mechanism for the CycWEC, it is stated in Siegel, 2019 that the most recent design iteration includes two independent permanent magnet direct drive generators [1]. The particular CycWEC design being discussed is the intermediate depth jack-up device design outlined here in Section 2.2.1. One generator is mounted in each nacelle element. The generators are noted to be shaft based, as opposed to being radial which may be assumed from consideration of the structural form. It is also stated that each generator incorporates a spring-actuated shaft-brake which is capable of stopping the shaft at full design torque without any external power requirements.

In addition, there is a short discussion of generator sizing presented in Siegel, 2012 [2]. In short, the work considers the impact of generator sizing on the annual energy production of an otherwise similar CycWEC device. The study was conducted using two-dimensional potential flow simulations with first principles viscous corrections (see Section 2.2.2.1 and 2.2.2.3). The results found that for the particular system employed, an increase in generator sizing by 700% (the amount required to allow the generator to convert all available shaft power to electrical power) only increased annual power yield by 20%. The authors subsequently concluded that it was not economical to attempt to convert all available wave energy to electrical output, and that generators should be sized by consideration of more than simply maximising power capture. In this work, the authors present the trade-off between annual energy yield and generator size. This comparison, which presents both the *Annual Efficiency* and the *Capacity Factor* as a function of Maximum Generator Power is reproduced here in Figure 22.

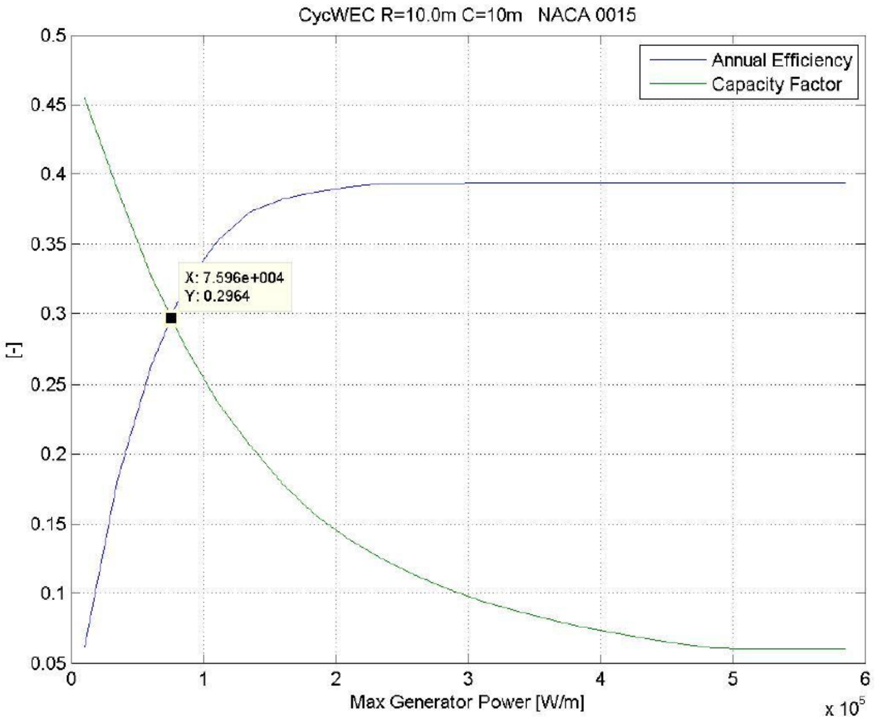

*Figure 22: Capacity Factor and Annual Efficiency with Generator Sizing. Taken from Siegel, 2012 [2].*

In this work, Annual Efficiency is defined as the mean annual efficiency of the system in converting incident wave energy to electrical energy (thus presumably including generator losses). The Capacity Factor indicates the mean annual fraction of the rated generator power at which the system operates. The authors suggest a design choice of 75kW/m for the generator sizing which will achieve both an annual average efficiency and capacity factor of approximately 30%. This is stated to be on par with conventional wind turbines which typically achieve 20%-40% capacity factor depending on location, make and model.

### *2.2.8.3 Structural loading*

In Siegel, 2019 [1], a structural loading assessment was conducted to permit the benchmarking of an intermediate water depth CycWEC system, (see Section 2.2.1) against a variety of traditional Wave Energy Converter concepts. The approach taken to the assessment of structural loading is outlined in Section 2.2.4, however may be summarised as a first principles approach where hand calculations were used to propagate loads through the structure based on the estimation of lift, drag and pitching moment coefficients of blade profiles taken from published literature found in Sheldahl and Kilmas, 1981 [14]. Loads were calculated for three different sea states as outlined in Table 2.

*Table 2: CycWEC Design Sea States. Taken from Siegel, 2019 [1].*

| Wave | Height | Period | Power | Max. Particle Velocity |
|---|---|---|---|---|
| | [m] | [s] | [kW/m] | [m/s] |
| Design | 2.25 | 10.5 | 27 | 0.61 |
| Storm | 15 | 15 | 38 | 3.85 |
| Shortest | 1.75 | 6 | 15 | 1.1 |

Using this approach, the author found that the operational loads experienced during a 1 in 100 year storm event did not exceed those experienced under productive operation in the design sea state. This is stated to be due to the fact that *“the rotational speed in operation is always equal to the period of the incoming wave, and since the wave period for the storm sea state is much larger than for the operational sea state, the storm loads are smaller”*. Whilst the writing does not state the following and may in fact appear contradictory, it is assumed that the author is suggesting that for a fixed radius system, the rotational speed of the system must be greater in shorter period waves as the same distance must be travelled in a shorter time. Then, as the device velocity is increased, so too must be the structural loads as both lift and drag forces generated are proportional to the relative fluid velocity experienced by the foil. This assumption is supported by the authors following statement which reads *“the sea state causing the largest foil lift loads is actually the shortest highest wave”*. Note that as the system is assumed to be fully submerged, the authors have not conducted any impact or slam load assessment. In addition, loading due to wave-action on structural elements other than the hydrofoils themselves has not been included.

In the event of system failure, CycWEC includes a ‘Survival Mode’ where the generator systems engage a spring-actuated shaft-brake which is capable of stopping the shaft at full design torque without any external power requirements. Structural loading in the survival mode is stated to be lower than that experienced during operation as the majority of the relative velocity typically experienced by the hydrofoils is due to their self-motion. Thus, loading due solely to the typical wave-induced fluid velocity is significantly reduced. It is stated that as a result of the unique operational aspects of this type of device, coupled with the approach taken to mechanical design, storm survival mode for the CycWEC system can be maintained as long as at least one of the two generator shaft brakes and blade pitch actuator brakes are operational. Thus, even in the event of two failed generators, failed main shaft bearings and failed blade pitch systems, the system can survive a storm event. Furthermore, since the brakes are spring actuated, no internal or external power is required for storm survival. Nor is there any requirement for the blade pitch control system to be operational. Note that this and a number of other mechanical system redundancies are described in more detail in Siegel, 2019 [1]. In

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addition, the same source details the perceived structural loading regimes experienced by various mechanical components, however these are not included in this review for brevity.

No results in terms of loading, load path analysis or structural optimisation are presented in the same work however there is discussion on the absorbed energy/unit mass ratio of the device which is found to be approximately one order of magnitude (10x) larger for CycWEC compared to a variety of traditional Wave Energy Converters (for more on the comparison see Section 2.2.6.8). Here it is stated that the ten-fold advantage of the CycWEC over more traditional WEC concepts is due to three main factors:

1. CycWEC operates with a *“high blade speed”* compared to the water particle speed, whereas traditional WECs are stated to operate typically at or below the water particle velocity. This is exampled for the case of a CycWEC operating with a rotational velocity of 3.6m/s in the design wave of period 10.5s, where water particle velocities at the surface peak at 0.61m/s. The velocity ratio of 5.8 is stated to permit the lowering of Power Take Off forces by the same amount whilst allowing extraction of the same level of energy. Thus, performance is maintained whilst structural loading (and thus mass required) are reduced.
2. The fully submerged nature of the CycWEC allows it to avoid slam and impact loads associated with storm events.
3. The design of the support strut system is such that it is not subject to bending. All structural loads in these elements are stated to be *“push-pull loads”*, thus allowing for more efficient use of materials.

#### *2.2.8.4 Deployment Concepts for Shallow, Deep and Intermediate Water Depths*

Prior to the jack-up device design comprising the most recent CycWEC iteration (Siegel, 2019 [1]), Atargis Energy considered at least two other potential deployment options. The two alternative potential deployment configurations are mentioned in Siegel, 2012 [2] and may be described as; (1) a freely-floating, modular, multi-CycWEC raft, and (2) a rigid monopile structure supporting a pair of CycWEC devices. An illustration of both the free-floating multi-CycWEC raft and the rigid monopile arrangement is presented in Figure 23.

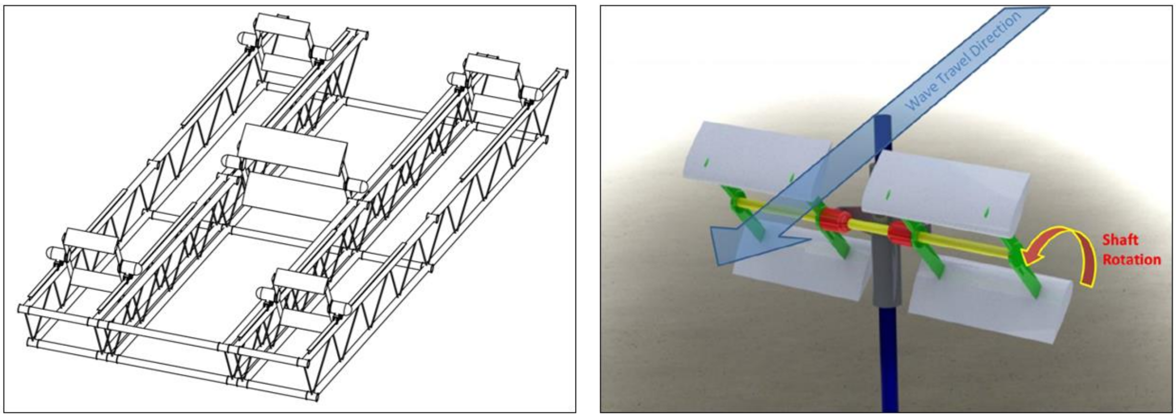

*Figure 23: Illustration of previous CycWEC deployment concepts. Left: free floating, multi-CycWEC raft. Right: Monopile support structure holding two CycWEC devices. Images taken from Siegel, 2012* [2].

In the work it is stated that as part of a project funded by the US Department of Energy, Atargis Energy undertook detailed studies to investigate potential means of installation and deployment of the CycWEC. Based on their work, protection was sought for two distinct approaches, as outlined previously. These protections exist in the form of patents and refer to *“Ocean Floor Mounting of Wave Energy Converters”* [25] and *“Clustering of Cycloidal Wave Energy Converters”* [26].

The work presented in Siegel, 2012 [2] notes that the patents arose in response to the finding that the most cost-efficient method of deploying CycWEC systems (free-floating vs ocean floor attached configurations) was found to vary depending on water depth. In short, Siegel stated that as a result of the intention to place multiple CycWECs within a single raft, the use of a free-floating solution requires the deployment of a structure with its length being at least equal to or greater than one incident wavelength. It is subsequently argued that therefore, when deployment depths are significantly less than one incident wavelength, ocean floor attachment becomes a more cost-efficient option as a result of the smaller size and thus decreased cost of the structure. Siegel goes on to make the case for the use of a monopile foundation arrangement in shallow water depths, citing particular benefits including; (1) the reduced capital requirement, (2) recent experience developed in the offshore wind industry and (3) the permissible realignment of the CycWEC system with varied incident wave direction.

When considering the more recent use of a jack-up strut deployment method (see Section 2.2.1) in an intermediate water depth, it would appear that the Atargis team suggests the use of alternative deployment strategies dependent on water depth. In particular the combined works seem to suggest:

- Deep water (>80m depth): free-floating mutli-CycWEC raft
- Intermediate water (40-80m depth): jack-up strut support
- Shallow water (<40m depth): monopile support system

It is noted however that the suggestions for deep and shallow water have not been reviewed for some time and the team’s hydrodynamic understanding has likely moved on since these works were published and so may not represent current thinking.

### 2.2.9 Operations & Maintenance

As a result of the conceptual nature of the CycWEC system, there is little published material relating to Operation and Maintenance. A short note on the perceived operations is however included in Siegel, 2019 [1]. This note is presented in relation to the most recent design iteration of the CycWEC system (at the time of writing) which is outlined in this report in Section 2.2.1. In short, the system may be described as a rotor consisting of a single pair of opposing hydrofoils spanning 60m in length and operating at a constant radius of 6m. Each end of the rotor is held in place by a nacelle which houses a permanent magnet generator and acts as a structural element attaching the power train and prime mover elements to the support structure. The support structure consists of 4 retractable, telescopic jack-up legs which are hinged at the nacelles such that they can be folded along the length of the rotor for ease of installation, recovery and transport. The feet of the retractable legs are located in position during deployment by means of attachment to guide-cables descending from 4 floating buoys marking the position of the foundation/moorings. The feet are then locked in place to four pre-deployed foundation elements.

It is further noted that the entire CycWEC device is designed to be assembled at port and subsequently towed to the deployment location by means of tugboats, thus eliminating the need for renting of expensive, specialist jack-up vessels. At the deployment location the mooring points would be pre-installed, and the locations indicated by marker buoys. The mooring lines of these marker buoys engage with the aforementioned proprietary strut attachment system which is noted to allow the struts to connect to the mooring points without any need for diver or ROV intervention. The telescopic struts allow for the system to be raised out of the water column for maintenance however no detailed mechanical description of these elements is given.

### 2.2.10 Levelized Cost of Energy

The Levelized Cost of Energy (LCoE) of the CycWEC system was considered by Siegel, 2012 [2] as part of the works funded by the US Department of Energy. This project was funded to support further development of the CycWEC system (which was at Technology Readiness Level 2 – 3 at the time) and bring it closer to readiness for a potential prototype deployment. As such, the study was conducted at an early stage in the development pathway. It does not appear that more recent estimates of the Levelized Cost of Energy are available in the public domain and so the reader is advised that the structural implementation of the CycWEC system appears to have changed significantly since this publication.

At the time of publication, the author states that Atargis Energy had recently shifted focus on design from a free-floating option to an *“ocean floor attached CycWEC”* [2]. In the same publication, the authors describe perceived advantages of the use of a monopile foundation for the CycWEC system and present Figure 24 as an illustration of the potential configuration. Whilst not explicitly stated, it is assumed that the calculation of CycWEC’s Levelized Cost of Energy is conducted for a system such as that presented in Figure 24.

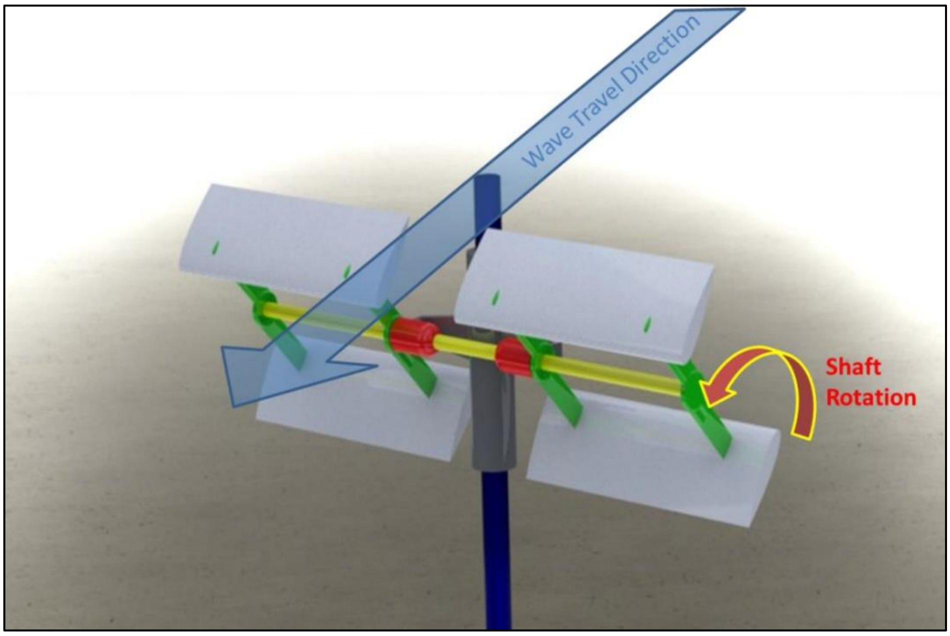

*Figure 24: A set of two CycWECs mounted on a monopile. The hydrofoils (white) are the only component extracting energy from the waves, and are attached by means of struts (green) to a main shaft (yellow). The main shaft drives one or more generators (red) that are attached to the monopile in a fashion where the depth of the WEC can be adjusted to avoid storm damage (low position) or maintenance (above water level, high position). The hydrofoils remain fully submerged in normal operation. Figure and caption taken from Siegel, 2012 [2].*

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The calculation of Levelized Cost of Energy presented in Siegel, 2012 [2] is conducted both for a single CycWEC and an array of 40 CycWEC devices installed in a single deployment. The LCoE is calculated using an approach presented by Short et al, 1995 [27] in their report published by the National Renewable Energy Laboratory.

Siegel, 2012 [2] uses a modified version of equation 4.7 (page 48) from Short et al, 1995 [27], to calculate the LCoE. The modified equation used by Siegel is reproduced here as Equation 2.

$$LCoE = (CapEx/Q)(UCRF) + OpEx$$

*Equation 2: Equation for LCoE used by Siegel, 2012*

Here, $LCoE$ refers to the Levelized Cost of Energy, $CapEx$ is the total Capital Expenditure in Cents (USD), $OpEx$ is the Operating Expenditure in Cents/kWh, $Q$ is the annual energy production in kWh and $UCRF$ is the Uniform Capital Recovery Factor which is calculated using Equation 3.

$$UCRF = \alpha(1+\alpha)^{\beta}/\left[(1+\alpha)^{\beta} - 1\right]$$

*Equation 3: Equation for Uniform Capital Recovery Factor Employed by Siegel, 2012*

Where, $\alpha$ is the discount rate and was set to $\alpha = 0.1$ and $\beta$ was the number of years which was set to $\beta = 20$.

It is then stated that all estimations of Levelized Cost of Energy were based on an installed array of 40 CycWECs at a given North Atlantic site where each CycWEC was specified with a peak power output of 5MW. Cost estimates were conducted with both high and low estimates. Estimates of the Capital Expenditure from Siegel, 2012 [2] are reproduced here as Table 3. The associated text states that estimated costs for constructing the cluster range between 2,058 \$/kW and 3,206 \$/kW (note there appears to be unit typo in the table taken from Siegel, 2012 may cause confusion between the numbers stated in the text and the results presented in the table).

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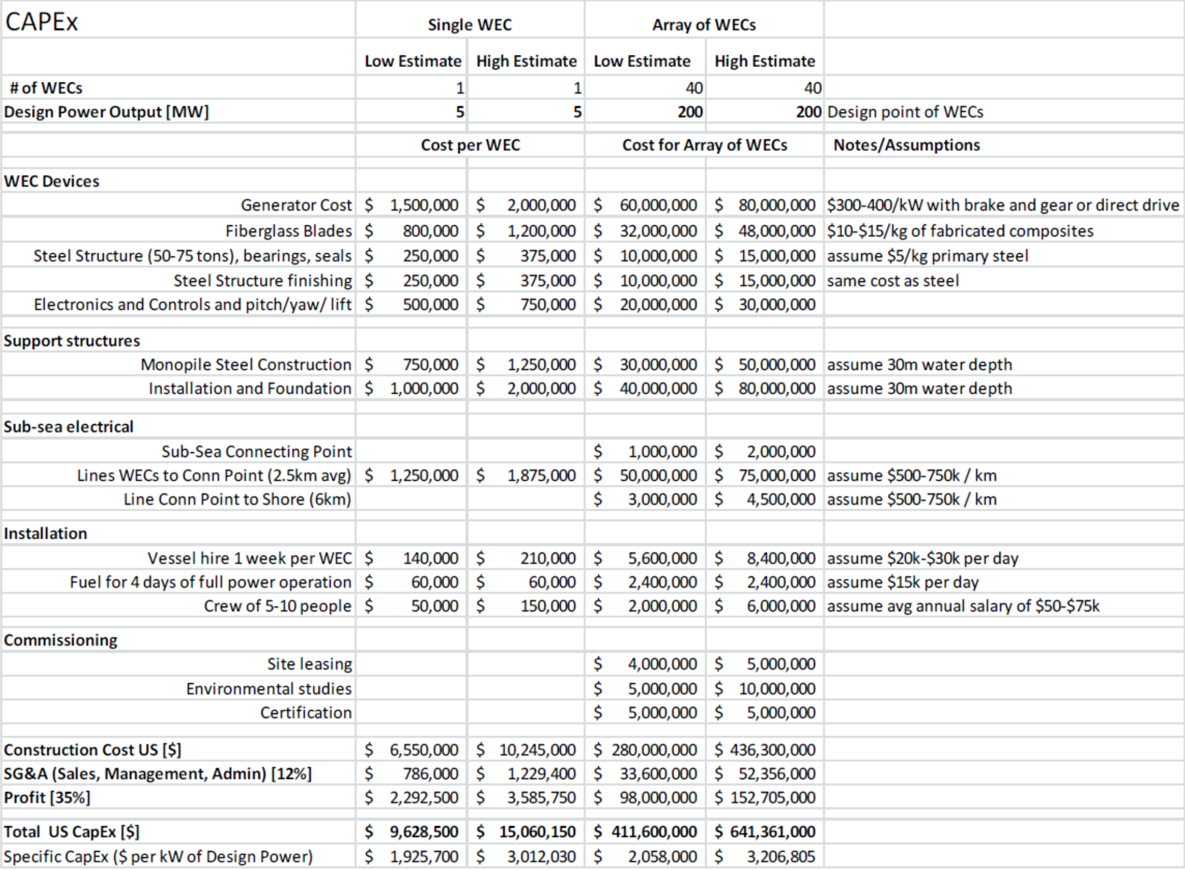
*Table 3: Cost estimates for CycWEC Capital Expenditure as given by Siegel 2012 [2].*



| CAPEx | Single WEC | | Array of WECs | | |
|---|---|---|---|---|---|
| | Low Estimate | High Estimate | Low Estimate | High Estimate | |
| # of WECs | 1 | 1 | 40 | 40 | |
| **Design Power Output [MW]** | **5** | **5** | **200** | **200** | Design point of WECs |
| | **Cost per WEC** | | **Cost for Array of WECs** | | **Notes/Assumptions** |
| **WEC Devices** | | | | | |
| Generator Cost | $ 1,500,000 | $ 2,000,000 | $ 60,000,000 | $ 80,000,000 | $300-400/kW with brake and gear or direct drive |
| Fiberglass Blades | $ 800,000 | $ 1,200,000 | $ 32,000,000 | $ 48,000,000 | $10-$15/kg of fabricated composites |
| Steel Structure (50-75 tons), bearings, seals | $ 250,000 | $ 375,000 | $ 10,000,000 | $ 15,000,000 | assume $5/kg primary steel |
| Steel Structure finishing | $ 250,000 | $ 375,000 | $ 10,000,000 | $ 15,000,000 | same cost as steel |
| Electronics and Controls and pitch/yaw/ lift | $ 500,000 | $ 750,000 | $ 20,000,000 | $ 30,000,000 | |
| **Support structures** | | | | | |
| Monopile Steel Construction | $ 750,000 | $ 1,250,000 | $ 30,000,000 | $ 50,000,000 | assume 30m water depth |
| Installation and Foundation | $ 1,000,000 | $ 2,000,000 | $ 40,000,000 | $ 80,000,000 | assume 30m water depth |
| **Sub-sea electrical** | | | | | |
| Sub-Sea Connecting Point | | | $ 1,000,000 | $ 2,000,000 | |
| Lines WECs to Conn Point (2.5km avg) | $ 1,250,000 | $ 1,875,000 | $ 50,000,000 | $ 75,000,000 | assume $500-750k / km |
| Line Conn Point to Shore (6km) | | | $ 3,000,000 | $ 4,500,000 | assume $500-750k / km |
| **Installation** | | | | | |
| Vessel hire 1 week per WEC | $ 140,000 | $ 210,000 | $ 5,600,000 | $ 8,400,000 | assume $20k-$30k per day |
| Fuel for 4 days of full power operation | $ 60,000 | $ 60,000 | $ 2,400,000 | $ 2,400,000 | assume $15k per day |
| Crew of 5-10 people | $ 50,000 | $ 150,000 | $ 2,000,000 | $ 6,000,000 | assume avg annual salary of $50-$75k |
| **Commissioning** | | | | | |
| Site leasing | | | $ 4,000,000 | $ 5,000,000 | |
| Environmental studies | | | $ 5,000,000 | $ 10,000,000 | |
| Certification | | | $ 5,000,000 | $ 5,000,000 | |
| **Construction Cost US [$]** | $ 6,550,000 | $ 10,245,000 | $ 280,000,000 | $ 436,300,000 | |
| **SG&A (Sales, Management, Admin) [12%]** | $ 786,000 | $ 1,229,400 | $ 33,600,000 | $ 52,356,000 | |
| **Profit [35%]** | $ 2,292,500 | $ 3,585,750 | $ 98,000,000 | $ 152,705,000 | |
| **Total US CapEx [$]** | **$ 9,628,500** | **$ 15,060,150** | **$ 411,600,000** | **$ 641,361,000** | |
| Specific CapEx ($ per kW of Design Power) | $ 1,925,700 | $ 3,012,030 | $ 2,058,000 | $ 3,206,805 | |

Following presentation of the breakdown for Capital Expenditure, the ultimate Levelized Cost of Energy is reproduced in Table 4. Based on the analysis presented, the Levelized Cost of Energy for the CycWEC system was estimated by Siegel, 2012 to be in the range of 10 to 17 cents (USD) per kWh. It is stated that the cost is expected to fall with time due to reductions in the Operational Expenditure occurring with experience.

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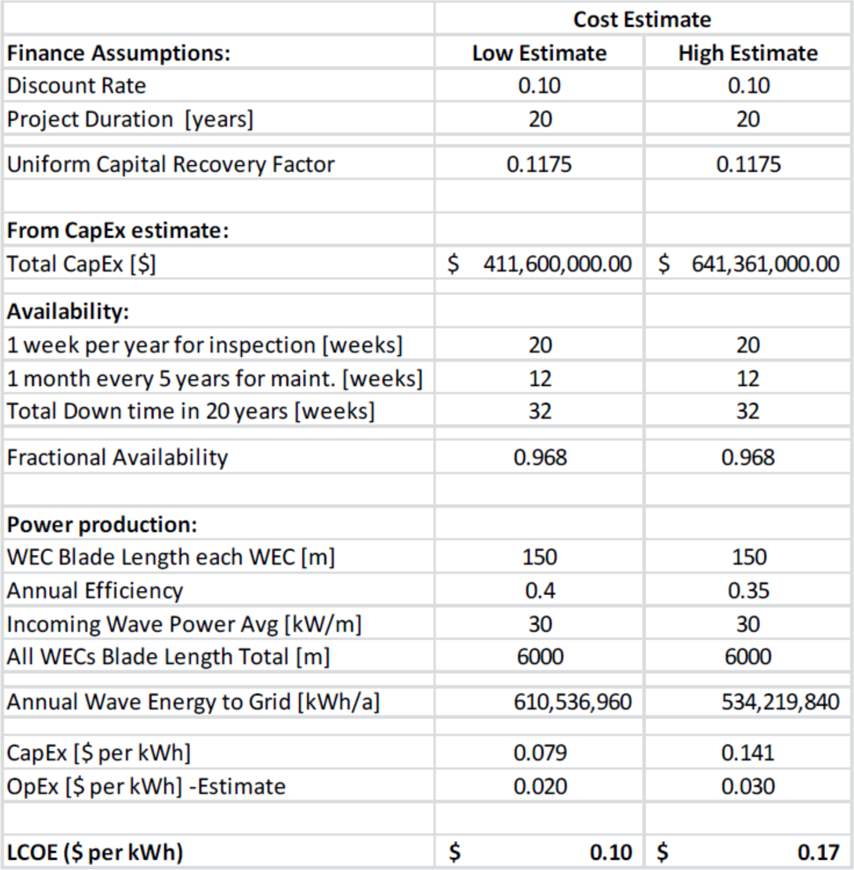
*Table 4: Estimation of Levelized Cost of Energy for CycWEC as presented by Siegel, 2012 [2].*



| | **Cost Estimate** | |
|---|---|---|
| **Finance Assumptions:** | **Low Estimate** | **High Estimate** |
| Discount Rate | 0.10 | 0.10 |
| Project Duration [years] | 20 | 20 |
| Uniform Capital Recovery Factor | 0.1175 | 0.1175 |
| | | |
| **From CapEx estimate:** | | |
| Total CapEx [$] | $ 411,600,000.00 | $ 641,361,000.00 |
| **Availability:** | | |
| 1 week per year for inspection [weeks] | 20 | 20 |
| 1 month every 5 years for maint. [weeks] | 12 | 12 |
| Total Down time in 20 years [weeks] | 32 | 32 |
| Fractional Availability | 0.968 | 0.968 |
| | | |
| **Power production:** | | |
| WEC Blade Length each WEC [m] | 150 | 150 |
| Annual Efficiency | 0.4 | 0.35 |
| Incoming Wave Power Avg [kW/m] | 30 | 30 |
| All WECs Blade Length Total [m] | 6000 | 6000 |
| Annual Wave Energy to Grid [kWh/a] | 610,536,960 | 534,219,840 |
| CapEx [$ per kWh] | 0.079 | 0.141 |
| OpEx [$ per kWh] -Estimate | 0.020 | 0.030 |
| | | |
| **LCOE ($ per kWh)** | **$ 0.10** | **$ 0.17** |

## 2.3 OTHER DEVICES

The remaining sub-sections of Section 2 now present literature surveys for a variety of other lift-based and potentially relevant device concepts. Note that due to the lesser amounts of literature available these are typically much shorter than the literature survey conducted on the CycWEC device.

### 2.3.1 Wave Harvester

The Wave Harvester is a lift-based wave energy converter proposed by P. Wegener and J. Berg and filed as a US patent [28]. A company, Waveberg Development, appears to have been set-up in 2017 with P. Wegener as President and J. Berge as Inventor, with a website – www.waveberg.com. However, this website is not currently active, and the patent expired in October 2018 due to non-payment of maintenance fees. Following the reference to Waveberg Development links to a post from 2012 (https://seaenergytag.wordpress.com/tag/waveberg/) that says "*extensive development work taken by the company dates back to the 1970s. Recent testings have proved 14 months survival in open ocean conditions and shown capacity factors of 60-85 per cent*." Unfortunately, there are no links to justify these claims or provide further information. Moreover, no other references to this concept have been found in the literature or in the public domain and it is unknown whether the concept was supported by numerical or physical modelling.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

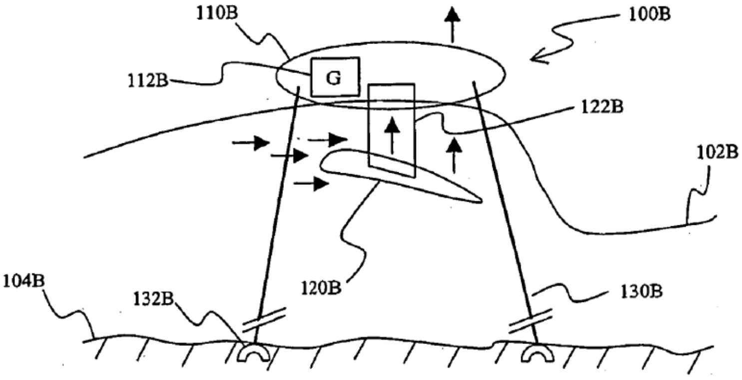


*Figure 25: Exemplary Wave Energy Harvester* – reproduced from [28]

An "*exemplary wave energy harvester*" proposed by Wegener and Berg is shown in Figure 25. The hydrofoil (120B) is described a number of times in the patent application as "*an amplifier element*" because it is designed to work with the buoyancy forces to amplify the vertical force on the body. The fundamental operation of the Wave Harvester is to extract energy from the vertical motion of the buoy/hydrofoil relative to the seabed. The patent also describes a variant of the Wave Harvester where the hydrofoil can pitch to control the lift force, with a further variant where the buoy is fully submerged and neutrally buoyant to allow submergence during a storm event.

Although it is not explicitly stated in the patent, the description of the invention suggests that the Wave Harvester would be deployed in shallow water. This is based on the absence of any reference to vertical fluid velocities in the patent, whilst in deep water the vertical fluid velocities have a similar magnitude to the horizontal fluid velocities. This is also supported by the figures that show a steep-fronted wave, although this could simply be the interpretation of the graphic artist that produced the illustrations for the patent. The patent also states that "*the water molecules are moving forward at approximately the apparent speed of the wave*". This condition is only true for breaking waves, but it is not clear whether this implies that the device would only be deployed in the breaking zone, or it is a misunderstanding of wave mechanics by the inventors. However, for completeness, both possible interpretations will be considered.

First consider the interpretation that the Wave Harvester is deployed in shallow water within the breaking zone. Waves typically break when the wave height is about 80% of the water depth and so for a typical North Atlantic wave height of 3.0 metres this would imply that the concept would need to be deployed in water depth of less than about 4.0 metres. However, most potential coastlines are likely to have a tidal range of between 2 – 4 metres and this complicates selection of the deployment depth. This is because at high tide the number of breaking waves at a particular location will reduce significantly, which will reduce power capture. Then, at low tide there will be limited depth for vertical motion of the buoy/hydrofoil. This is significant because power is the product of the force and body velocity and the body velocity is limited by its range of motion so at low tide the power capture will also be limited.

Now consider the interpretation that the Wave Harvester is deployed in deep water. In this case, the typical water particle velocity for a site in the North Atlantic would be about 0.9 m/s (a 10 second wave with a height of 3.0 metres). However, this typical water particle velocity is circular and so is equal to the peak horizontal water particle, with the average absolute value of the horizontal water particle velocity being about 0.6m/s. The specific lift force (lift force per unit area of the hydrofoil) $f_L$ is given by

$$f_L = 0.5\rho C_L V^2$$

The lift coefficient $C_L$ depends on the hydrofoil profile as well as the characteristics of the flow. The horizontal motion the water particles will be continually oscillating, and this unsteady characteristic of the incident flow is likely to result in a reduction in the lift coefficient. However, assuming that the lift coefficient is minimally influenced by the unsteady flow and then assuming a hydrofoil lift coefficient of 2.0 the specific lift force will be approximately 0.4 kN/m$^2$. This compares to a specific buoyancy force (buoyancy force per unit surface piercing area) of approximately 10 kN/m$^2$. Thus, the lift force generated by the hydrofoil will typically be about 4% of the buoyancy force and so at best could make a marginal contribution to the power capture.

Based on this admittedly limited analysis the Wave Harvester does not appear to be a particularly viable concept due to the limited power capture from lift forces. However, it is always worth considering whether there are potential ideas within the concept that may be useful (although this is not meant to imply that they are necessarily recognised as part of the patent). The idea that may provide some interesting possibilities is the combination of the lift force with other sources of wave force. The Wave Harvester only considers the lift force in combination with the buoyancy force, but the diffraction force (due to the water particle accelerations) could also be combined with the lift force. Indeed, a diffraction force on the hydrofoil will always occur and so it may be important to consider this in the development of LiftWEC concepts to ensure that at least the diffraction force does not oppose the lift force although it may not make a significant contribution to the power capture.

### 2.3.2 Wave Rotor

The Wave Rotor is a lift-based wave energy converter that was originally proposed by Budal and Lillebeken [29], [30], where the lift is generated by a rotating cylinder rather than a hydrofoil. Further experimental work on this concept was completed by Retzler [31], [32] resulting in a prediction for the hydrodynamic performance of the Wave Rotor configuration shown in Figure 26 developed by Chaplin and Retzler [33], [34].

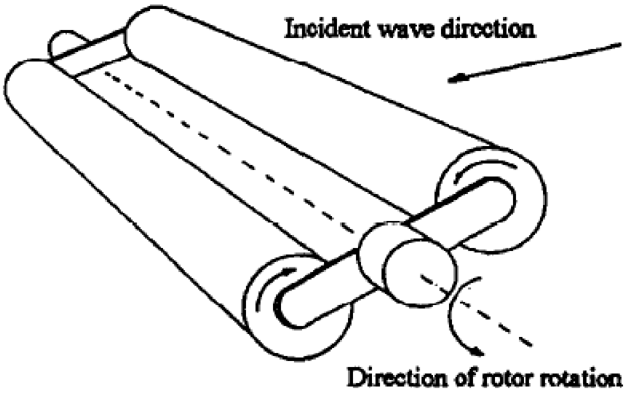


*Figure 26: Wave Rotor configuration, reproduced from* [33]

It is shown using potential flow model of the spinning cylinder [29] that the theoretical wave force on single cylinder can be approximated as:

$$F_e = \left(1 + \frac{\omega_r}{\omega}\right) F_0$$

Where:

$F_0$ the wave force on the non-spinning cylinder
$\omega_r$ cylinder rotational frequency
$\omega$ wave frequency

Thus, if the cylinder spins about its own axis at the same frequency as the waves then the incident wave force can either double or reduce to zero, depending on the direction of rotation of the cylinder. It is then possible, through the Haskind Relations, to relate this excitation force to the radiated wave amplitude in two-dimensional flow. Experiments undertaken by Lillebeken and Falnes indicate that whilst the increase in wave force is a reasonable approximation, at least when the cylinder rotational frequency is similar to the excitation frequency, the model appears to significantly over-estimate the amplitude of the radiated wave [30]. It is tentatively suggested by Lillebeken and Falnes that this is due to viscous effects, but the need for further research is identified.

A 2D potential-flow model of the twin-cylinder Wave Rotor is develop by Chaplin and Retzler [33]. The waves generated by this model are compared to wave-tank experiments [31], [35], which show good agreement when the circulation generated by the spinning cylinder is 20% of the theoretical circulation assuming a no-slip boundary on the moving cylinder surface. The potential-flow model indicates that together with a wave radiated at the rotation frequency of the twin-cylinder rotor, there are also waves radiated at harmonics of this frequency. These harmonic waves represent a loss of energy and the maximum 2D efficiency of the Wave Rotor is calculated as 98% when the cylinders are spinning at eight times the wave frequency ($\alpha$ = 8) and the axis of the twin-rotor is submerged 3.55 times the rotor radius (*h/a* = 3.55), The variation in efficiency away from this peak is shown in Figure 27.

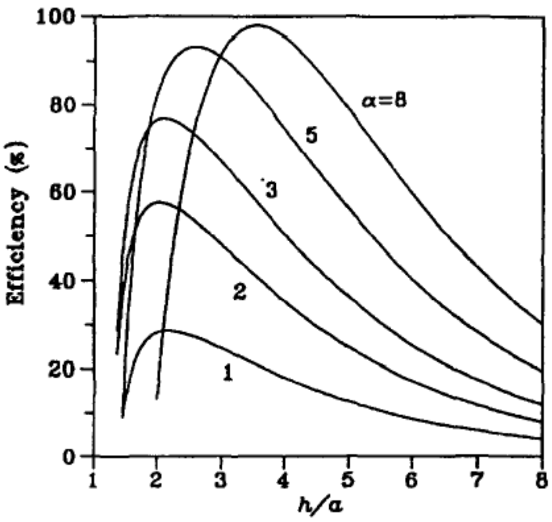


*Figure 27: Efficiency of Wave Rotor at various spin speeds, α, and a function of the relative submergence, h/a - reproduced from* [33]

However, Chaplin and Retzler recognise that this theoretical efficiency is not achievable due to "*the effect of separation in generating form drag, and in limiting the production of circulation around a spinning cylinder in a cross flow*". Chaplin and Retzler also note that these predictions also assume that the phase of the Wave Rotor's rotation is optimal, which will not in general be the case and so there will also be a reduction in efficiency due to a sub-optimal phase.

Further work by Retzler looked at how the 2D efficiency of the Wave Rotor may vary in realistic North Atlantic sea-states [32]. In this configuration the Wave Rotor had an overall diameter of 5.8 metres, each cylinder had a diameter of 2.4 metres and spinning at 18 rpm. The maximum 2D efficiency of the Wave Rotor for this configuration was estimated to be around 20% in waves with an Energy period ~ 8 seconds and a significant wave height ~ 2.0 metres.

### 2.3.3 Wave Harrow

The Wave Harrow is a lift-based wave energy converter that has been developed at the Technical University of Hamburg and the topic of the PhD thesis of Scharmann [36]. The Wave Harrow concept appears to build on the patent of Siegel [37], which itself has been inspired by Voith-Schneider Rotors for ship propulsion and manoeuvring [38]. Scharmann considers a wide range of potential solutions within his thesis but concludes that the 4-bladed concept shown in Figure 28 is the most promising and is considered as an exemplar of the Wave Harrow.

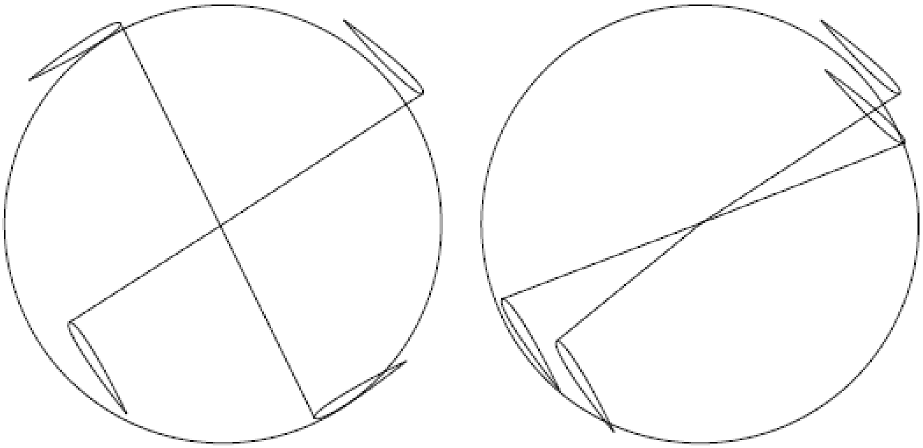


*Figure 28: Morphing form of 4-foil rotor, reproduced from* [36]

The fundamental operational principle of the Wave Harrow is that it rotates at approximately constant speed dependent on the incident waves conditions, but not maintaining any strict phase relationship with the incident waves. The justification provided for this phase independent rotation (where it is recognised that a phase-locked rotation would have a higher power capture) is that it is anticipated to be too difficult to maintain the correct phase with the wave, although no significant efforts appear to be have been made to achieve this. Then, four blades are used to achieve a more constant wave-induced torque and the pitch of the blades are fixed to simplify the technology used. Finally, a "scissor" mechanism is included so that the torque can be reduced in the case of extreme wave conditions.

Both numerical models (Ansys CFX and OpenFOAM) and physical models have been used to investigate the performance of Wave Harrow. The numerical modelling in particular has been used to investigate the optimal rotor design to maximise performance for monochromatic wave with a period of 10.5 seconds and amplitude of 0.95 metres. This monochromatic wave was considered to be representative of the nominal EMEC sea-state, which is the wave climate for which the Wave Harrow has been designed. The reasonableness of using a monochromatic wave is investigated by comparing the results with those for a numerical simulation using an eight-component polychromatic wave. The difference in the mean efficiency was found to be less than about 10% and so the use of the monochromatic waves for optimisation appears to be justified.

With the monochromatic numerical modelling it is shown that transforming the hydrofoil so that its chord-line is curved along the path of motion significantly reduces the drag coefficient of the hydrofoil. Investigations into the effect of hydrofoil thickness shows that this does not appear to have a significant impact on performance for hydrofoil thicknesses of between 8 - 15% of the chord length. Finally, the numerical modelling indicated that the optimum chord length of the hydrofoil should be similar to the rotor radius. It is argued that this is the result of a compromise between maximising the lift force, whilst minimising drag and negative interactions between successive blades.

The 2D efficiency of the Wave Harrow for 3, 4 and 5 blade configurations are shown in Figure 29. It can be seen that the number of blades does not appear to have a significant impact on the efficiency, which provides a justification for using 4 blades as this lends itself most naturally to implementation of the "scissoring" action. Figure 29 also shows that the peak efficiency is about 25% and this occurs when the rotor angular frequency is approximately 0.4 of the wave frequency. Moreover, further numerical modelling indicates that the optimum rotor angular frequency ratio varies between 0.2 and 0.6, which means that the Wave Harrow should always rotate at less than the wave frequency to maximise power capture.

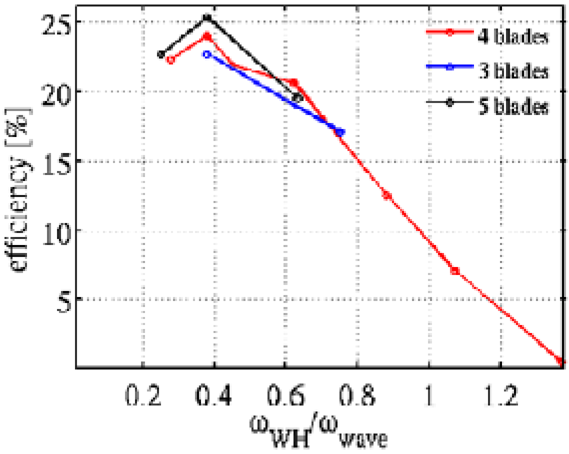


*Figure 29: Wave Harrow efficiency variation with rotor angular frequency relative to waves for 3 – 5 blade configurations, reproduced from* [36]

Both the numerical and physical models have been used to investigate the effect of depth of submergence of the rotor on efficiency. As would be expected, the Wave Harrow efficiency reduces with depth of submergence as a result of the reduction in wave-induced water particle velocities with depth below the surface. The comparison of the numerical and physical model results also provide some validation of the numerical model, with the numerical model appearing to work well at low rotational frequencies, albeit with a reduction in accuracy at higher rotational frequencies. It is argued that this divergence at higher rotational speeds is because the rotor arms and other attached parts are not modelled in CFD and these results in additional drag forces that reduce the efficiency.

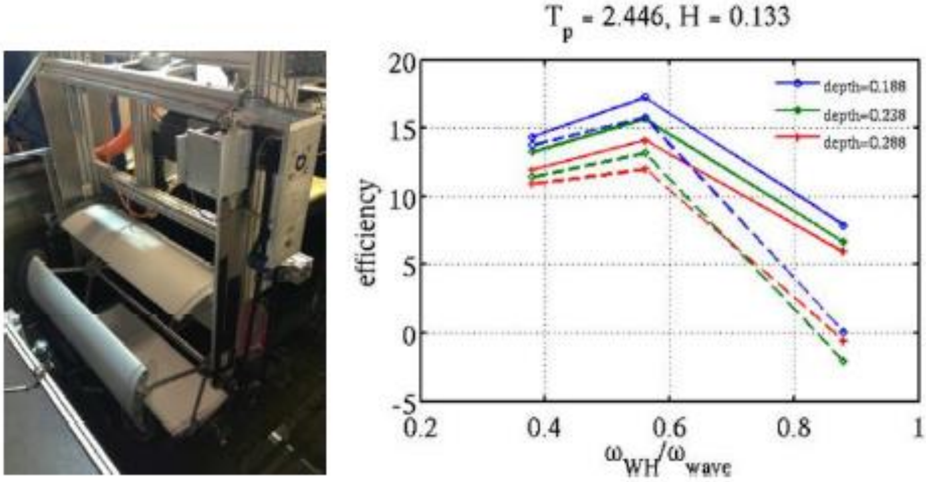


*Figure 30: Effect of depth of submergence on Wave Harrow efficiency (solid lines CFD results, dashed lines experimental results), reproduced from* [36]

The numerical model has also been used to produce an efficiency matrix for the Wave Harrow rotor as shown in Figure 31, although only for the most commonly occurring sea-states. For each state a 64 component polychromatic sea state was simulated for 10 minutes and the rotor speed varied to maximise the power capture. In Figure 31, an efficiency of less than 0% means that the Wave Harrow will not operate, which means that it will only generate electricity in sea-states with a significant wave height of more than about 2.0 metres. In addition, it can be seen that the Wave Harrow has its highest efficiencies in the largest sea-states, where incident power densities are greatest and the power most likely to be limited by the plant rating.

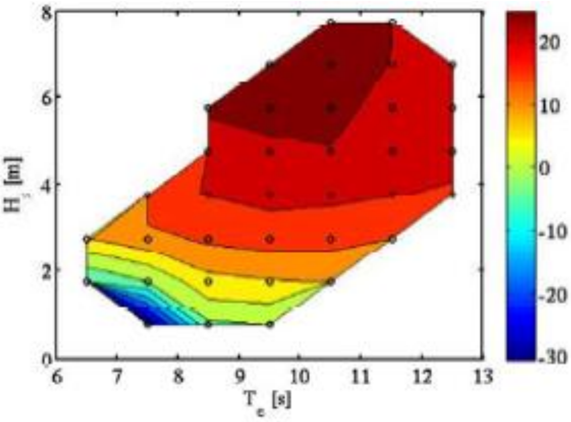


*Figure 31: Wave Harrow efficiency matrix, reproduced from* [36]

### 2.3.4 Darrieus-Wells Rotor

The Darrieus-Wells Rotor is a lift-based wave energy converter that was patented by P. Scheijgrond in 2009 [39]. A relatively significant amount of modelling, both numerical and physical, was done by Ecofys on the Darrieus-Wells Rotor technology [40], including, according to the OceanMill[2] website, (https://sites.google.com/site/oceanmilltest) the following wave-tank tests:

- Glasgow University Towing Tank (1997)
- Danish Maritime Institute (1999)
- Nissum Bredning, Denmark (2002)
- NAREC, United Kingdom (2004)
- IFREMER, France (2007)
- CEHIPAR, Madrid, Spain (2010)

However, although the initial concept was for extraction of wave energy, the current focus of OceanMill, who have obtained an exclusive global licence on the Darrieus-Wells Rotor technology from Ecofys, is tidal energy. Notwithstanding the focus of OceanMill on tidal energy, research has continued into the Darrieus-Wells Rotor concept for the extraction of wave energy at other research institutions [41]–[45].

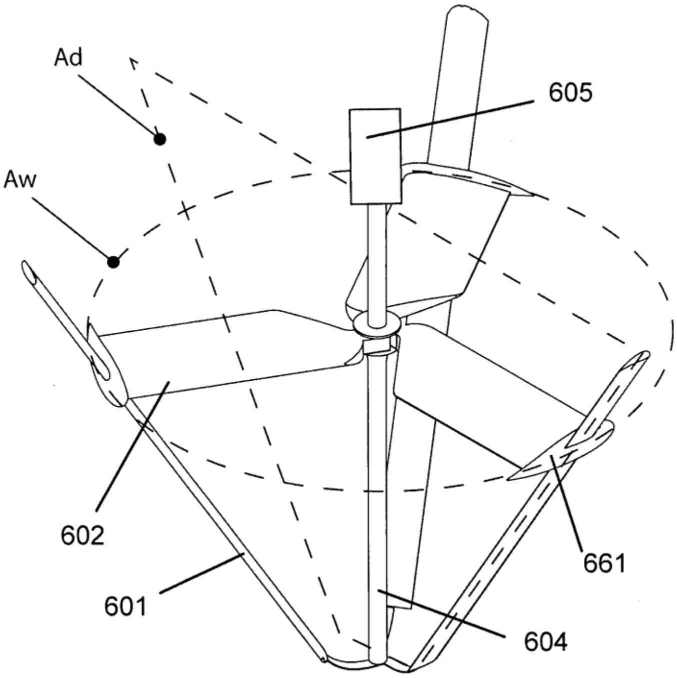


*Figure 32: Darrieus-Wells Rotor reproduced from* [39]

The basic configuration of the Darrieus-Wells Rotor is shown in Figure 32. The Darrieus-Wells Rotor essentially consists of two different types of rotor attached to a single vertical axis. A Darrieus rotor (601 in Figure 32), with approximately vertical blades, is used to extract energy out of the horizontal water particle motion induced by the waves, whilst a Wells rotor (602 in Figure 32), with horizontal

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[2] who now have an exclusive licence to develop the Wave Rotor

blades is used to extract energy out of the vertical water particle motion induced by the waves. The number of blades in the Darrieus-Wells Rotor is not fixed, but typically 3 blades of each type have been proposed. Analysis suggests that the incident wave-induced water particle velocities for the Darrieus rotor will result in a different and changing angle of attack for each blade as well as a variation with the wave cycle due to the oscillatory nature of the horizontal wave-induced water particle velocity. Conversely, the incident wave-induced water particle velocities for the Wells rotor will have the same angle of attack for each blade, but this will vary throughout the wave cycle due to the oscillatory nature of the vertical wave-induced water particle velocities.

Research undertaken by Ecofys and included in the patent application [39] indicates that for the configurations tested the power capture of the Darrieus-Wells Rotor is greater than the sum of the power captures when the two rotors act independently as shown in Figure 33. This implies that there is constructive coupling between the Darrieus and Wells rotors at least for some tip-speed ratios, although it can be seen in Figure 33 that there are also tip-speed ratios that result in destructive coupling between the two rotors.

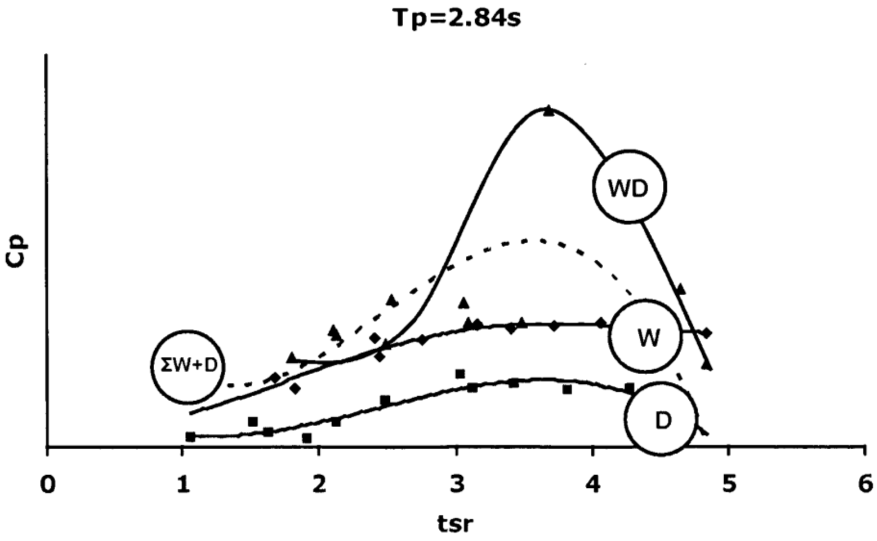

*Figure 33: variation of power coefficient (Cp) with tip-speed ratio (tsr) from the Darrieus rotor (D), Wells rotor (W), the sum of the two rotors (ΣW+D) and the Darrieus-Wells rotor (WD), reproduced from* [39]

A slightly different configuration (see Figure 34) of the Darrieus-Wells Rotor has been experimentally investigated by Yang *et al.* [42], [43]. The experiments performed by Yang *et al.* involved moving the rotor in still water to simulate waves. Although this does not represent the effect of waves on the rotor correctly it is expected to provide some indication of how the Darrieus-Wells turbine operates. The other key difference with the experiments and a more realistic system is that the rotor is undamped and "*free-wheeling*", with increased coupling indicated by higher rotational speeds of the rotor.

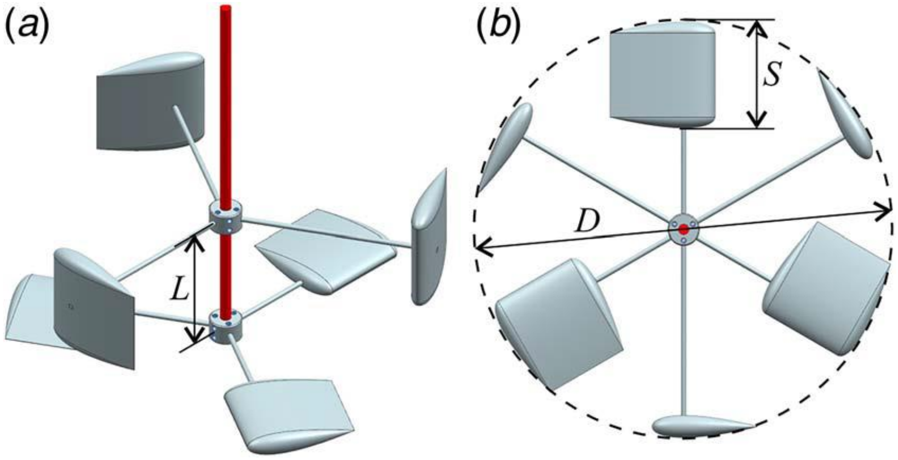

*Figure 34: Darrieus-Wells Rotor investigated by Yang et al., reproduced from* [42]

In one set of experiments, Yang *et al.* moved the Darrieus-Wells rotor in a circular motion (to best represent waves) as well as with purely horizontal and vertical oscillations. The results of these experiments are shown in Figure 35. These indicate that similar rotational speeds were obtained for a circular and vertical motion of the rotor, whilst significantly lower speeds were obtained for the purely horizontal motion. This suggests that the Darrieus rotor, which is excited by the relative horizontal motion of the water particles may be relatively weakly coupled with the water.

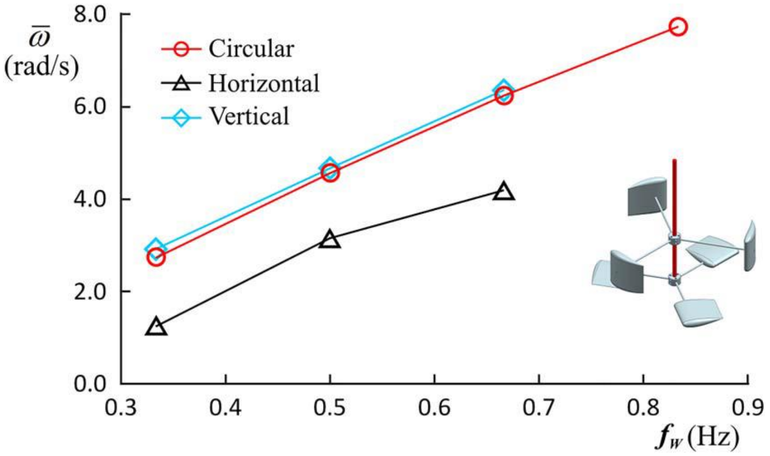

*Figure 35: Effect of different excitation motions on rotor speed, reproduced from* [42]

Yang *et al.* also conducted a range of experiments with just a single blade for each rotor and compared them to the case with three blades. In these experiments similar rotational speeds were obtained when a single rotor was used compared to three rotors. This may be expected as the balance of excitation and drag forces are likely to dictate the rotational speed and changing the number of blades will change the excitation and drag forces equally. However, this does suggest that there is minimal interaction between the blades in each rotor and so provides some justification for treating each blade independently, at least when considering the near-field interactions.

Yang *et al.* also investigated the effect of different hydrofoil profiles used for the rotors as shown in Figure 36. The results show that using the smaller NACA0021 profile resulted in a significantly smaller rotational speed, whilst at low excitation frequencies the thicker NACA0035 profile resulted in higher rotational speeds of the rotor, but that any difference with the thinner NACA0021 profile disappeared at higher excitation frequencies. The cambered profile was only used for the Darrieus rotor, but this resulted in a doubling of the rotational speed when compared to the symmetrical profile for all excitation frequencies. It is reasonably argued by Yang *et al.* that this higher speed of the cambered profile is due to a reduction in the drag coefficient of the cambered blade.

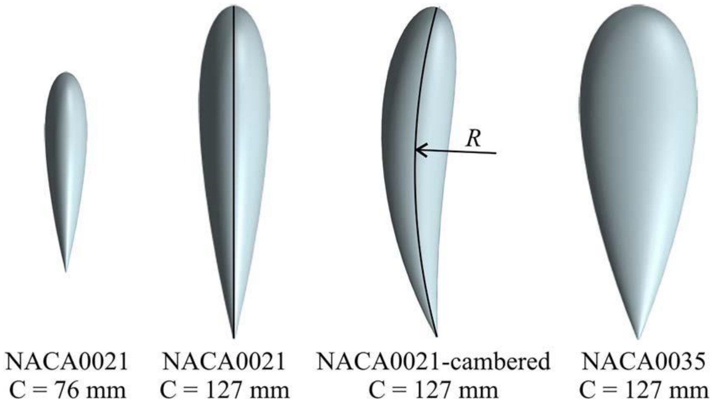

*Figure 36: Hydrofoil profiles used by Yang et al., reproduced from* [42]

Yang *et al.* have also investigated a configuration of the Darrieus-Wells Rotor where the Darrieus and Wells rotors are merged together [45] with a curved transition region as shown in Figure 37. In addition to the smooth transition between the rotors, two additional changes from the previous configurations tested by Yang *et al.* have been included. These are that multiple sets of blades are tested with reduced dimensions, and an offset angle around the rotation axis has been added for two adjacent sets of blades. Unfortunately, Yang *et al.* does not report any difference in performance for this alternative rotor configuration compared to the earlier configuration.

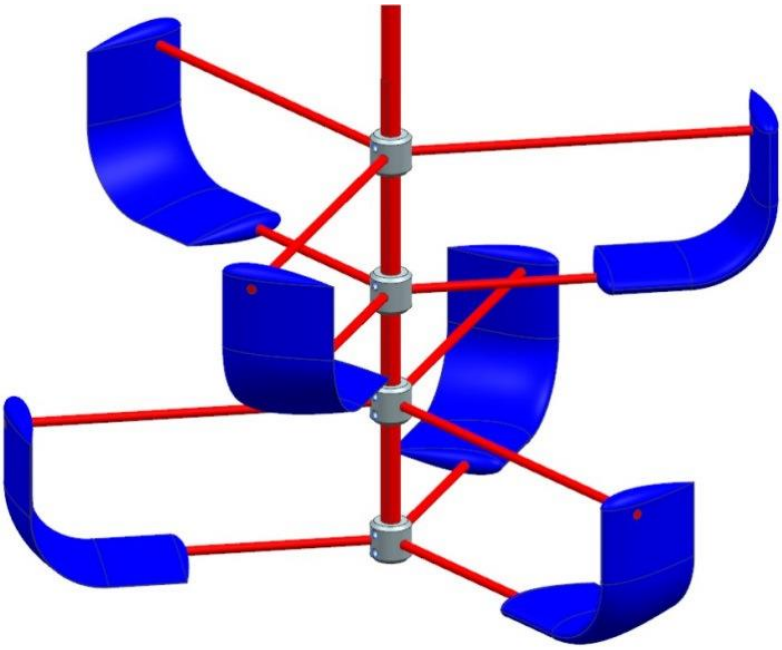

*Figure 37: Merged Darrieus-Wells rotor configuration, reproduced from* [45]

Finally, 2D numerical simulations using ANSYS Fluent 17.2 of the Darrieus element of the Darrieus-Wells Rotor have also been performed ignoring the effects of the free-surface [44]. The model was validated by comparing the rotor's no-load rotational speed against experiments with the rotor driven in still water. A constant torque was applied to the rotation of the rotor in the numerical model to simulate power extraction. The CFD simulations considered both unidirectional and oscillatory flow and indicated that the efficiency of the energy extraction reduced with the oscillating frequency as shown in Figure 38, although the paper does not discuss how the damping torque was set and so it is not clear whether the efficiency has been maximised at each frequency. However, it is argued that the reduction in efficiency is due to "increased dissipation of the internal flow" and that the oscillating flow is significantly reducing the power capture.

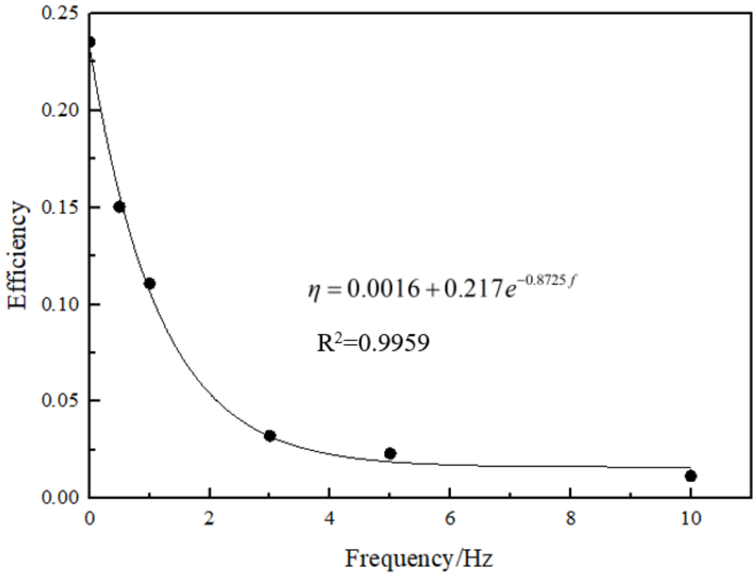

*Figure 38: Efficiency of Darrieus Rotor in oscillatory flow, reproduced from* [44]

### 2.3.5 Savonius-Type Rotors

Although Savonius turbines do not use lift to generate a driving torque they do use the wave-induced water particle velocities to extract energy. Savonius turbines are drag devices and effectively use a deficit in the velocity of the rotor relative to the wave-induced water particle velocities to create a force on the rotor and extract energy. This characteristic means that they have a significantly lower maximum power coefficient than lift-based turbines [46], which in wind turbines has led to Savonius turbines only being used where power generation is not a primary requirement, e.g. anemometers, air extraction, etc. Thus, Savonius turbines are generally not considered suitable for wave energy converters because of the primary requirement for power generation. However, in many cases it is not immediately obvious whether a proposed wave energy converter concept that uses the wave-induced water particle velocities is a lift or drag-based device. Consequently, a short summary of the literature that considers drag-based wave energy converters is included.

A horizontal Savonius rotor as shown in Figure 39 was tested by Faizal *et al.* [47]. The results obtained show that the rotational velocity of the rotor increases with the wave frequency and decreases with depth of submergence. Research then progressed to considering different configurations of rotors [48]. It was found that a blade with a 70° curvature gave the highest rotational speeds. It was also found that higher rotational speeds could be obtained when three rotors were placed behind each other in the direction of wave propagation. It is argued that this could be a promising configuration for power extraction, although no power was extracted in these tests and there is no necessary link between larger rotational velocities and power capture.

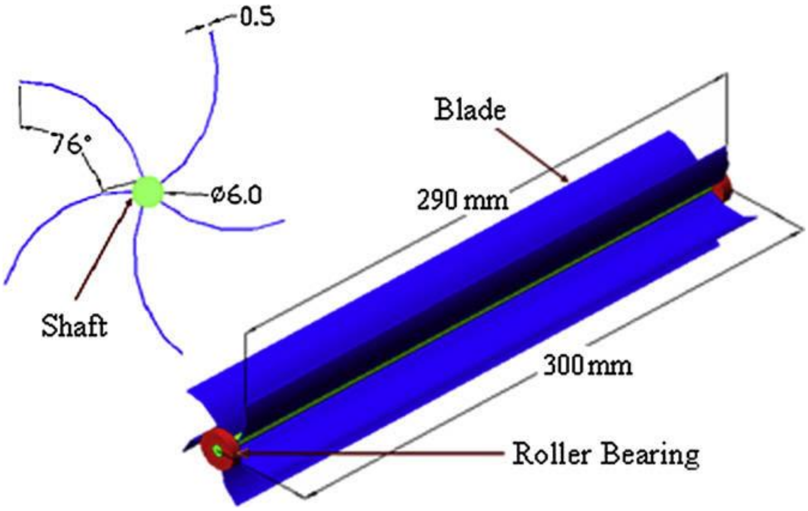

*Figure 39: Savonius rotor tested by Faizal et al., Reproduced from* [47]

The performance of a "*single-bucket drag-type cross-flow turbine*" as shown in Figure 40 has been investigated by Akimoto *et al.* [49]. It is argued by Akimoto *et al.* that this type of turbine is not sensitive to marine growth, which would rapidly reduce the performance of a hydrofoil and require frequent cleaning to maintain their performance. In this single-bucket design it is noted that the turbine is expected to rotate at the same frequency as the incident waves. Numerical modelling and wave-tank experiments undertaken by Akimoto *et al.* suggest an efficiency of about 3.5% may be expected from this concept.

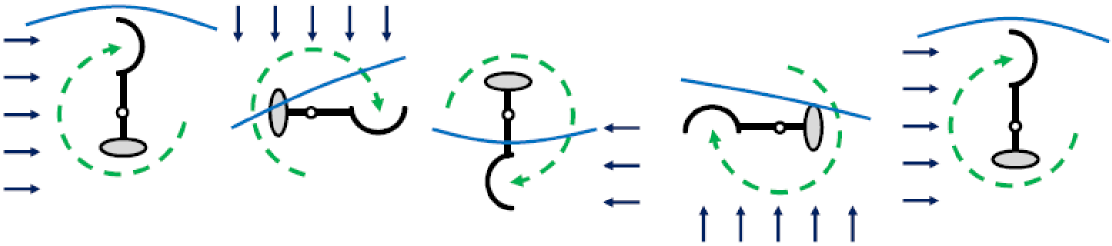

*Figure 40: Single-bucket drag-type cross-flow turbine, reproduced from* [49]

A vertical-axis rotor with multiple (4) sets of cups similar to a standard cup anemometer has been tested in a wave-tank by Yang *et al.* [50]. The experiments demonstrated that the waves caused the rotor to rotate in a single direction, with a velocity that fluctuated at twice the wave frequency (as would be expected from the oscillatory nature of the horizontal wave-induced water particle velocities. Unfortunately, the paper does not provide any details of the power capture of the rotor and only notes that the rotational velocity reduces as the damping torque is increased.

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### 2.3.6 OIST Turbine

The OIST Turbine is a lift-based wave energy converter that has been developed at the Okinawa Institute of Science and Technology (OIST) with support from the Kokyo Tatemono Company Limited (Kokyo). The OIST Turbine is designed to be installed in the breaking zone [51]. The focus in the development of this concept has been on the engineering and a prototype has been installed in the Maldives [52], [53].

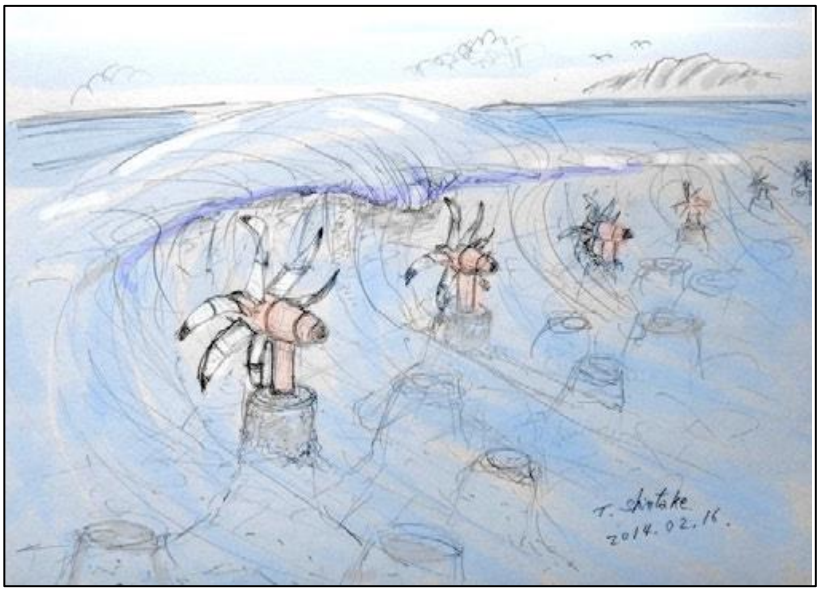

*Figure 41: Image of OIST Turbine, reproduced from* [51]

An artistic impression of an array of OIST Turbines created by the project leader is shown in Figure 41. The OIST Turbine is designed to interact with only the forward velocity of the incident waves, with the axis of the turbine positioned slightly above the mean sea level. It is also intended that it is located just before the waves break as it is considered that it is difficult to extract energy from the highly random and aerated water that exists after the waves break [51]. It is argued that just before the wave breaks the water particle velocity will be equal to the phase velocity of the wave and typically between 4 – 8 m/s, with power densities of approximately 30 – 250 kW/m$^2$ (where the reference area is in a vertical plane orthogonal to the direction of wave propagation). It is however recognised that this power density is not constant, but will arrive in pulses, where it is assumed that the “duty factor” will be approximately 20%.

Shintake *et al.* also consider the potential impact that the turbines may have on marine mammals and argue that the tip speed of the turbines should be less than the maximum swimming speed of a marine mammal, which is estimated to be about 10 m/s, to ensure that it is safe. This implies a maximum turbine tip-speed ratio of 2.0 for an incident water particle velocity of 5 m/s. This tip-speed ratio is then used with standard turbine power efficiency curves to argue that the OIST Turbine should have five blades, with a peak power efficiency of about 33%.

A variety of deployment locations are considered by Shintake *et al.* including placing the turbines in front of breakwaters, to improve coastal protection as well as on submerged breakwaters to better regulate the tendency for waves to break just after the location of the OIST Turbine, although it is recognised that the cost of constructing submerged breakwaters just for the installation of the turbines would make this configuration uneconomic. Another co-deployment proposal from Shintake *et al.* is to install the turbines within ducts of a seawall, where preliminary experiments have suggested that up to ten times more power can be generated per turbine. It is also recognised by Shintake *et al.* that suitable locations will need to have a relatively small tidal range for the OIST Turbine to be viable.

Following the development philosophy that is led by experimentation, two half-scale 1 kW prototypes were deployed in the Maldives in May 2018, followed by two full-scale 8 kW prototypes in November 2018 near the same locations. Figure 42 shows the two half-scale OIST Turbines that were deployed at different heights (1.0 metres and 1.5 metres) to investigate the effect that this may have on performance. The results of the prototype deployments have primarily been reported as voltages generated by the turbine. Based on the generator characteristics provided (Figure 18 in [52]) and a stated electrical load of more than 150 Ω for the tests implies that minimal electrical power was generated during the tests. In normal operation it would be expected that the electrical load would need to be varied to obtain the optimum tip-speed ratio for each wave as well as maximise the efficiency of the electrical generation.

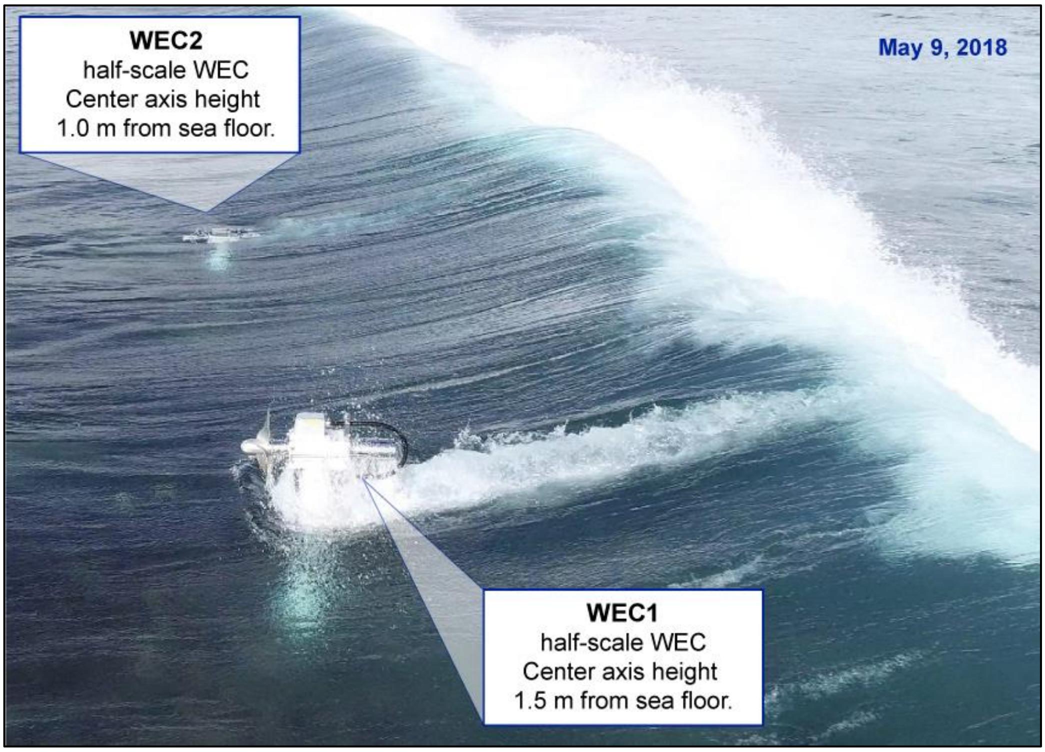

*Figure 42: Half-scale OIST Turbines deployed in the Maldives, reproduced from* [53]

The limited tidal range in which the OIST Turbine can be deployed, together with the potential acceptability and safety issues for deploying technology is such shallow water and relatively close to the shoreline mean that this concept is unlikely to be suitable for utility-scale electricity production in Europe. The variability of the waves at any location, both due to the spectral content of a sea-state as well as the annual variation in the wave climate is also likely to reduce the average energy production of the OIST Turbine.

# 3 CONCEPT IDEAS AND PRELIMINARY CONFIGURATIONS

## 3.1 PROCESS OVERVIEW

The generation of new ideas and configurations is a naturally continual process with the potential for new ideas and configurations to occur at any time as a *Eureka* moment. However, whilst these *Eureka* moments can occur spontaneously, it is also possible to encourage their generation using structured processes that have been shown to be effective. In particular, it has been found that workshops can be very productive for the generation of new ideas, especially when the participants in the workshop have a range of skills and knowledge, which can help to support the cross-fertilisation of ideas. A workshop can also provide an opportunity for participants to share ideas that may have occurred in earlier *Eureka* moments but had not been formally recorded. With a clear catalogue of ideas that can be used in configurations it is then advantageous to have the same wide range of skills and knowledge to consider how best to combine the ideas into different configurations.

A 3-day workshop for the generation of new ideas and configurations was originally planned to be held in Lisbon in May 2020. Unfortunately, the severe lock-down in most of the countries in Europe meant that a physical meeting at this time was not possible. To ensure that the LiftWEC project remained on schedule it was decided that this workshop would be held virtually through the internet. The virtual conferencing tool Zoom was chosen as the primary tool to support the workshop, where it was found to be very effective. In addition, a number of bespoke web-based tools were also produced to support the workshop, including

- Guided Brainstorming tool (see Section 3.2.1)
- Functional Analysis drawing tool (see Section 3.2.2)
- Ideas catalogue tool (see Section 3.3)
- Configuration catalogue tool (see Section 3.4)
- Configuration scoring tool (see Section 3.6)

These tools were in general also found to be very effective in supporting the process of idea and configuration generation. Indeed, although future project workshops, planned for Months 18 and 30 will hopefully be held in person, it is possible that some of these tools (or refinements of them) will be retained because of their ability to ensure a good structure to information entered and the facilitation of the sharing of this information.

*Figure 43: Structure for 3-day workshop*

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The structure of the 3-day workshop was such there were effectively three phases, with each phase occurring on a separate day as shown in Figure 43.

The first day, *Familiarisation*, involved identification of the Problem Scope and presentations by relevant project work package leaders on the influences on design from their perspective. The work packages that gave presentations were

- WP2 – Concept development and evaluation
- WP5 – Control strategy
- WP6 – Structural design
- WP7 – Operations and maintenance
- WP8 – Cost of energy
- WP9 – Environmental and social impact

The final part of the first day included a presentation by Jochem Weber on the use of Structured innovation for the development of novel wave energy converter concepts. Jochem Weber is Chief Engineer of NREL Water Power Program and following his PhD in the modelling and optimisation of wave energy converters has 21 years of research technology development of wave energy. In addition, he was the developer of the Technology Performance Level (TPL) metric that is now commonly used in wave energy and initiator and PI for the Structured Innovation / WaveSPARC project. Thus, Jochem Weber has a wealth of experience in managing the development of novel wave energy concepts, which he was very willing to share with the workshop.

The second day consisted of small group work, each of 3 – 5 participants, where ideas could be generated and saved for potential application to configurations. Three different techniques were used for ideas generation, namely

- Guided brainstorming
- Functional Analysis
- TRIZ Standard solutions

Further details on each of these techniques are provided in sub-sections below.

The first session of the final day involved small group work, each with 3 – 5 participants, generating three to six configurations for lift-based wave energy converters. Effectively, the ideas generated on the previous day, together with any other ideas that may not have been explicitly captured where used to generate potential Preliminary Configurations for the LiftWEC project. In the second session of the day the Evaluation Criteria from project Deliverable D2.2 were presented, and an opportunity was provided to discuss these criteria. The workshop then separated back into small groups, but with different memberships from the first session so that the configurations could be discussed before participants scored each of the configurations using the Evaluation Criteria as qualitative guidance. Then, the small groups re-united to discuss the scoring to assess how best to progress with the specification of the Preliminary Configurations, which was the primary objective of the workshop.

Each of these steps, together with their outputs are described in more detail in the following sub-sections.

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## 3.2 IDEA GENERATION TECHNIQUES

### 3.2.1 Guided brainstorming

Each brainstorming session lasted 2 hours and a Facilitator was assigned to the group prior to the start of the session. It was the Facilitator's responsibility to ensure the agenda for the session was followed and maintained.

Brainstorming is a well-known group creative process whereby a group of people meet to generate new ideas for a particular problem. Key characteristics of a brainstorming session are that all ideas are noted down without criticism and only evaluated after the brainstorming process. A range of different brainstorm techniques exist where the separation between the production of ideas and their sharing with the group is moderated in different ways; *Guided Brainstorming* was used for these sessions.

In *Guided Brainstorming* sessions, the first task is to define a set of problems; each problem is then analysed in turn. For each problem, every participant has to write down a solution to the problem. This solution is then passed to another member of the group that are asked to improve or modify or comment on the idea. This process is repeated three of more times. The final solutions are then discussed in the group to allow the identification of further refinements. Finally, the solutions were rationalised by the group and included in the *Ideas Catalogue* (see Section 3.3).

**Draft agenda**

| Step | Time | Activity |
|---|---|---|
| 1 | 5' | Facilitator explains process and participants connect to LucidChart |
| 2 | 5' | Practice changing name and adding tick to box in LucidChart |
| 3 | 5' | Participants add problems to Zoom chat – transferred to spreadsheet by Facilitator |
| 4 | 5' | Participants provide short explanation of their proposed problem(s) |
| 5 | 5' | Participants select three problems (Facilitator selects last and has casting vote) |
| 6 | 5' | Participants write initial solutions to most popular Problem (use tick to show ready) |
| 7 | 20' | Participants improve/refine/modify/comment on solutions received when ready |
| 8 | 15' | Group agree solutions to be entered into *Ideas Catalogue* |
| 9 | 15' | BREAK |
| 10 | 40' | Repeat steps 6 – 8 for second most popular Problem (if appropriate) |
| | **120'** | |

The web-enabled software tool LucidChart was used for sharing ideas using a template that was designed specifically for this workshop. As an example, the output from one of the Guided Brainstorming Session is shown in Figure 44.

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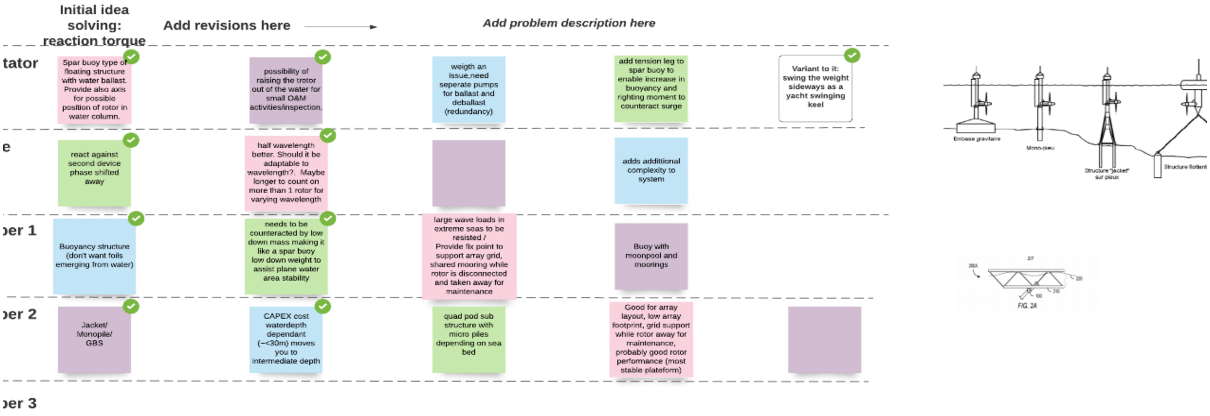

Spar buoy type of floating structure with water ballast. Provide also axis for possible position of rotor in water column.

possibility of raising the trotor out of the water for small O&M activities/inspection.

weigth an issue,need seperate pumps for ballast and deballast (redundancy)

add tension leg to spar buoy to enable increase in buoyancy and righting moment to counteract surge

Variant to it: swing the weight sideways as a yacht swinging keel

react against second device phase shifted away

half wavelength better. Should it be adaptable to wavelength?. Maybe longer to count on more than 1 rotor for varying wavelength

adds additional complexity to system

Buoyancy structure (don't want foils emerging from water)

needs to be counteracted by low down mass making it like a spar buoy low down weight to assist plane water area stability

large wave loads in extreme seas to be resisted / Provide fix point to support array grid, shared mooring while rotor is disconnected and taken away for maintenance

Buoy with moonpool and moorings

Jacket/ Monopile/ GBS

CAPEX cost waterdepth dependant (~<30m) moves you to intermediate depth

quad pod sub structure with micro piles depending on sea bed

Good for array layout, low array footprint, grid support while rotor away for maintenance, probably good rotor performance (most stable plateform)

*Figure 44: Example output from Brainstorming session*

### 3.2.2 Functional Analysis

Each Functional Analysis session lasted 2 hours and a Facilitator and Scribe were assigned to each group prior to the start of the session. It was the Facilitator's responsibility to ensure that the agenda for the session is followed and maintained. It was the Scribe's responsibility to ensure that findings from the session are recorded and the *ideas Catalogue* (see Section 3.3) is updated appropriately.

TRIZ is a systematic approach used to understand and solve challenging problems [54]. A key element of a TRIZ analysis is the creation of a Functional Analysis of the system that shows the relationships between components of the system in a *Subject-action-Object* relationship, where each relationship can be useful (further defined as insufficient, adequate or excessive) or harmful. It is possible to produce a Bare Functional Analysis that shows the fundamental inputs and outputs of the system, which is illustrated in Figure 45. A range of different ways can be envisaged for how these elements connect to produce the system, each representing in a different concept, containing a number of ideas some of which may be novel.

This session involved developing the Functional Analysis to provide the required system, with the identification of ideas that can be added to the *Ideas Catalogue* as the Functional Analysis is produced.

**Draft agenda**

| Step | Time | Activity |
|---|---|---|
| 1 | 10’ | Introduction to session |
| 2 | 90’ | Revision and modification of Functional Analysis (adding to *Ideas Catalogue* as they occur) |
| 3 | 20’ | Review of Functional Analysis to ensure that all ideas have been captured in the *Ideas Catalogue* |
|  | **120’** |  |

A link to the Base Functional Analysis in LucidChart was provided to all participants in each workshop. Once registered all participants can add and modify elements in the Functional Analysis simultaneously.

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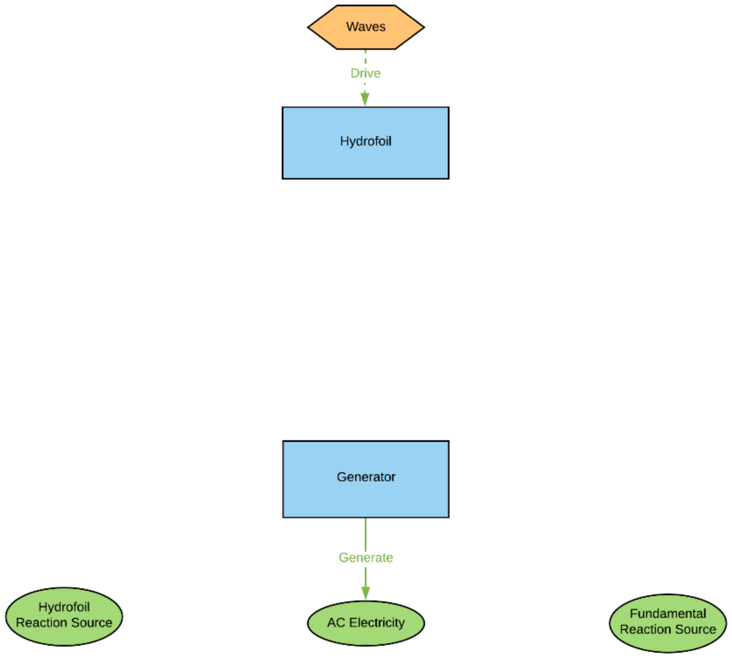

*Figure 45: Bare Functional Analysis of LiftWEC*

### 3.2.3 TRIZ standard solutions

Each TRIZ Standard Solutions session lasted 2 hours and a Facilitator and Scribe were assigned to the group prior to the start of the session. It was the Facilitator's responsibility to ensure that the agenda for the session is followed and maintained. It was the Scribe's responsibility to ensure that findings from the session are recorded and the *ideas Catalogue* (see Section 3.3) is updated appropriately.

TRIZ is a systematic approach used to understand and solve challenging problems [54]. A key element of a TRIZ analysis is the creation of a Functional Analysis of the system that shows the relationships between components of the system in a *Subject-action-Object* relationship, where each relationship can be useful (further defined as insufficient, adequate or excessive) or harmful. Unfortunately, in many cases the useful relationship is accompanied by a harmful relationship which reduces the quality of the solution. TRIZ provides a set of 35 Standard Solutions for dealing with Insufficient relationships (Appendix A Table 1) and 24 Standard Solutions for dealing with Harmful relationships (Appendix A Table 2).

The TRIZ Standard Solutions session started with the familiarisation and revision of the Functional Analysis of the LiftWEC configuration used for illustration in the proposal to identify the insufficient and harmful relationships. The insufficient and harmful relationships in the Functional Analysis are provided in Table 3. It is clearly important that all members of the group are comfortable with the Functional Analysis and that they understand the characteristics of the insufficient and harmful relationships in the system. Then the insufficient and harmful relationships should be prioritised so that those with the most impact on design are considered first. A flowchart for the session is provided in Figure 46.

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**Draft agenda**

| Step | Time | Activity |
|---|---|---|
| 1 | 10’ | Introduction to session and link to *Ideas Catalogue* |
| 2 | 20’ | Familiarisation with Functional Analysis of LiftWEC concept in proposal |
| 3 | 5’ | Vote for choice of the relationships to investigate |
| 4 | 35’ | Follow TRIZ Standard Solution process for first relationship |
| 5 | 15’ | BREAK |
| 6 | 35’ | Follow TRIZ Standard Solution process for second relationship |
|  | **120’** |  |

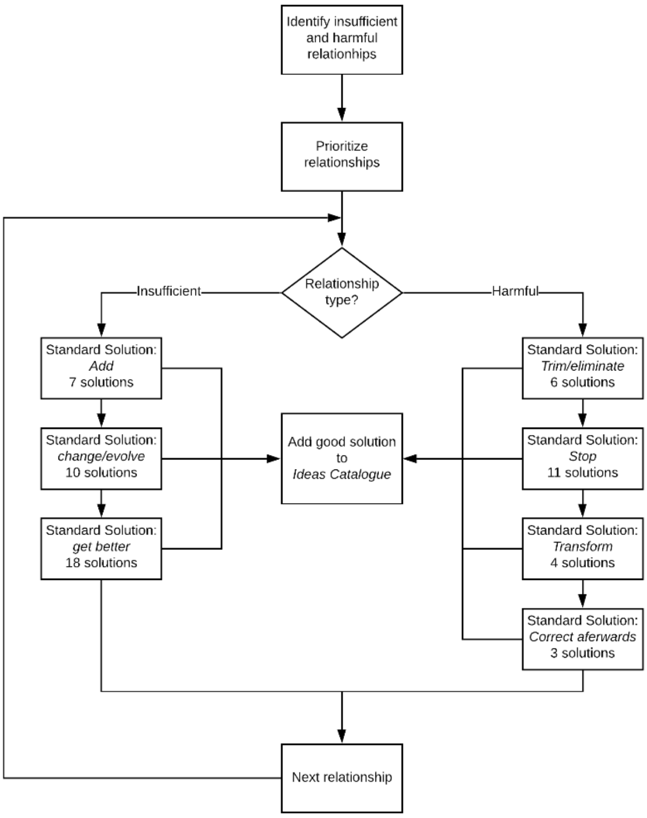

*Figure 46: TRIZ Standard Solutions process*

## 3.3 IDEAS GENERATED

A web-based tool has been developed to support the cataloguing and distribution of *ideas* that could be relevant to the development of the LiftWEC Preliminary Configurations. The tool essentially consists of a *New Ideas Form* with a number of fields that need to be completed for each idea. Once the idea has been entered through the form it is automatically added to the *Ideas Catalogue*, which can also be accessed through a web browser. A screenshot of the *New Ideas Form* is shown in Figure 47, whilst a screenshot of the *Ideas Catalogue* is shown in Figure 48.

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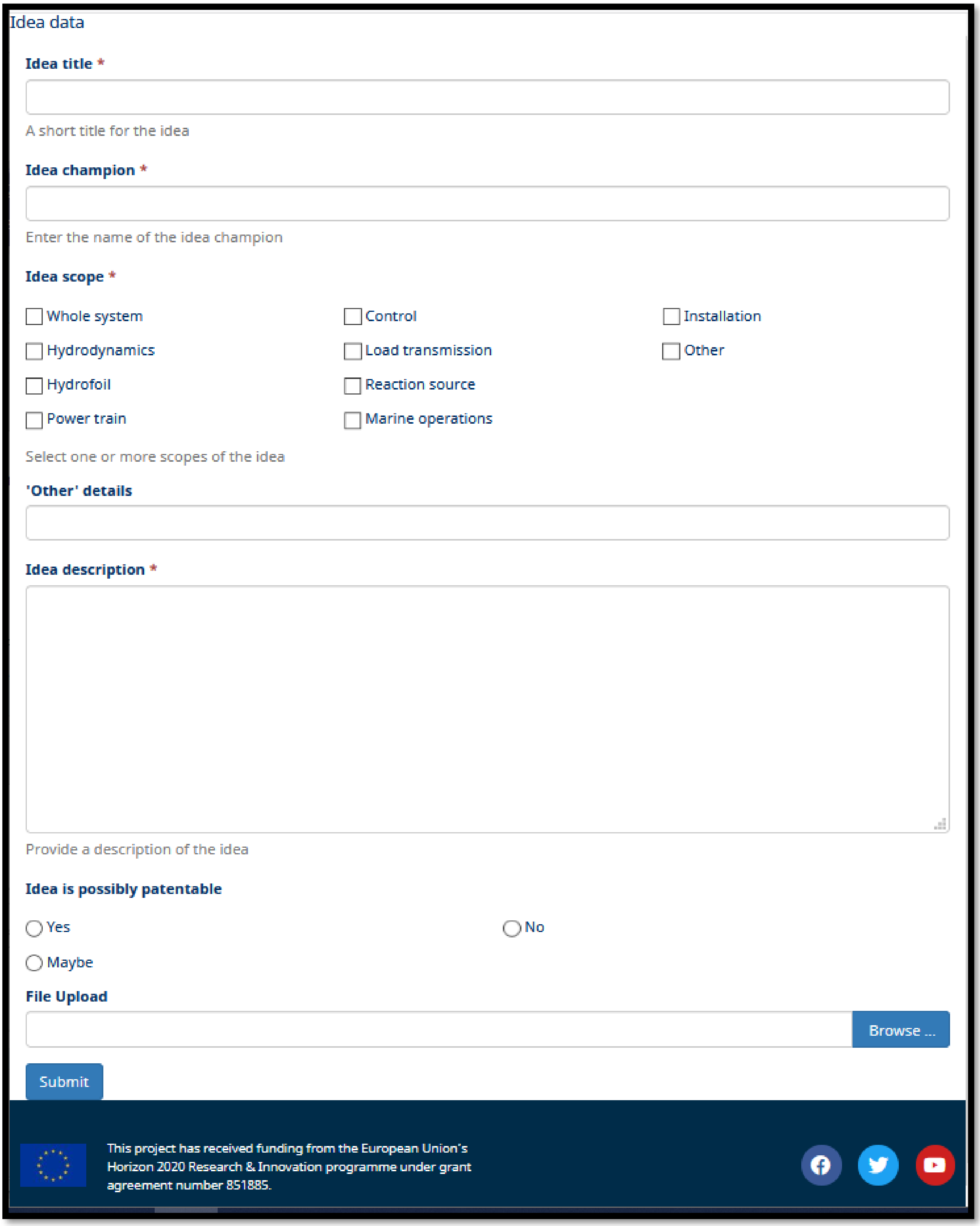

Idea data

**Idea title** *

A short title for the idea

**Idea champion** *

Enter the name of the idea champion

**Idea scope** *

☐ Whole system
☐ Hydrodynamics
☐ Hydrofoil
☐ Power train
☐ Control
☐ Load transmission
☐ Reaction source
☐ Marine operations
☐ Installation
☐ Other

Select one or more scopes of the idea

**'Other' details**

**Idea description** *

Provide a description of the idea

**Idea is possibly patentable**

○ Yes
○ No
○ Maybe

**File Upload**

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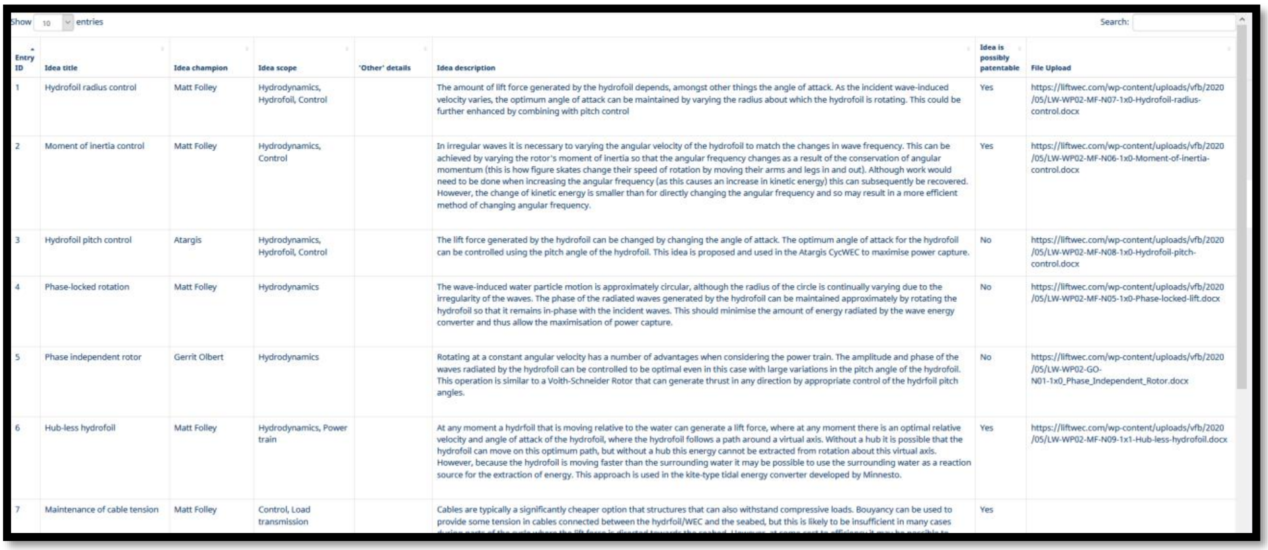
*Figure 47: Screenshot of New Idea Form*

The *New Ideas Form* contains the following fields

- Idea title
    - A short title for the idea that can be used to label it
- Idea champion
    - The name of a person that can provide further information about the idea. In the majority of cases this would be the idea generator, but this is not necessary
- Idea scope
    - Ten options for the idea scope are provided (including 'other') that can be used to categorise the idea. Any idea can be related to more than one idea scope as these are check-boxes. The ten options are
        - Whole system
        - Hydrodynamics
        - Hydrofoil
        - Power train
        - Control
        - Load transmission
        - Reaction source
        - Marine operations
        - Installation
        - Other
- Idea description
    - A description of the idea with sufficient detail that users of the *Ideas Catalogue* can understand the fundamental characteristics of the idea
- Is the idea patentable
    - An initial indication for whether the idea is patentable
- Upload file
    - This allows further information (images, references, etc.) to be linked to the idea



| Entry ID | Idea title | Idea champion | Idea scope | 'Other' details | Idea description | Idea is possibly patentable | File Upload |
|---|---|---|---|---|---|---|---|
| 1 | Hydrofoil radius control | Matt Folley | Hydrodynamics, Hydrofoil, Control | | The amount of lift force generated by the hydrofoil depends, amongst other things the angle of attack. As the incident wave-induced velocity varies, the optimum angle of attack can be maintained by varying the radius about which the hydrofoil is rotating. This could be further enhanced by combining with pitch control | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N07-1x0-Hydrofoil-radius-control.docx |
| 2 | Moment of inertia control | Matt Folley | Hydrodynamics, Control | | In irregular waves it is necessary to varying the angular velocity of the hydrofoil to match the changes in wave frequency. This can be achieved by varying the rotor's moment of inertia so that the angular frequency changes as a result of the conservation of angular momentum (this is how figure skates change their speed of rotation by moving their arms and legs in and out). Although work would need to be done when increasing the angular frequency (as this causes an increase in kinetic energy) this can subsequently be recovered. However, the change of kinetic energy is smaller than for directly changing the angular frequency and so may result in a more efficient method of changing angular frequency. | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N06-1x0-Moment-of-inertia-control.docx |
| 3 | Hydrofoil pitch control | Atargis | Hydrodynamics, Hydrofoil, Control | | The lift force generated by the hydrofoil can be changed by changing the angle of attack. The optimum angle of attack for the hydrofoil can be controlled using the pitch angle of the hydrofoil. This idea is proposed and used in the Atargis CycWEC to maximise power capture. | No | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N08-1x0-Hydrofoil-pitch-control.docx |
| 4 | Phase-locked rotation | Matt Folley | Hydrodynamics | | The wave-induced water particle motion is approximately circular, although the radius of the circle is continually varying due to the irregularity of the waves. The phase of the radiated waves generated by the hydrofoil can be maintained approximately by rotating the hydrofoil so that it remains in-phase with the incident waves. This should minimise the amount of energy radiated by the wave energy converter and thus allow the maximisation of power capture. | No | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N05-1x0-Phase-locked-lift.docx |
| 5 | Phase independent rotor | Gerrit Olbert | Hydrodynamics | | Rotating at a constant angular velocity has a number of advantages when considering the power train. The amplitude and phase of the waves radiated by the hydrofoil can be controlled to be optimal even in this case with large variations in the pitch angle of the hydrofoil. This operation is similar to a Voith-Schneider Rotor that can generate thrust in any direction by appropriate control of the hydrfoil pitch angles. | No | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-GO-N01-1x0_Phase_Independent_Rotor.docx |
| 6 | Hub-less hydrofoil | Matt Folley | Hydrodynamics, Power train | | At any moment a hydrfoil that is moving relative to the water can generate a lift force, where at any moment there is an optimal relative velocity and angle of attack of the hydrofoil, where the hydrofoil follows a path around a virtual axis. Without a hub it is possible that the hydrofoil can move on this optimum path, but without a hub this energy cannot be extracted from rotation about this virtual axis. However, because the hydrofoil is moving faster than the surrounding water it may be possible to use the surrounding water as a reaction source for the extraction of energy. This approach is used in the kite-type tidal energy converter developed by Minnesto. | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N09-1x1-Hub-less-hydrofoil.docx |
| 7 | Maintenance of cable tension | Matt Folley | Control, Load transmission | | Cables are typically a significantly cheaper option that structures that can also withstand compressive loads. Bouyancy can be used to provide some tension in cables connected between the hydrfoil/WEC and the seabed, but this is likely to be insufficient in many cases | Yes | |

*Figure 48: Screenshot of Ideas Catalogue*

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The web-based access to the *Ideas Catalogue* is a simple table, with the addition that it can be filtered using the Search option that can be seen in the top right-hand side of the screenshot shown in Figure 48.

During the workshop, a total of ten idea generation groups met, which resulted in a final total of 79 ideas being generated. These ideas are shown in Appendix B.

## 3.4 CONFIGURATION GENERATION

The session for the generation of potential LiftWEC Preliminary Configurations lasted 2 hours. Small groups were used for this configuration generation to maximise the opportunity for all participants to contribute. Each group consisted of 3 – 5 participants with a Facilitator and Scribe. It was the Facilitator's responsibility to ensure that the agenda for the session was followed and maintained. It was the Scribe's responsibility to ensure that findings from the session were recorded and the *Configurations Catalogue* updated appropriately. The *Configurations Catalogue* was added to using the *New Configuration Form*. The *New Configuration Form* has the following fields

- Configuration title
    - This is the name of the configuration so that it can be easily referenced when required
- Configuration champion/owner
    - This the name of one or more people that developed the configuration and can provide further details on the configuration if required
- Ideas used
    - This is a set of check-boxes, where each check-box is an idea title from the *Ideas Catalogue*. The ideas used in generating the configuration should be checked
- Configuration general description
    - A description of the configuration with sufficient detail that users of the *Configuration Catalogue* can understand the fundamental characteristics of the configuration
- Further details
    - Individual text boxes are provided to allow further details on specific aspects of the configuration. These further details are
        - Hydrofoil design
        - Number/layout of hydrofoils
        - Fundamental Reaction Source
        - Hydrofoil Reaction Source
        - Method of lift force control
        - Method of phase control
        - Electrical generator
        - Structural details
        - Installation / O&M techniques
- Upload file
    - This allows further information (images, references, etc.) to be linked to the configuration

It was requested that each group generate three to six configurations and include them in the *Configurations Catalogue.* There were no specific requirements for how the configurations should be generated and recorded, but the following guidance was provided

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- The configurations should cover as wide a range of concepts as possible
- The *Ideas Catalogue* can be used for inspiration, but configurations are not limited these ideas
- No more than 45 minutes should be spent on generating any one configuration
- The views of all participants should be encouraged by the Facilitator
- A shared document (through Zoom) can be used to collect thoughts on each configuration
- Once a configuration has been identified a single member of the team should be tasked with entering it into the *Configuration Catalogue*, which is then shown to other participants (through Zoom Screen Share) prior to submission. The other participants can start to work on a new configuration

A total of 15 configurations were generated during the workshop, which have been added to the Atargis Jack-Up CycWEC configuration and the configuration described in the LiftWEC project proposal to make a total of 17 configurations for consideration. The details for all of these configurations are provided in Appendix C.

## 3.5 EVALUATION CRITERIA

The evaluation criteria to be used for the assessment of LiftWEC concepts are detailed in the Deliverable D2.2 *Identification of Evaluation Criteria*. This document defines five thematic categories, with fifteen Level 1 Criteria and twenty-six Level 2 Criteria, which are:

**Energy production**

- Energy capture
    - Energy absorption potential
    - Control potential
    - Load shedding abilities
    - Versatility
- Energy conversion
    - Storage
    - Efficiency

**Survivability**

- Load shedding abilities
    - Rotor shedding abilities
    - Structural support abilities
- Loads in extreme events
    - Extreme loads
    - Snap loads / end stop risks

**Affordability**

- Structural requirement
    - Rotor structural requirement
    - Support structure structural requirement
    - Structural versatility
- Station keeping requirement
- Install-ability
    - Safety

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    - Transport to site required
    - Boat / asset requirement
    - WEC installation time
    - Farm installation time
- Manufacturability
    - Rotor
    - Support structure
    - PTO
- Maintainability
    - Connection / disconnection requirement
    - Modular O&M
    - Boats / asset requirement
    - Safety
    - Critical elements

**Acceptability**

- Regulatory and environmental
- Societal impact

**Developability**

- Physical test requirements
- Numerical modelling complexity
- Scalability
- Secondary markets

The suitability of these evaluation criteria was discussed at the workshop in a plenary session with all consortium members present. There was a general agreement that these evaluation criteria would be suitable for the evaluation of LiftWEC configurations. This is perhaps not surprising because these criteria are based on, and are very similar to, evaluation criteria that have been developed for wave energy converters previously.

In addition to reaching a consensus on the evaluation criteria to use for LiftWEC configurations, the discussion also helped to familiarise the workshop participants with the factors that should be considered when scoring each of the configurations.

## 3.6 RANKING OF CONFIGURATIONS

An assessment of each of the configurations using the Evaluation Criteria would require significantly more information that is available at this early stage of configuration development. However, it is generally possible for people with experience and knowledge in a field to make a reasonable judgement on the relative value of a configuration. Furthermore, it is generally found that the average opinion of a group of people is more reliable than that of a single individual. Moreover, this judgement is typically enhanced following a group discussion on the judgements that need to be made. Based on these observations the process of ranking the configurations involved an initial discussion of the configurations in small groups, where the groups were formed so that they each contained a member from each group that produced the configurations. This means that there was a representative of each configuration generation group in each configuration evaluation group to provide further information

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as required. Then, following the group discussion, each participant had to score each configuration using a single score of 0 – 100. The guidelines for the scoring were:

- 0 – configuration would not work / unacceptable impact
- 50 – configuration on cusp of being worth investigating
- 100 – configuration has no apparent weaknesses

The results of the configuration scoring are provided in the table below.

| **ID** | **Title** | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | Redacted | **Average** | **Min** | **Max** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | Jack-up CycWEC | 50 | 50 | 10 | 75 | 60 | 90 | 60 | 20 | 60 | 55 | 50 | 50 | 70 | 80 | 75 | 10 | 35 | 56 | **53** | **10** | **90** |
| 4 | LiftWEC proposal configuration | 50 | 50 | 50 | 81 | 40 | 90 | 70 | 50 | 50 | 60 | 100 | 90 | 70 | 59 | 80 | 50 | 60 | 62 | **65** | **40** | **100** |
| 5 | Hydrofoil mounted Turbine PTO | 50 | 50 | 65 | 60 | 70 | 60 | 65 | 60 | 60 | 65 | 50 | 50 | 75 | 50 | 75 | 50 | 50 | 37 | **58** | **37** | **75** |
| 6 | Adaptable - Reconfigurable WECs | 50 | 50 | 75 | 86 | 35 | 80 | 35 | 5 | 40 | 45 | 0 | 65 | 50 | 0 | 10 | 10 | 40 | 56 | **41** | **0** | **86** |
| 7 | Twin-moored buoyant structure with Minesto PTO | 50 | 50 | 70 | 82 | 85 | 90 | 50 | 50 | 50 | 70 | 0 | 70 | 70 | 40 | 75 | 50 | 40 | 48 | **58** | **0** | **90** |
| 8 | Spar buoy with phase free rotor | 50 | 50 | 40 | 90 | 61 | 95 | 50 | 10 | 90 | 45 | 100 | 70 | 60 | 80 | 75 | 10 | 40 | 22 | **58** | **10** | **100** |
| 9 | Parabolic with flaps and stiff single-point V-mooring | 76 | 50 | 45 | 86 | 50 | 65 | 50 | 20 | 65 | 50 | 50 | 65 | 70 | 50 | 80 | 10 | 20 | 21 | **51** | **10** | **86** |
| 10 | Phase-locked contra-rotating | 63 | 49 | 5 | 71 | 55 | 85 | 55 | 20 | 90 | 30 | 50 | 60 | 70 | 64 | 50 | 10 | 35 | 3 | **48** | **3** | **90** |
| 11 | Struts based single rotor with submergence control | 80 | 50 | 5 | 40 | 85 | 90 | 70 | 15 | 60 | 55 | 100 | 55 | 65 | 70 | 70 | 10 | 50 | 30 | **56** | **5** | **100** |
| 12 | Tethered mono-hydrofoil with wing mounted turbine | 0 | 50 | 5 | 37 | 27 | 55 | 60 | 15 | 60 | 40 | 0 | 30 | 75 | 20 | 65 | 10 | 35 | 31 | **34** | **0** | **75** |
| 13 | Direct hydrofoil rotor PTO | 75 | 50 | 55 | 53 | 45 | 90 | 65 | 50 | 70 | 65 | 50 | 50 | 65 | 45 | 80 | 10 | 40 | 28 | **55** | **10** | **90** |
| 14 | Slack moored LiftWEC semisub with multiple rotors | 64 | 50 | 40 | 65 | 65 | 90 | 75 | 40 | 85 | 60 | 99 | 80 | 65 | 70 | 70 | 10 | 35 | 52 | **62** | **10** | **99** |
| 15 | Hydraulic PTO on main rotational shaft | 0 | 50 | 50 | 11 | 60 | 60 | 70 | 10 | 70 | 55 | 98 | 40 | 65 | 50 | 80 | 50 | 50 | 4 | **49** | **0** | **98** |
| 16 | Hubless wing with mounted turbines | 85 | 50 | 50 | 83 | 49 | 85 | 60 | 25 | 70 | 65 | 50 | 65 | 75 | 45 | 55 | 10 | 35 | 7 | **54** | **7** | **85** |
| 17 | Radius Control Focused Config | 50 | 50 | 50 | 81 | 71 | 85 | 60 | 40 | 65 | 65 | 99 | 60 | 68 | 75 | 50 | 50 | 65 | 53 | **63** | **40** | **99** |
| 18 | Planetary Gear End Plates | 50 | 50 | 70 | 94 | 76 | 75 | 65 | 50 | 65 | 55 | 50 | 50 | 60 | 60 | 55 | 70 | 25 | 58 | **60** | **25** | **94** |
| 19 | Single Strut Hydrofoil with Minesto-Type Turbine | 88 | 50 | 33 | 65 | 64 | 90 | 60 | 30 | 65 | 65 | 100 | 40 | 70 | 45 | 80 | 10 | 50 | 13 | **57** | **10** | **100** |

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# 4 SPECIFICATION OF PRELIMINARY CONFIGURATIONS

## 4.1 OVERVIEW OF SPECIFICATIONS

A consideration of the Preliminary Configurations suggests that there is significant commonality between many of the different configurations. Indeed, almost all configurations have a majority of their specifications in common with one or more of the other configurations. This suggests that the best approach for the specification of these Preliminary Configurations is not to consider each configuration in isolation, but to consider the particular facets of the configurations based on their relationship to design. Each configuration then becomes a combination of the solution for the particular facets. An additional advantage of this approach is that additional configurations may become evident as a result of a unique combination of the facets that was not included as one of the Preliminary Configurations generated in the workshop. Indeed, this process should facilitate the inclusion of further solutions that may not currently be evident but become apparent as a result of the investigation into the current configurations.

Consideration of these facets suggests that the design can be separated into six areas of hydrodynamics, control strategy, structural design, operations & maintenance, cost of energy and social & environmental impact, which conveniently map approximately onto the work packages within the project. The specifications for physical and numerical modelling can also be added to these areas as it is appropriate to specify how these can be most effectively used to support the development of the understanding of the Preliminary Configurations. The specifications for these eight areas are provided in the sub-sections below.

Although this additive approach to the design has many attractive features, it is possible that in some cases only the totality of the configuration can be used for evaluation. In these cases, it would seem appropriate to use the highest scoring configuration to define the specifications, which was the *LiftWEC proposal configuration* (Config ID: 4). The Preliminary Configurations developed during the workshop can be found in *Appendix A: Preliminary Configurations Developed*.

## 4.2 SPECIFICATION FOR HYDRODYNAMICS

The specification for hydrodynamics involves assessment of the fundamental operational nature of the Preliminary Configurations. In particular this work stream is concerned with the identification of what particular hydrodynamic processes exist, and how a potential LiftWEC system might seek to exploit those processes. As a result of the *LiftWEC Problem Scope*[3] which sets the boundaries for investigation, Potential Configurations should seek to exploit lift forces through the rotation of one or more hydrofoils spinning about an axis aligned orthogonal to the primary direction of wave propagation.

Across the 17 configurations developed, it was found that only two distinct *modes of operation* were suggested; (1) phase-locked and (2) phase-free[4] operation.

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[3] See document *LW-WP02-MF-N11-1x1 TRIZ LiftWEC problem scope.*

[4] Also termed *phase-independent* operation.

*Phase-locking* is the requirement for the hydrofoil to rotate at the same frequency as the incident waves such that the hydrofoil maintains a continuous, consistent angle between its own tangential velocity and the instantaneous direction of the wave-induced fluid velocity. If the hydrofoil does rotate at the same frequency as the incident waves with constant phase angle, then changes in water velocity relative to the hydrofoil are only associated with changes in wave amplitude. Within the wave energy industry, it is typically assumed that systems benefit from being phase-locked as a result of the far-field hydrodynamic approach taken to the estimation of power capture. Consequently, the vast majority of traditional Wave Energy Converters are at least weakly phase locked. Note that for a rotating hydrofoil, phase-locked operation necessitates that the direction of rotation is consistent with the wave-induced fluid particle motions. For a more complete description of phase locking including a discussion on the hydrodynamic implications, the reader is directed to the previous LiftWEC deliverable; D2.1 Preliminary Report on Synthesis of Design Knowledge (filename: *LW-D02-01-2x0 Preliminary Report on Synthesis of Design Knowledge*).

An alternative to phase-locked operation exists in the form of phase-free, or phase-independent, operation. Phase-free operation eliminates the coupling between orbital particle motions of the fluid and hydrofoil rotation. Rather, the optimal angle of attack for a series of hydrofoils operating throughout the phase space is achieved using continuous pitch control. This eliminates any requirement of the controller to match the rotor speed to that of orbital particle velocities at the operational radius. To achieve this, the motion of the hydrofoils needs to be similar to that for a Voith-Schneider propeller, where the hydrofoils change their pitch angle dependent on their angular position. One potential benefit of this approach is that the rotor speed may not need to be controlled on a wave-by-wave basis in irregular seas if the ideal pitch angle for each blade can be predicted and applied. In addition, it may be that much greater rotational velocities can be achieved than if the system were restricted to matching the rotational frequency of the waves.

Another fundamental hydrodynamic consideration identified involves specification of the rigidity of the axis about which the hydrofoils rotate. In essence, this might represent the difference between the use of a rigid mooring/support structure arrangement versus a slack-moored platform. In a rigid arrangement, there will be no tendency/potential for the hydrofoil’s axis of rotation to move either due to wave action or otherwise. Alternatively, where a slack-moored system (or other movable support/mooring arrangement) is employed there will be the opportunity for relative motion of the axis of rotation.

In terms of the influence on potential for hydrodynamic power capture, only two critical variables were noted; (1) extraction via a hub-based generator and (2) extraction via a hydrofoil-mounted turbine. Various possible implementations of each of these approaches was suggested, but from a hydrodynamic perspective all can be filtered down into one of the previously mentioned descriptors.

Consequently, the hydrodynamic specification therefore recommends consideration of:

1. Phase-locked and phase-free operation.
2. Fixed and moving hydrofoil rotational axis.
3. Hub-based generator and hydrofoil-mounted turbine.

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## 4.3 SPECIFICATION FOR CONTROL STRATEGY

A large range of control strategies have been proposed in the different configurations; however, in all cases the strategy was based on controlling one or more of six control variables. These control variables are:

- Pitch
- Radius of action
- Moment of inertia
- Generator speed (either hub-based or hydrofoil-mounted)
- Generator torque (either hub-based or hydrofoil-mounted)
- Depth of submergence

The rate at which the control variable could be modified was also part of the specifications, with the pitch, radius of action, moment of inertia, generator reactive energy and generator torque all being controlled on a wave-by-wave basis in various combinations in the configurations, and pitch, radius of action, moment of inertia and submergence being controlled on a sea-state basis.
The potential impact on the energy production as well as the structural loads needs to be investigated to assess the effect of the control specification on the performance of the different configurations.

## 4.4 SPECIFICATION FOR STRUCTURAL DESIGN

In general, there was only a limited amount of information provided on the structural design for the different configurations. This suggests that in many cases the standard structural solutions are expected and appropriate. It is possible to separate the different structural designs for the proposed configurations into three fundamental areas:

- Hydrofoil structure
- Hub/spoke structure
- Support structure

Within the design of the hydrofoil, solutions involved the use of different materials and variations on the shape of the hydrofoil, including the hydrofoil profile, the use of “winglets” and surface details such as “tubercles”. Options with the hub/spoke structural design included a single central hydrofoil support and hydrofoil supports at each end. In addition, the configurations included supports that were made up of spokes to each hydrofoil, or a solid disk.

The type of support structure depended on the reaction source of the configuration with the use of monopiles, space-frames or taut-moored buoyant structures for configurations that reacted against the seabed. It is likely, that the choice of the support structure when reacting against the seabed will be highly dependent on the water depth, which may be the key factor on the choice of the support structure. Whilst minimal details were provided for the configurations that reacted against inertia, it may be presumed that this would be a fairly conventional structure.

## 4.5 SPECIFICATION FOR OPERATIONS AND MAINTENANCE

Three general approaches to operation and maintenance are specified within the Preliminary Configurations. The general characteristics of these three approaches are:

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- Take the device back to port/sheltered location for maintenance operations
- Bring the device to the surface for maintenance operations at site
- Use divers or Remotely Operated Vehicles (ROVs) to perform some maintenance operations under water

It is possible that a combination of these general approaches can be used by some configurations, with only some options being available for other configurations.

A novel approach to operations and maintenance was proposed by Configuration 16, which proposed using a Chevron to produce a calmer area for access during maintenance (Idea number 36). However, it is possible that other configurations may be modifiable so that they can exploit this idea. For this reason, this specification deserves further investigation and analysis.

## 4.6 SPECIFICATION FOR COST OF ENERGY

In many cases the specification of the cost of energy is dependent on the specifications for the other facets of the design. That is, the energy production and costs will depend on the specifications of the configuration as defined by the other facets in design, i.e. the structure design. Thus, the specification of the cost of energy needs to be strongly coupled to these facets and in particular work with these specifications to determine parametric representations of their impact on energy production and costs. The production of parametric representations linked to the configuration specifications is particularly important because this allows for the design space to be more effectively explored within each configuration, including the sensitivity of the cost of energy to particular parameters and how different configurations may favour different combinations of critical parameters such as the device width.

## 4.7 SPECIFICATION FOR SOCIAL AND ENVIRONMENTAL IMPACT

In the process of generating the Preliminary Configurations the identification of how the different configurations may have different social or environmental impacts was not strongly identified. This suggests that the social and environmental impact may be similar for all of the Preliminary Configurations. Notwithstanding this observation, it would seem that the specification of a generator in the hub or the use of a turbine mounted on the hydrofoil may have different impacts on the environment, due to their potential harm to marine fauna both from blade impact and from noise generation. Whether the device is floating or rigidly attached to the seabed will also be a specification that has an effect on the social and environmental impact. The main impacts from both types will be the physical/physical-chemical impact to the seabed and water column and to marine organisms through different means. For example, changes in the seabed configuration and release of contaminants trapped in sediment layers may occur from drilling/pilling activities and from moorings and cables sweeping the seabed. This will not only affect seabed organisms but also those in the water column, as a consequence of increased turbidity and decreased light penetration and potential resuspension of the contaminants. Also, the noise generated during those activities will have particular impact on marine mammals in the area and potentially kilometres away from it. While not fully considered during this phase of Preliminary Configurations development, the possibility of LiftWEC to function in arrays may have socioeconomic effects in the sense that a larger area at sea occupied by a wave energy farm will reduce fishery potential of that area, with consequent negative impact on local communities that use fishing as primary income.

## 4.8 SPECIFICATION FOR PHYSICAL MODELLING

At this stage, it was felt that explicit replication of one or more particular preliminary configurations in the physical modelling test campaign would not be the best use of resources. Rather it was determined that the 2-dimensional physical models would be better suited to be designed such that they could best inform on what are thought to be some of the most critical design decisions at this stage. It is particularly fortunate that two physical models are to be produced for the 2-dimensional testing as this permits investigation of both the *phase-locked* and *phase-free* modes of operation (see Section 4.2), each of which received approximately equal interest across the 17 configurations developed.

It is therefore proposed that, as planned, two distinct physical models are produced for the two-dimensional test campaign. The models may be summarised as follows:

1. Model A: 2-Hydrofoil rotor with phase-locked operation
2. Model B: 4-Hydrofoil rotor with phase-free operation

It would be ideal if both models could permit real-time blade pitch and radius of action control/variation. If real-time radius control is unachievable, both models should allow manual variation of the fixed operational radius of action. If real-time blade pitch control/variation is unachievable both models should allow manual variation of the fixed operational blade pitch.

Operation in both regular and irregular wave climates could be assessed. It is expected that feed-in from numerical and control simulations would significantly assist with the design of the physical models as well as development and execution of the physical test campaign.

## 4.9 SPECIFICATION FOR NUMERICAL MODELLING

As with the physical modelling, it is thought that rather than explicitly modelling one or more given LiftWEC configurations, a better use of time would be to investigate the influence of a number of the commonalities extracted from the variety of preliminary LiftWEC configurations. In particular it is thought that modelling of both phase-locked and phase-free hydrofoil systems with a view to improving understanding of their operational nature and their potential extraction of ocean wave energy would significantly assist with building a better understanding of the potential design space. Indeed at least the phase-free option of hydrofoil extraction of ocean wave energy appears to be devoid of scientific literature. It is therefore suggested that the numerical modelling is tied closely to the physical modelling and effort is spread across development of methods capable of estimating the performance of both phase-locked and phase-free systems. As with the physical testing, it would be ideal if numerical simulations could permit real-time blade pitch and radius of action control/variation. Where possible, simulations should seek to assess the performance of these systems in both regular and irregular seas with a suitable number of waves considered to ensure control strategies are suitably tested. It is envisioned that the aforementioned investigations could significantly inform future development of the LiftWEC concept even without explicit consideration of any given support structure.

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Beyond this, considering the influence of near structures, both physical and hydrodynamic, on the operation of rotating hydrofoil systems would allow for a greater understanding of the permissible support structures and power take off arrangements that best suit this type of device. In particular, consideration of central shafts, end struts, central struts, side-hubs/nacelles, monopile systems and free-surface interactions would cover the majority of the design space options outlined in the 17 preliminary configurations developed. The influence of a hydrofoil-mounted turbine on hydrofoil performance, both in terms of the turbine's physical structure and the induced hydrodynamic interference with the performance of the subject hydrofoil, and indeed any lee-foil, remains unknown. Furthermore, the influence of the wake effect of a forward hydrofoil on a lee-foil's performance remains an interesting point of investigation.

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# APPENDIX A: PRELIMINARY CONFIGURATIONS DEVELOPED

This appendix gives an overview of the various configurations generated during the LiftWEC Project Workshop held from 25th – 27th May 2020.

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## Jack-Up CycWEC

| | | | |
|---|---|---|---|
| **Title:** | Jack-up CycWEC | | |
| **Champion:** | | **Entry ID:** | 2 |

**Ideas Employed:**

- Hydrofoil pitch control
- Phase-locked rotation
- Control of the submerged depth
- Requirements for waves and lift force forecasting
- Collapsable system for transportation
- Uniform Radius Hydrofoil (along span)
- Use generator torque control to act as modifying inertia
- Fixed Rotational Axis
- Jack-up Strut Supports
- Use of 2 opposing hydrofoils

**Description:**

This is the CycWEC configuration as described by Siegel [2019]. The most recent iteration of the CycWEC design and comprises two hydrofoils attached to a central shaft in order to extract ocean wave energy and convert it to rotational shaft energy. This rotational energy of the shaft is subsequently converted to electricity by means of an electrical generator. In operation both hydrofoils are set a fixed radius from the central shaft and are intended to remain fully submerged beneath the free water surface at all times. Hydrofoil pitch control is employed to control the angle of attack experienced by the hydrofoil in an attempt to maximise hydrodynamic performance. In general terms, the CycWEC system can be assumed to consist of; (1) the rotor assembly, (2) the nacelles, (3) the jack-up struts and (4) the mooring system. In operation the entire rotor section is free to rotate about the rotational axis along which the central shaft is located. The two nacelles house the stator components of the direct-drive generators, the main shaft bearings as well as the power and control system electronics. Each nacelle is held in position by two telescoping jack-up struts which are length adjustable through the use of a series of rack-and-pinion gear systems. The struts are attached to four mooring points installed on the ocean floor. In addition, the struts are hinged at the supported nacelle such that they can be folded parallel to the main shaft for transportation and installation. This folding is achieved through the use of winches mounted on the opposing nacelle. Cables connecting the struts to the opposing side winches provide stability along the main shaft direction during deployment and operation.

**Hydrofoil Design:**

A curved hydrofoil with the curvature equal to the radius of rotation

**Number/Layout of Hydrofoils:**

Two hydrofoils separated by 180 degrees

**Fundamental Reaction Source:**

Seabed through telescopic legs

**Hydrofoil Reaction Source:**

Seabed through telescopic legs

**Method of Lift Force Control:**

Pitch control on the hydrofoils

**Method of Phase control:**

Reactive control through the motor/generator

**Electrical Generator:**

Permanent magnet generator

**Structural Details:**

None given.

**Installation/O&M techniques:**

Collapsible for easy towing and assembly in port

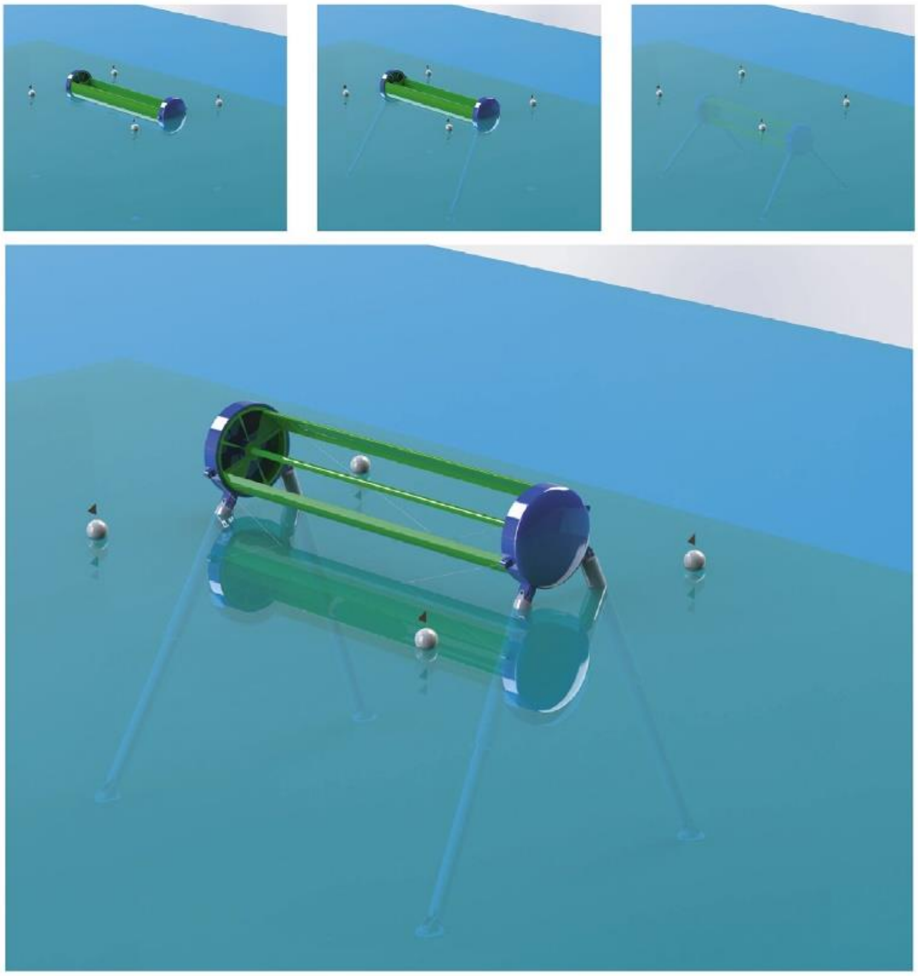

*Figure 49: 3D CAD Model of "Jack-Up CycWEC" taken from Siegel, 2019 [1]*

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## LIFTWEC PROPOSAL CONFIGURATION

| | | | |
|---|---|---|---|
| **Title:** | LiftWEC proposal configuration | | |
| **Champion:** | | **Entry ID:** | 4 |

**Ideas Employed:**

- Hydrofoil pitch control
- Phase-locked rotation
- Control of the submerged depth
- Requirements for waves and lift force forecasting
- Collapsible system for transportation
- Uniform Radius Hydrofoil (along span)
- Use generator torque control to act as modifying inertia
- Fixed Rotational Axis
- Jack-up Strut Supports
- Use of 2 opposing hydrofoils

**Description:**
This is the configuration alluded to in the LiftWEC proposal. The key focus of the configuration is to achieve the correct angle of attack by using a changing radius and the correct phase by controlling the angular frequency through conservation of momentum. A reaction to the seabed is used because this is considered to be the simplest and there is no need to use a more complex reaction source and the extreme loads can be avoided by stopping the hydrofoils from spinning (similar to the survival strategies of wind turbines).

**Hydrofoil Design:**
A curved hydrofoil with the curvature equal to the radius of rotation

**Number/Layout of Hydrofoils:**
Two hydrofoils separated by 180 degrees

**Fundamental Reaction Source:**
Seabed

**Hydrofoil Reaction Source:**
Seabed

**Method of Lift Force Control:**
Variation in radius of action of the hydrofoil

**Method of Phase control:**
Variation in moment of inertia to vary angular velocity from conservation of angular momentum

**Electrical Generator:**
Non-specific

**Structural Details:**
None given

**Installation/O&M techniques:**
None given

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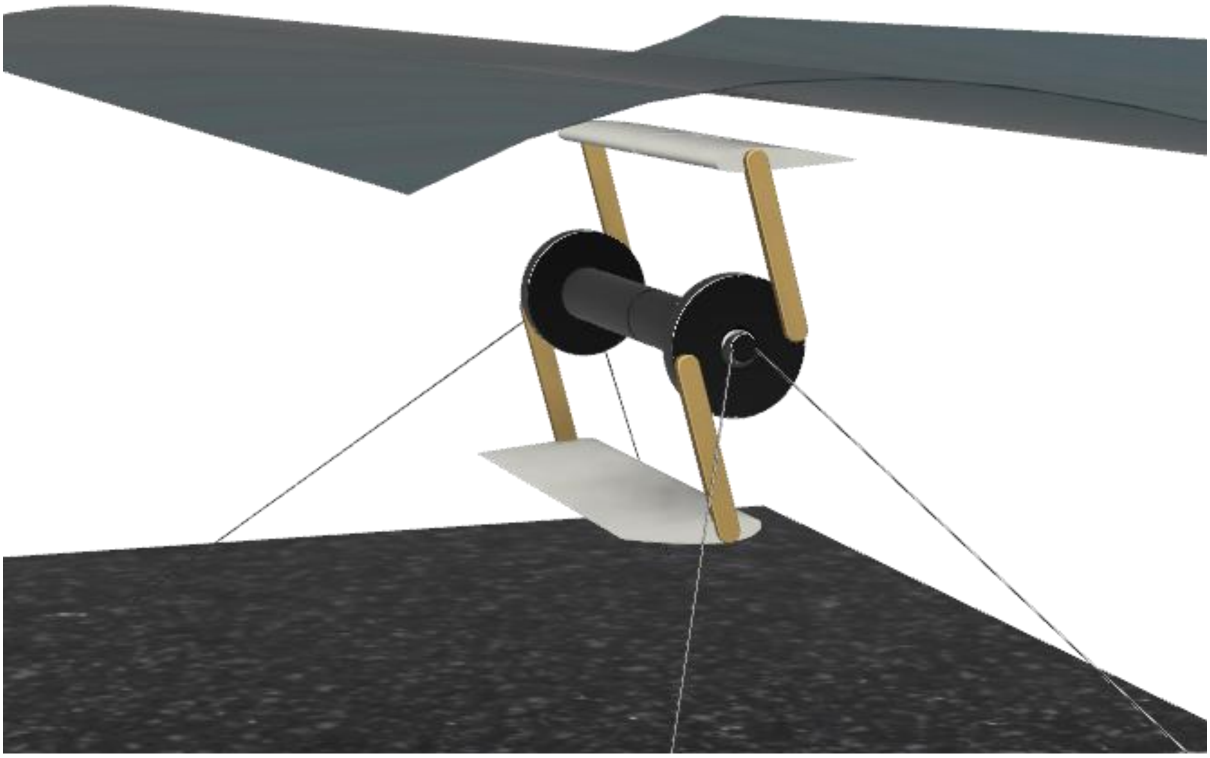

*Figure 50: 3D CAD Image of "LiftWEC Proposal Configuration"*

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## HYDROFOIL MOUNTED TURBINE PTO

| | | | |
|---|---|---|---|
| **Title:** | Hydrofoil mounted Turbine PTO | | |
| **Champion:** | | **Entry ID:** | 5 |

**Ideas Employed:**

- Hydrofoil radius control
- Phase-locked rotation
- Fixed Rotational Axis
- Keep angle of attack at optimal value
- Minesto-Type PTO
- High-Speed Fly Wheels
- Use of 2 opposing hydrofoils
- Hydrofoil Radius of rotation variation to tune to wave height and period and maintain optimal angle of incidence

**Description:**

Two symmetrical hydrofoils rotating about a shaft connected to the seabed via a triangular structure and micro piles. Power take off via a propeller mounted above hydrofoil (so that the velocity can be increased). Driving the main hydrofoils continuously via water jets/propellers so that the system is constantly rotated i.e. maintaining momentum. Characterised by very low drag. Mass to maintain momentum (inertia)

**Hydrofoil Design:**

NACA 00 hydrofoil

**Number/Layout of Hydrofoils:**

Two

**Fundamental Reaction Source:**

Seabed

**Hydrofoil Reaction Source:**

Radial struts

**Method of Lift Force Control:**

Angular velocity control

**Method of Phase control:**

Thrusters to maintain angular velocity

**Electrical Generator:**

not specified

**Structural Details:**

not specified

**Installation/O&M techniques:**

Micro piles to seabed

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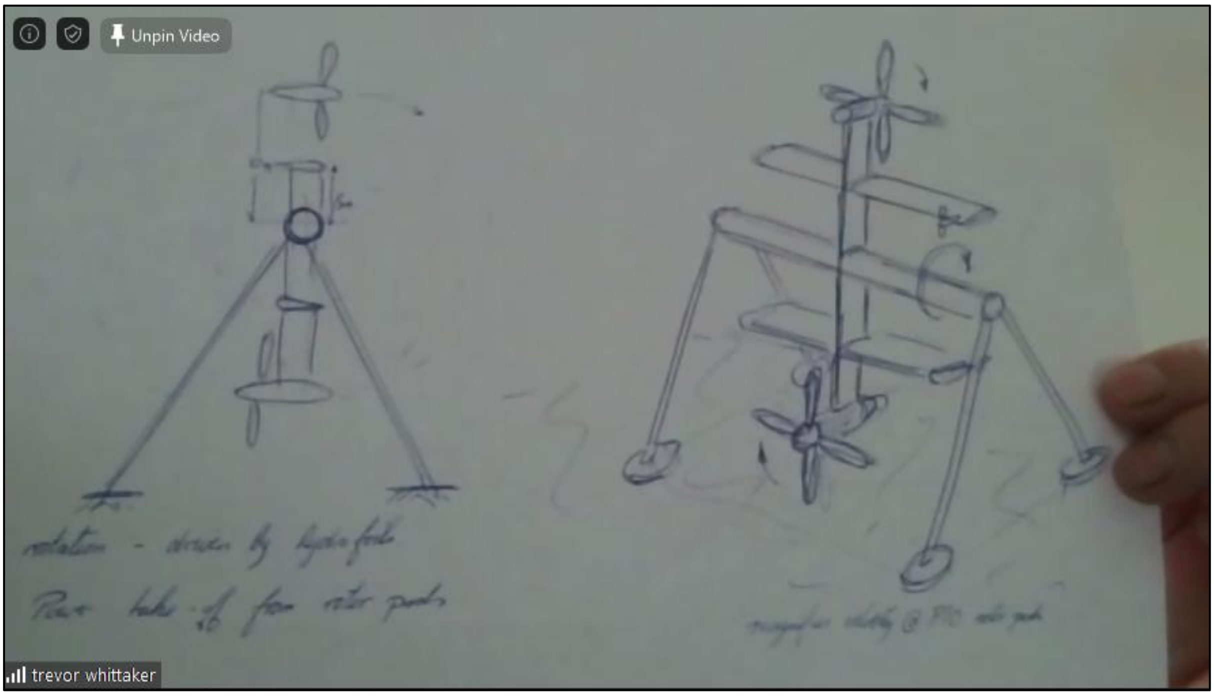

*Figure 51: Hand Sketch of "Hydrofoil mounted Turbine PTO"*

## Adaptable - Reconfigurable WECs

| | | | |
|---|---|---|---|
| **Title:** | **Adaptable - Reconfigurable WECs** | | |
| **Champion:** | | **Entry ID:** | 6 |

**Ideas Employed:**

- Hydrofoil radius control
- Hydrofoil pitch control
- Phase independent rotor
- Control of the submerged depth
- Requirements for waves and lift force forecasting
- Use inertia modification to harvest energy
- Fixed Rotational Axis
- Telescopic cantilever to connect rotational centre and hydrofoil
- Use of 2 opposing hydrofoils
- Shaft-Based Generator
- Variable WEC submergence

**Description:**

Most WECs are designed to work on one or a limited range of wave velocities and frequencies with maximum efficiency, however reconfigurable abilities of cyclorotor can significantly expand the range of effectively operated inputs. This reconfigurable WECs allow adaptation of the hydrodynamic gain. One benefit of adapting the hydrodynamic gain is to modulate the wave load on the device, in particular under high-power or extreme waves. Another benefit is that the level of the wave power captured by the device can be tuned. This LiftWEC is based on the ocean bottom. The LiftWEC should have 2-3 optimal working configurations to response to the different weather conditions. These configurations are determined by submerged depth and active radius. The device should be destined to have 2-3 working forms and work stable in them. Depth and acting radius are slow control inputs and pitching and PTO torque control are fast active.

**Hydrofoil Design:**

Not specified

**Number/Layout of Hydrofoils:**

Two

**Fundamental Reaction Source:**

Seabed

**Hydrofoil Reaction Source:**

Support structure

**Method of Lift Force Control:**

Two active: Pitching & PTO Torque; Slow control: submerged depth and radius

**Method of Phase control:**

not specified

**Electrical Generator:**

not specified

**Structural Details:**

not specified

**Installation/O&M techniques:**

not specified

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## TWIN-MOORED BUOYANT STRUCTURE WITH MINESTO PTO

| | | | |
|---|---|---|---|
| **Title:** | Twin-moored buoyant structure with Minesto PTO | | |
| **Champion:** | | **Entry ID:** | 7 |

**Ideas Employed:**

- Hydrofoil radius control
- Hydrofoil pitch control
- Phase independent rotor
- Aluminium hydrofoil
- Vaning system for orientation
- Synthetic lines for mooring
- Passive survival mode
- Single point V shape mooring and loading transmission system
- Minesto-Type PTO
- High-Speed Fly Wheels
- Passive radial motion
- Induction based energy transmission
- Hydrofoil Manufacturing Ideas
- Generator Mounted in Nacelle(s)

**Description:**

*Foil:* Radius control and pitch control through circular end plates covering the whole orbital path similar to Atargis concept. The foil is made from aluminium. No phase lock is used, the number of foils may be 2 or higher.

*Hub*: The foils are supported on radial guide rods/rails with a spring force pulling them inwards. Increase in radius has to be actively controlled.

A central shaft is used to connect the two end plates and extends through the end plates

*PTO:* A Minesto-type turbine is used which is either attached to the pressure side of the foils or the outer side of the end plates. The energy transmission to the central shaft is realized via induction and not slip rings.

*Mooring*: Two single-point moorings are used at front and rear. A V-Shape mooring is used in front and a Y-shaped mooring with spring compliance at rear to render the system weather-vaning around front mooring point.

**Hydrofoil Design:**

not specified

**Number/Layout of Hydrofoils:**

2-4

**Fundamental Reaction Source:**

not specified

**Hydrofoil Reaction Source:**

Mooring to seabed

**Method of Lift Force Control:**

Radius control, pitch control

**Method of Phase control:**

None

**Electrical Generator:**

Minesto-type turbine on foils or end plates

**Structural Details:**

End plates bear foils

**Installation/O&M techniques:**

not specified

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## SPAR BUOY WITH PHASE-FREE ROTOR

| | | | |
|---|---|---|---|
| **Title:** | Spar buoy with phase free rotor | | |
| **Champion:** | | **Entry ID:** | 8 |

**Ideas Employed:**

- Hydrofoil pitch control
- Phase independent rotor
- Control of the submerged depth
- Uniform Radius Hydrofoil (along span)
- Eccentric mass to counteract torque
- Keep angle of attack at optimal value
- Slack Moored system

**Description:**

This is a slack moored platform of type spar. The reaction torque is provided by a ballast at the bottom of the spar. The rotor is phase independent with pitch controlled foils. Multiple foils can be used (>3). This type of rotor can be of a smaller radius than phase locked ones, therefore the foils will be supported by a disc instead of spokes. This will also house the pitching mechanism of the foils. The spar could support 2 rotors. The rotors submergence could also be controlled by raising or lowering them along the axes of the spar. The device will be towed in a horizontal position, and water ballasted on-site to be vertical. In operation the spar angle will vary as a function of the rotor torque inputs. This can be seen as a form of energy storage before the generator as it will smooth peaks of power. The yaw stability of such device might be an issue as the rotor will want to be aligned with the waves, not perpendicular. The mooring system should provide it. This can be achieve by a central mooring point upwave from the device, the device can then weather vane with the waves. Some form of the horizontal beam would be required to provided the yaw stability. Considering the O&M, single point mooring in the front should be used to connect together mooring and dynamic cable for easy connexion/disconnection. The single point mooring is also used to provide array grid support when one device is disconnected. O&M will be conducted onsite (observations, possibly rising the rotors), in protected areas still vertical (small maintenance action), or in a harbour after towing in a horizontal position.

**Hydrofoil Design:**

Not Specified

**Number/Layout of Hydrofoils:**

3 or more. That decision should be the results of later optimisation.

**Fundamental Reaction Source:**

inertia

**Hydrofoil Reaction Source:**

rotor linked to generator

**Method of Lift Force Control:**

pitch control of the foils

**Method of Phase control:**

this is a phase independant rotor. All the foils should see the same flow field at each instant.

**Electrical Generator:**

Nothing special, the generators are mounted on the nacelle which can be up and down the spar.

**Structural Details:**

none yet

**Installation/O&M techniques:**

horizontal towing, single point mooring and electrical connection/disconnection

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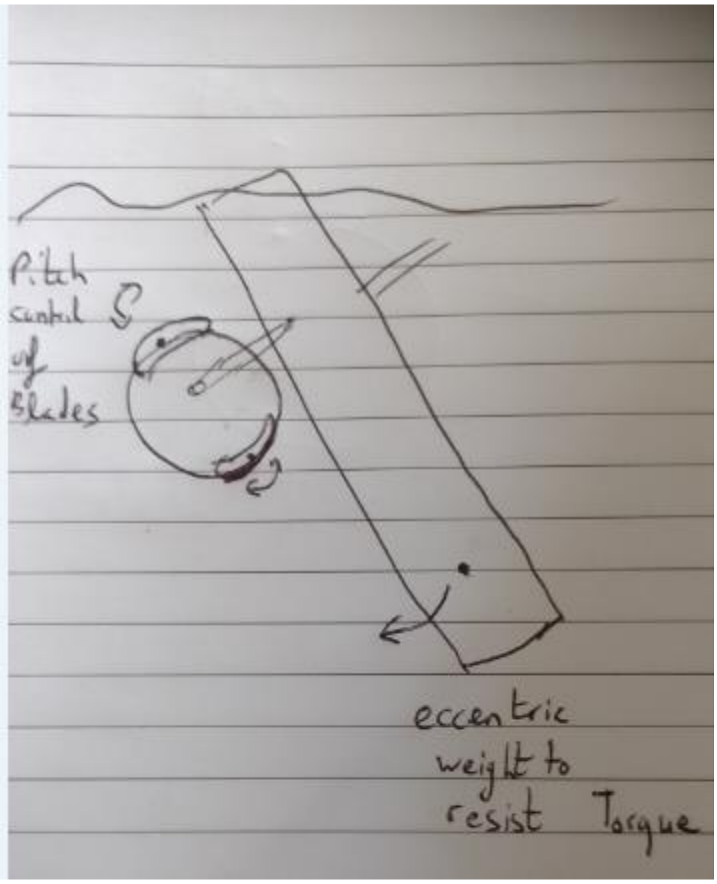

*Figure 52: Hand Sketch of "Spar buoy with phase free rotor"*

## PARABOLIC WITH FLAPS AND STIFF SINGLE-POINT V-MOORING

| | | | |
|---|---|---|---|
| **Title:** | Parabolic with flaps and stiff single-point V-mooring | | |
| **Champion:** | | **Entry ID:** | 9 |

**Ideas Employed:**

- Hydrofoil pitch control
- Phase independent rotor
- Parabolic Hydrofoil
- Vaning system for orientation
- Single point V shape mooring and loading transmission system
- High-Speed Fly Wheels
- Flow attaching devices
- Shaft-Based Generator

**Description:**
*Foil:* Two parabolic hydrofoils with span-wise sections for flap-type pitch control are attached to a central shaft.
*PTO*: Shaft generator
*Mooring*: A stiff frame consisting of two tubes an adjustable reaction shoe are connected to the sea bed in a single spherical joint. In non-operating condition, the shoe is laying on the sea bed and has to be actively raised for operation.

**Hydrofoil Design:**

**Number/Layout of Hydrofoils:**

**Fundamental Reaction Source:**

**Hydrofoil Reaction Source:**

**Method of Lift Force Control:**

**Method of Phase control:**

**Electrical Generator:**

**Structural Details:**

**Installation/O&M techniques:**

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## PHASE-LOCKED CONTRA-ROTATING

| | | | |
|---|---|---|---|
| **Title:** | Phase-locked contra-rotating | | |
| **Champion:** | | **Entry ID:** | 10 |

**Ideas Employed:**

- Phase-locked rotation
- Contra-Rotating LiftWEC
- Passive radial motion
- Taking learning from tidal energy in terms of fixed platform design

**Description:**

The system is phased lock and consists of 2 contrarotating rotors. This provides reference for the poorer generation and doubles the rotational speed of the rotors. The drawback is that one of the rotor will rotate against the wave direction which is not as good from a structural standpoint. Moreover, the two rotors probably needs to be of slightly different dimensions so that the load on each of them is similar despite the fact that the work differently (different direction of rotation). Control and survivability rely on being able to vary the radius of the rotor to adjust angle of attack of the foils. The foundation of the system is fixed (i.e. not free-floating). The details of that foundation is not specified here as it is site-specific (piling, gravity…)

**Hydrofoil Design:**

Not specified: optimisation problem

**Number/Layout of Hydrofoils:**

2 per rotor

**Fundamental Reaction Source:**

seabed

**Hydrofoil Reaction Source:**

2 contra-rotating rotors

**Method of Lift Force Control:**

radius variation and/or pitch control

**Method of Phase control:**

radius variation

**Electrical Generator:**

Permanent magnet direct drive

**Structural Details:**

seabed mounted fixed structure (gravity or pile... to be decided)

**Installation/O&M techniques:**

Dumb foundation always at the bottom with automated winching system for recovering and installing rotor/generator assembly (no diver)

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Number 10 on LiftWEC.com/config-catalogue.

Does bot have to be fixed. Main idea is to increase the rotational speed.

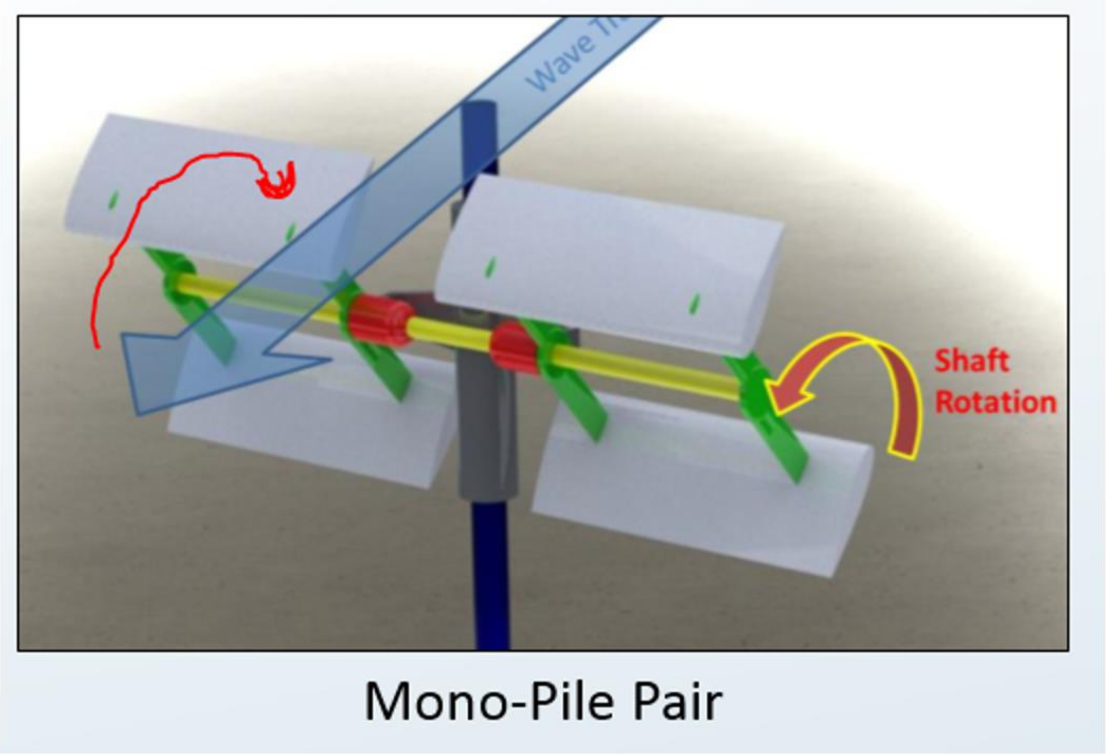

*Figure 53: Illustration of "Phase-locked contra-rotating" with base imaged taken from [2]*

## STRUTS BASED SINGLE ROTOR WITH SUBMERGENCE CONTROL

| | | | |
|---|---|---|---|
| **Title:** | Struts based single rotor with submergence control | | |
| **Champion:** | | **Entry ID:** | 11 |

**Ideas Employed:**

- Phase-locked rotation
- Control of the submerged depth
- Internal stiffness within the hydrofoil
- Collapsable system for transportation
- Uniform Radius Hydrofoil (along span)
- Fixed Rotational Axis
- Jack-up Strut Supports
- Use of 2 opposing hydrofoils
- Radial Generator (alternative to shaft-based generator)

**Description:**

A device where the complexity is concentrated on the support structure. A jack-up strut is used for a fixed sea bed connection.

That structure should be able to control the rotor submergence for exposure control and even provide a means to raise the device above the water for O&M.

A direct drive,  wet type of generator technology is used to reduce the mechanical design complexity. The foils can be directly connected to the generator rotor.

2 generators can be used at each end of the rotor, providing a symmetric design, some redundancy in the power train, and the possibility to have smaller generators with higher capacity factor

**Hydrofoil Design:**

phase locked type with 2 hydrofoils. Foils to be supported at each end

**Number/Layout of Hydrofoils:**

2

**Fundamental Reaction Source:**

seabed through jack-up strut structure

**Hydrofoil Reaction Source:**

directly against generator rotor

**Method of Lift Force Control:**

fixed pitch device / submergence is controlled with the strut to regulate exposure => provide survival strategy in extreme event.

**Method of Phase control:**

Fixed radius, controlled by rotor speed

**Electrical Generator:**

Direct drive generator, large diameter with generator rotor directly supporting the foils. Possibly of wet type technology such as Edinburgh University CGen. Possibly using 2 generators, one at exh rotor end =< symatric design, add redundancy, can be use to improve generator capacity factor

**Structural Details:**

generator structure is directly used as rotor support. Strut can regulate the rotor submergence.

**Installation/O&M techniques:**

device can be towed into position. Strut support structure is folded for towing operations. Device can be raised for Maintenance operation

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## TETHERED MONO-HYDROFOIL WITH WING MOUNTED TURBINE

| | | | |
|---|---|---|---|
| **Title:** | Tethered mono-hydrofoil with wing mounted turbine | | |
| **Champion:** | | **Entry ID:** | 12 |

**Ideas Employed:**

- Hydrofoil radius control
- Hydrofoil pitch control
- Phase-locked rotation
- Hub-less hydrofoil
- Maintenance of cable tension
- Control of the submerged depth
- Synthetic lines for mooring
- Secondary Generator Mounted on Hydrofoil
- Minesto-Type PTO

**Description:**

A single hydrofoil is tethered to the seabed at either end using cables that can vary in length using cable-winches or property of the cables. Tension in the cables is maintained by a small positive bouyancy of the hydrofoil and lift forces directed vertical upwards. The magnitude of the lift force is increased during the phase of the wave where the wave-induced velocities are positive upwards to extract energy from the waves. At other points in the wave cycle the lift forces are reduced to minimise losses. The lift can be modified by varying the shape of the hydrofoil either using a deformable hydrofoil or otherwise. Power is extracted from the motion of the hydrofoil using a turbine that is mounted on the hydrofoil using the reaction from the surrounding water. The submergence can be increased during storms to increase survivability

Although the power capture of this configuration is reduced due to the requirement to maintain tension in the cables, the structural requirements are also reduced. Moreover, the hydrofoil can be maintained by allowing it to move to the surface and installation involves the connection to two pre-installed cables. The cable-winches or cable property controller can be included in the hydrofoil so that there is minimal technology on the seabed.

**Hydrofoil Design:**

Bouyant hydrofoil with shape control to vary lift

**Number/Layout of Hydrofoils:**

One

**Fundamental Reaction Source:**

Seabed through tethers

**Hydrofoil Reaction Source:**

Surrounding water

**Method of Lift Force Control:**

Modification of the hydrofoil shape based on position and wave phase

**Method of Phase control:**

Not specified

**Electrical Generator:**

Linked to turbine mounted on hydrofoil

**Structural Details:**

Hollow structure for hydrofoil -probably a composite

**Installation/O&M techniques:**

Pre-install anchors, installation and O&M from surface

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## DIRECT HYDROFOIL ROTOR PTO

| | | | |
|---|---|---|---|
| **Title:** | Direct hydrofoil rotor PTO | | |
| **Champion:** | | **Entry ID:** | 13 |

**Ideas Employed:**

- not specified

**Description:**
Two symmetrical hydrofoils with propellers/thrusters (rotors) mounted directly to the hydrofoils. Minimal resultant torque reaction translated to the support structure: fixed or floating support solutions.

**Hydrofoil Design:**
NACA 00 hydrofoil

**Number/Layout of Hydrofoils:**
Two

**Fundamental Reaction Source:**
Seabed or floater

**Hydrofoil Reaction Source:**
Radial struts

**Method of Lift Force Control:**
Angular velocity control

**Method of Phase control:**
rotor to maintain angular velocity

**Electrical Generator:**
not specified

**Structural Details:**
not specified

**Installation/O&M techniques:**
not specified

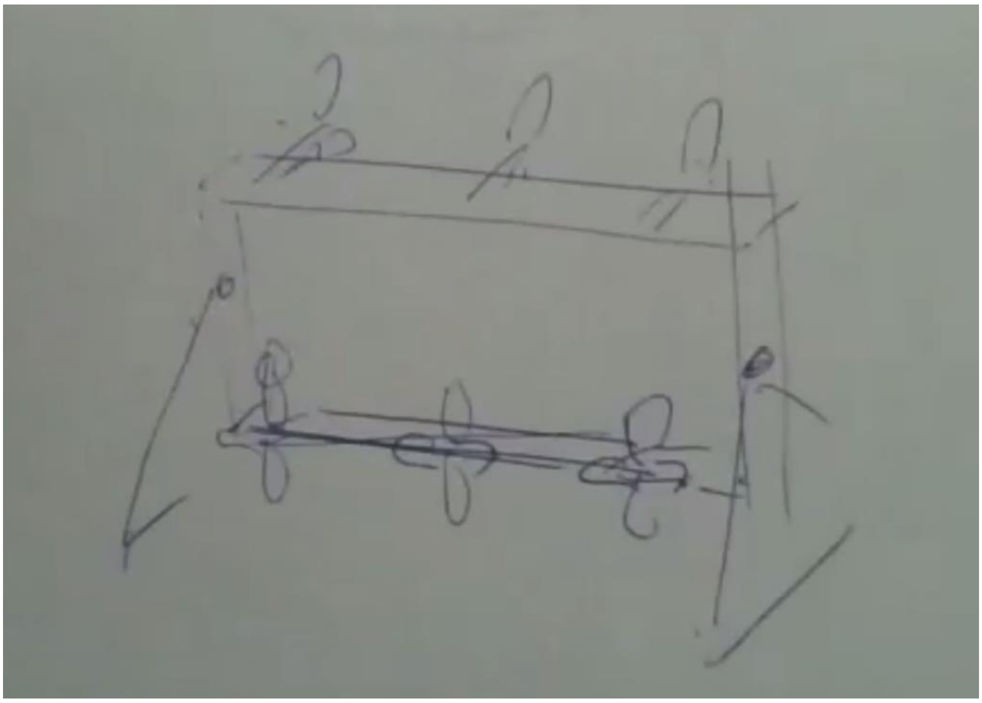

*Figure 54: hand Sketch of "Direct hydrofoil rotor PTO"*

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## Slack Moored LiftWEC Semi-sub with Multiple Rotors

| | | | |
|---|---|---|---|
| **Title:** | Slack moored LiftWEC semisub with multiple rotors | | |
| **Champion:** | | **Entry ID:** | 14 |

**Ideas Employed:**

- Control of the submerged depth
- Centrally supported hydrofoil
- Synthetic lines for mooring
- Use a central hub and eliminate the endplates
- and use winglets to limit drag
- Passive survival mode, Slack Moored system
- Central Hub and Spoke Structure
- Variable WEC submergence

**Description:**

Passive load shedding through optimized design for normal conditions, pour efficiency in storm conditions, and/or block/overload via generator.

T shaped horisontally placed support structure, vertiacl semisub towers at each end point of the T (3 in total). At bottom of each tower - one generator with a turbine to each side.

Ballasting of semisub for control of submersion depth, and support of installation and O&M operations.

**Hydrofoil Design:**

Central hubs, cantilever blades with winglets

**Number/Layout of Hydrofoils:**

2-5

**Fundamental Reaction Source:**

Slack moored through upwave single buoy, rear constraining mooring line to avoid 360 deg. rotation (allow +- 60 deg weather vaning)

**Hydrofoil Reaction Source:**

Floating semisub structure

**Method of Lift Force Control:**

Speed/torque control via generator

**Method of Phase control:**

Speed/torque control via generator

**Electrical Generator:**

Traditional generator and gear solution with individual AC-DC inv., common DC bus, and DC/AC inv. to grid, all placed dry inside semisub towers

**Structural Details:**

T shaped support structure connecting the semisub towers constructed as lattice girders placed above rotors.

**Installation/O&M techniques:**

Tow in place, quick connect. Easy access to generator equipment etc.

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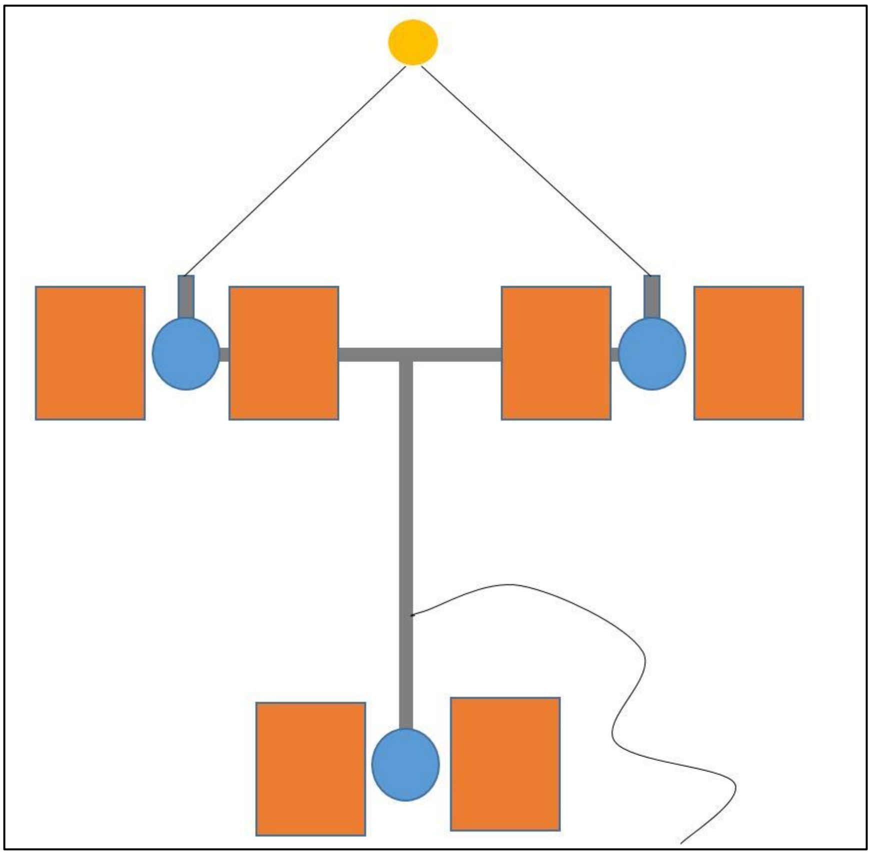

*Figure 55: Quick Sketch of " Slack moored LiftWEC semisub with multiple rotors "*

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## HYDRAULIC PTO ON MAIN ROTATIONAL SHAFT

| | | | |
|---|---|---|---|
| **Title:** | Hydraulic PTO on main rotational shaft | | |
| **Champion:** | | **Entry ID:** | 15 |
| **Ideas Employed:**<br>- not specified | | | |
| **Description:**<br>PTO on main shaft with hydraulic ring cam pumps etc., Can either be sea bed mounted or floater supported on swath hulls. Opportunity for alternative energy output e.g. desalination, chemical production (e.g. hydrogen). Inherent short-term energy store peripheral flywheels/ring cams negating need for active position adjustment. Could incorporate thrusters on the foils. | | | |
| **Hydrofoil Design:**<br>NACA 00 hydrofoil | | | |
| **Number/Layout of Hydrofoils:**<br>Two | | | |
| **Fundamental Reaction Source:**<br>Seabed or floater | | | |
| **Hydrofoil Reaction Source:** | | | |
| **Method of Lift Force Control:**<br>Angular velocity control | | | |
| **Method of Phase control:**<br>Thrusters to maintain angular velocity | | | |
| **Electrical Generator:**<br>Hydraulic PTO | | | |
| **Structural Details:**<br>not specified | | | |
| **Installation/O&M techniques:**<br>not specified | | | |

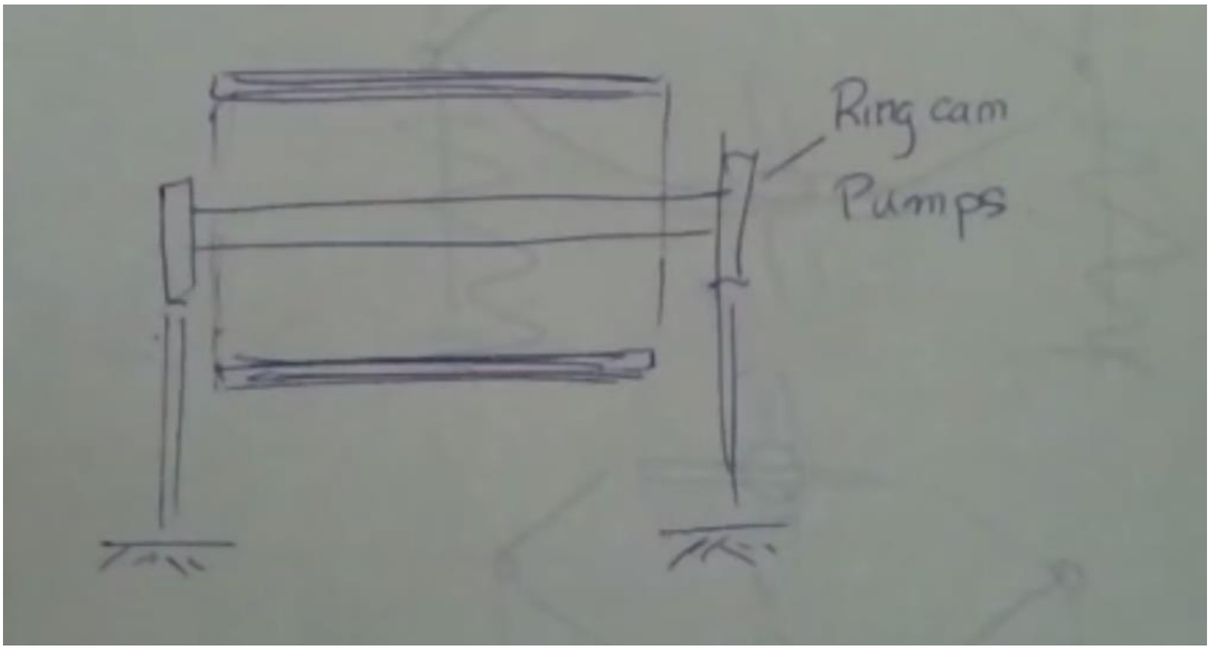

*Figure 56: Hand Sketch of "Hydraulic PTO on main rotational shaft"*

## HUBLESS WING WITH MOUNTED TURBINES

| | | | |
|---|---|---|---|
| **Title:** | Hubless wing with mounted turbines | | |
| **Champion:** | | **Entry ID:** | 16 |

**Ideas Employed:**

- Hydrofoil radius control
- Moment of inertia control
- Phase-locked rotation
- Hub-less hydrofoil
- Phase diversity as a reaction source
- Requirements for waves and lift force forecasting
- Aluminium hydrofoil
- Uniform Radius Hydrofoil (along span)
- Vaning system for orientation
- Use generator torque control to act as modifying inertia
- Fixed Rotational Axis
- Chevron configuration for ease of maintenance
- Use the inertia modifier as the primary PTO mechanism
- Secondary Generator Mounted on Hydrofoil
- (Whale inspired) tubercles on hydrofoils to reduce drag
- Minesto-Type PTO
- Use of 2 opposing hydrofoils
- Passive radial motion
- Wave-driven radial motion
- Hydrofoil Radius of rotation variation to tune to wave height and period and maintain optimal angle of incidence

**Description:**

Hubless design with several generator turbines mounted on the foils directly. This increases redundency/resiliency in case of single generator failure. To have less moving parts, pitch control is not used. The foils are connected by struts to a central axis and have winglet to increase efficiency. A prediction system for incoming waves is used to control the generator torque to be able to tune the system to the optimal inertia. (Optionally: The radial motion is allowed in order to harvest energy from the main direction of the lift forces (inwards and outwards, since the angle of attack in irregular seaways change sign are expected to change sign quite often) and is the primary source of energy. The system can be brought to a small diameter by passively using the lift forces move the foils inwards.)

**Hydrofoil Design:**

Low drag foils with moderate efficiency over a high range of angle of attacks, high stall angle, tubercles at leading edge

**Number/Layout of Hydrofoils:**

2

**Fundamental Reaction Source:**

Seabed

**Hydrofoil Reaction Source:**

Seabed

**Method of Lift Force Control:**

**Method of Phase control:**

Controlled by the PTO (inertia) and radial position of the blade to have the desired foil speed

**Electrical Generator:**

Several small turbines mounted on the blade

**Structural Details:**

| |
|---|
| |
| **Installation/O&M techniques:**<br>Install chevron first and lower foil body afterwards, possibly by using variable buoyency of the foils (sealed tanks) |

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## RADIUS CONTROL FOCUSED CONFIG

| | | | |
|---|---|---|---|
| **Title:** | Radius Control Focused Config | | |
| **Champion:** | | **Entry ID:** | 17 |

**Ideas Employed:**

- Hydrofoil radius control
- Moment of inertia control
- Hydrofoil pitch control
- Phase independent rotor
- Control of the submerged depth
- Fixed Rotational Axis
- Use the inertia modifier as the primary PTO mechanism
- Passive survival mode
- Passive & active hybrid radius control and momentum control
- Hydrofoil Manufacturing Ideas
- Shaft-Based Generator
- Low-energy radial actuator
- Wave-driven radial motion

**Description:**

This Radius Control Focused Config should enable the control of moment of inertia and the regulation of rotation speed by adjusting the foils rotation radius. This should lead to a constant rotation speed and the use of a phase independant generator. Moving the hydrofoil mass in the radial direction is part of the primary PTO mechanism.

The pitch control is here used to avoid overloading of the foils in extreme conditions.

In production condition, the pitch could be set to an average optimum angle of attacked which does not need to be updated at high frequency.

This configuration includes low energy radial actuator and wave driven radial actuator.

The support structure installed on the seabed.

**Hydrofoil Design:**

Hubs at hydrofoil ends

**Number/Layout of Hydrofoils:**

2 to 5

**Fundamental Reaction Source:**

Support structure installed on the seabed

**Hydrofoil Reaction Source:**

Support structure installed on the seabed

**Method of Lift Force Control:**

**Method of Phase control:**

Hydrofoils rotation radius control

**Electrical Generator:**

Standard generator

**Structural Details:**

**Installation/O&M techniques:**

## PLANETARY GEAR END PLATES

| | | | |
|---|---|---|---|
| **Title:** | Planetary Gear End Plates | | |
| **Champion:** | | **Entry ID:** | 18 |

**Ideas Employed:**

- Hydrofoil radius control
- Hydrofoil pitch control
- Aluminium hydrofoil
- Vaning system for orientation
- Synthetic lines for mooring
- Passive survival mode
- Single point V shape mooring and loading transmission system
- High-Speed Fly Wheels
- Flow attaching devices
- Hydrodynamic Reaction of Substructure

**Description:**

*Foil*: Two or more foils are attached to circular end plates covering the whole orbital path can be moved in radial direction with a passive force (Spring) pulling them inwards. Pitch control is enabled through end plates.

*Hub*: End plates

*PTO:* A planetary gear driving several smaller motors at higher velocity is build into the end plates

*Mooring:* Fixed mooring based on suction anchor and V-shaped tubes supporting/holding the end plates. System is buoyant.

**Hydrofoil Design:**

**Number/Layout of Hydrofoils:**

2-4

**Fundamental Reaction Source:**

Seabed

**Hydrofoil Reaction Source:**

**Method of Lift Force Control:**

Radius control, pitch control

**Method of Phase control:**

None

**Electrical Generator:**

Planetary Gear driving several smaller motors at high RPM

**Structural Details:**

**Installation/O&M techniques:**

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## SINGLE STRUT HYDROFOIL WITH MINESTO-TYPE TURBINE

| | | | |
|---|---|---|---|
| **Title:** | Single Strut Hydrofoil with Minesto-Type Turbine | | |
| **Champion:** | | **Entry ID:** | 19 |

**Ideas Employed:**

- Hydrofoil radius control
- Hydrofoil pitch control
- Phase independent rotor
- Brake and declutching systems
- Centrally supported hydrofoil
- Vaning system for orientation
- Synthetic lines for mooring
- Use a central hub and eliminate the endplates and use winglets to limit drag
- Passive survival mode
- Minesto-Type PTO
- High-Speed Fly Wheels
- Flow attaching devices
- Central Hub and Spoke Structure

**Description:**

*Foil*: A single central strut is used to support two hydrofoils. The foils can move in radial direction either fixed to a segment of a telescopic strut or along guide rails. Pitch can be adjusted through pitch actuator in strut.
*Hub*: A single strut connects the hydrofoils to a single central shaft which rotates with the hydrofoils
*PTO*: Minesto-type turbines are mounted either to the top of the central strut or below the hydrofoils.
*Mooring*: The central shaft is mounted in radial bearings which are held in place be a taut mooring system.

**Hydrofoil Design:**

**Number/Layout of Hydrofoils:**

**Fundamental Reaction Source:**

**Hydrofoil Reaction Source:**

**Method of Lift Force Control:**

**Method of Phase control:**

**Electrical Generator:**

**Structural Details:**

**Installation/O&M techniques:**

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# APPENDIX B: TRIZ HARMS AND INSUFFICIENCIES

*Table 5: TRIZ Insufficiencies Table*

| **I 1** | **Insufficiency: Add** |
|---|---|
| I 1.1 | Add something to/inside the subject or object |
| I 1.2 | Add something between the subject and the object that enhances/delivers the function |
| I 1.3 | Use the environment |
| I 1.4 | Add something into the environment/the surroundings of the subject and object |
| I 1.5 | Add something outside/around the subject or object |
| I 1.6 | Add something from the environment/surroundings to enhance the function |
| I 1.7 | Use/mobilise the environment/surroundings to enhance the subject and object |
| **I 2** | **Insufficiency: Change/evolve** |
| I 2.1 | Change/segment the subject or object – increase the degree of fragmentation |
| I 2.2 | Change the subject or object y introducing voids/fields/air/bubbles/foam |
| I 2.3 | Improve systems by multiplying similar (or dissimilar) system elements or combining with another similar (or dissimilar) systems |
| I 2.4 | Increase the efficiency of the system by making it more flexible/adaptable/dynamic |
| I 2.5 | Develop/improve the links between the system elements (links can be made more flexible or more rigid) |
| I 2.6 | System transition – increasing the differences between elements – up to opposites |
| I 2.7 | System improvement by delivering opposite incompatible functions at different system levels |
| I 2.8 | System improvement: transition function delivery to the micro-level |
| I 2.9 | Improve a system's effectiveness and controllability by developing one part of the system or one component to deliver its own extra functions |
| I 2.10 | Improve a system by changing the components/substances to deliver exactly what is needed in time and/or space |
| **I 3** | **Insufficiency: Enhance** |
| I 3.1 | Get an action – if a field is missing then add an appropriate action/field |
| I 3.2 | Add another action or extra field – if you cannot change the existing system elements |
| I 3.3 | Improve/evolve an action/field by finding a better one |
| I 3.4 | Improve the effectiveness of an action by changing from a uniform action/field (or uncontrolled field) to an action/field with predetermined patterns that may be permanent or temporary |
| I 3.5 | Improve the effectiveness of an action within a system by matching (or mismatching) the natural frequency of the actions (fields) with the natural frequency of the subject (tool) or the object it acts on |
| I 3.6 | Improve the effectiveness of the actions within a system by matching (or mismatching) the frequencies of the different actions/fields being used |
| I 3.7 | To achieve two incompatible actions – perform one action in the downtime of the other |
| I 3.8 | Use actions/fields present in the system to create another field |
| I 3.9 | Use actions/fields that are present in the environment (gravity, ambient temperature, pressure, sunlight) |
| I 3.10 | Achieve an extra action by using something already present in the system, or in the environment, as the source/provider of the extra fields/actions which can act as media or sources |

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| | |
|---|---|
| I 3.11 | Use excessive action |
| I 3.12 | Use a small amount of a very active additive |
| I 3.13 | Concentrate the additive at a specific location |
| I 3.14 | Introduce the additive temporarily |
| I 3.15 | Use a copy or model of the object in which the additives can be used, instead of the original object, if additives are not permitted in the original |
| I 3.16 | Improve an action/field by changing the phase of the existing field/substance |
| I 3.17 | Achieve an action by using the phenomena which accompany phase change |
| I 3.18 | Achieve an action with dual properties by using a substance capable of converting from one phase state to another |

*Table 6: TRIZ Harms Table*

| **H 1** | **Harms: Eliminate** |
|---|---|
| H 1.1 | For any component, do we need their useful action? |
| H 1.2 | Could the object perform the useful action? |
| H 1.3 | Could another component perform the useful action? |
| H 1.4 | Could a resource perform the useful action? |
| H 1.5 | Could we trim the subject after it has performed its useful action? |
| H 1.6 | Could we partially trim any harmful parts but leave the useful parts? |
| **H 2** | **Harms: Stop** |
| H 2.1 | Counteract the harmful action with an opposing field that neutralises the harm |
| H 2.2 | Change the object so that it is not sensitive to the harmful action |
| H 2.3 | Change the zone and/or duration of the armful action to decrease its effects |
| H 2.4.1 | Insulate from harmful action by introducing a new component/substance |
| H 2.4.2 | Insulate from harmful action by introducing a substance made from elements of the existing system |
| H 2.5 | Protect from harmful action with a sacrificial substance which attracts the harm to itself |
| H 2.6 | Protect from the harm of a necessary strong field by putting the full required force elsewhere |
| H 2.7 | Protect part of the system from harm |
| H 2.8 | Reduce harm by using a waker, minimum field/action and enhancing it locally where required |
| H 2.9 | Use the sub-systems to stop the harm |
| H 2.10 | Super-systems – use the environment to stop the harm |
| H 2.11 | Switch of harm – harms may exist because of certain properties in a system |
| **H 3** | **Harms: Transform** |
| H 3.1 | Use the harm to deal with the harm |
| H 3.2 | Use the harm for something good |
| H 3.3 | Add another harm so that the combination of the two harms is no longer harmful |
| H 3.4 | Amplify the harm until it delivers benefit |
| **H 4** | **Harms: Correct afterwards** |
| H 4.1 | After a harmful action eliminate any of the harmful consequences |
| H 4.2 | When there is an inevitable harmful effect of a harmful action, add an anti-action which controls/counteracts the harmful effect |
| H 4.3 | Anticipate and design to eliminate future harms – eliminate a predicted harm |

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# APPENDIX C: IDEAS CATALOGUE

| Entry ID | Idea title | Idea champion | Idea scope | 'Other' details | Idea description | Idea is possibly patentable | File Upload |
|---|---|---|---|---|---|---|---|
| 1 | Hydrofoil radius control | | Hydrodynamics, Hydrofoil, Control | | The amount of lift force generated by the hydrofoil depends, amongst other things the angle of attack. As the incident wave-induced velocity varies, the optimum angle of attack can be maintained by varying the radius about which the hydrofoil is rotating. This could be further enhanced by combining with pitch control | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N07-1x0-Hydrofoil-radius-control.docx |
| 2 | Moment of inertia control | | Hydrodynamics, Control | | In irregular waves it is necessary to varying the angular velocity of the hydrofoil to match the changes in wave frequency. This can be achieved by varying the rotor's moment of inertia so that the angular frequency changes as a result of  the conservation of angular momentum (this is how figure skates change their speed of rotation by moving their arms and legs in and out). Although work would need to be done when increasing the angular frequency (as this causes an increase in kinetic energy) this can subsequently be recovered. However, the change of kinetic energy is smaller than for directly changing the angular frequency and so may result in a more efficient method of changing angular frequency. | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N06-1x0-Moment-of-inertia-control.docx |
| 3 | Hydrofoil pitch control | | Hydrodynamics, Hydrofoil, Control | | The lift force generated by the hydrofoil can be changed by changing the angle of attack. The optimum angle of attack for the hydrofoil can be controlled using the pitch angle of the hydrofoil. This idea is proposed and used in the Atargis CycWEC to maximise power capture. | No | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N08-1x0-Hydrofoil-pitch-control.docx |
| 4 | Phase-locked rotation | | Hydrodynamics | | The wave-induced water particle motion is approximately circular, although the radius of the circle is continually varying due to the irregularity of the waves. The phase of the radiated waves generated by the hydrofoil can be maintained approximately by rotating the hydrofoil so that it remains in-phase with the incident waves. This should minimise the amount of energy radiated by the wave energy converter and thus allow the maximisation of power capture. | No | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N05-1x0-Phase-locked-lift.docx |
| 5 | Phase independent rotor | | Hydrodynamics | | Rotating at a constant angular velocity has a number of advantages when considering the power train. The amplitude and phase of the waves radiated by the hydrofoil can be controlled to be optimal even in this case with large variations in the pitch angle of the hydrofoil. This operation is similar to a Voith-Schneider Rotor that can generate thrust in any direction by appropriate control of the hydrfoil pitch angles. | No | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-GO-N01- |

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| Entry ID | Idea title | Idea champion | Idea scope | 'Other' details | Idea description | Idea is possibly patentable | File Upload |
|---|---|---|---|---|---|---|---|
| | | | | | | | 1x0_Phase_Independent_Rotor.docx |
| 6 | Hub-less hydrofoil | | Hydrodynamics, Power train | | At any moment a hydrfoil that is moving relative to the water can generate a lift force, where at any moment there is an optimal relative velocity and angle of attack of the hydrofoil, where the hydrofoil follows a path around a virtual axis. Without a hub it is possible that the hydrofoil can move on this optimum path, but without a hub this energy cannot be extracted from rotation about this virtual axis. However, because the hydrofoil is moving faster than the surrounding water it may be possible to use the surrounding water as a reaction source for the extraction of energy. This approach is used in the kite-type tidal energy converter developed by Minnesto. | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/LW-WP02-MF-N09-1x1-Hub-less-hydrofoil.docx |
| 7 | Maintenance of cable tension | | Control, Load transmission | | Cables are typically a significantly cheaper option that structures that can also withstand compressive loads. Bouyancy can be used to provide some tension in cables connected between the hydrfoil/WEC and the seabed, but this is likely to be insufficient in many cases during parts of the cycle where the lift force is directed towards the seabed. However, at some cost to efficiency it may be possible to control the lift forces so that lift (or other forces) towards the seabed are always less than the buoyancy forces maintaining the cable tension, thus ensuring that the cables are always kept in tension | Yes | |
| 8 | Phase diversity as a reaction source | | Reaction source | | Using the seabed as a reaction source can present challenges associated with high loads in extreme events, installation and the effect of tidal depth variations. However, two or more hydrofoils could be used to provide a mutual reaction source provided that they are sufficiently seperated in the direction of wave propagation so that the directions of the lift forces are out-of-phase. This approach has been proposed for many wave energy converters, including the Farley tri-plate and Pelamis. | No | |
| 9 | Inertia as a reaction source | | Reaction source | | Using the seabed as a reaction source can present challenges associated with high loads in extreme events, installation and the effect of tidal depth variations. However, a large inertia can also be used to provide a reation source, where the inertia may be either from a solid body or due to the added inertia of a submerged body. To avoid the body providing the inertia as a reaction source also being excited by the waves it is common to submerge the body to a depth where there is minimal wave action. This type of reaction source is used by Oscilla Powerâ€™s TDU2 and CPT's Stringray. | No | |
| 10 | Control of the submerged depth | | Whole system, Hydrodynamics, Control | | Changing the operational depth can help the cyclorotor to avoid extreme weather conditions and even continue energy production at a safe water depth.<br>If the cyclorotor can be relocated along the z-axis, it can be submerged into a region where the far-field incident velocity does not exceed the operational conditions. | Yes | |
| 11 | Circulation control | | Whole system, Hydrodynamics, Control | | Circulation control can dramatically increase lift coefficients in airfoils, although the Conda Effect has been recognised for decades, circulation control is still under research. It requires the installation of the additional Circulation control wing in front of cyclorotor. Controlling the circulation faces the same control challenges as pitching. | | |

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| Entry ID | Idea title | Idea champion | Idea scope | 'Other' details | Idea description | Idea is possibly patentable | File Upload |
|---|---|---|---|---|---|---|---|
| 12 | Brake and declutching systems | | Whole system, Control, Reaction source | | Some generators require constant rotation. This makes it impossible to implement discrete control strategy such as latching and declutching by manipulating of the PTO torque input.<br>However, these methods can be implemented by the inclusion of an additional brake system with the possibility of declutching the generator from the cyclorotor. | | |
| 13 | Morphing hydrofoils form | | Hydrodynamics, Hydrofoil, Control | | It is possible to consider the morphing hydrofoils made from composite structure.<br>Morphing could also be done via electro-active polymere spread over the foil. | | |
| 14 | Morphing cyclorotor form | | Whole system, Control, Load transmission, Reaction source | | The morphing Cyclorotor can be made by changing the angles between acting radiuses of hydrofoils. It also possible to shift the rotational centre. | | |
| 15 | Requirements for waves and lift force forecasting | | Whole system, Hydrodynamics, Control | | One of the biggest problem is to control cyclorotor in an irregular waves environment<br>Another common control problem for cyclorotors is to minimise the amount of reflected energy lost by waves radiated from WECs<br>To solve these problems the use of a horizontally aligned acoustic current doppler profiler or an array of wave-rider buoys to gain enough velocity data points from the incoming wave field should be considered.<br>The method of the LiftForce and circulation forecasting is needed | | |
| 16 | Centrally supported hydrofoil | | Hydrofoil | | Remove specific area of high stress. Continious structure similar to an aircraft wing box. | | |
| 17 | Aluminium hydrofoil | | Hydrofoil | | Use aluminium as material for the hydrofoil for good impact and abraision resistance properties. | | |
| 18 | Expendable system | | Whole system | | Modular system with cylindrical elements that could be attached to increase the capture width. Replace module for easy maintenance or repare. | | |
| 19 | Internal stiffness within the hydrofoil | | Hydrofoil | | Internal stiffener will add strength in addition to add the possibility to morph the hydrofoil surface. | Yes | |
| 20 | Ballastable Gravity Platform Foundation (for re-deployment & recovery) | | Reaction source, Marine operations, Installation | | The idea involves the use of a large submersible gravity platform which provides the 'foundation' and possibly support structure for LiftWEC. The idea would be that a large concrete or steel 'foundation block' can be used as a mobile foundation. If it could be constructed in a dry dock, then the entire WEC could be assembled on shore, floated like a barge and simply towed out to deployment location. You could then sink the platform to act as a large gravity foundation and refloat it to take the entire device away for maintenance or decommissioning. Naturally however this would require an appropriate bathymetry. There can be issues with sediment transport and theoretically the system could 'creep' or move over time. An example of this approach is the Waveroller concept by AW Energy. The call it the WaveBase - see picture. | | https://liftwec.com/wp-content/uploads/vfb/2020/05/waveroller-wavebase.jpg |

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| Entry ID | Idea title | Idea champion | Idea scope | 'Other' details | Idea description | Idea is possibly patentable | File Upload |
|---|---|---|---|---|---|---|---|
| 21 | Passive mechanical pitch control | | Control | | Use inertia to control the pitch of the hydrofoil. Mechnical system is likely to be more reliable than active electrical actuators. | | |
| 22 | Collapsable system for transportation | | Whole system | | Collapsable system for transportation and articulate when deployed. | | |
| 23 | Bottom supported hydrofoil in a floating configuration | | Whole system | | Bottom supported hydrofoil in a floating configuration | | |
| 24 | Top supported hydrofoil in a floating configuration | | Whole system | | Top supported hydrofoil in a floating configuration | | |
| 25 | Parabolic Hydrofoil | | Hydrofoil, Load transmission | | This idea could also be described as a hydrofoil with a spatially varied radius of action relative to the rotational axis. Instead of having the hydrofoil as a horizontal element which is parallel to the rotational axis, you could have a parabolic hydrofoil which runs like an arch from each bearing. This would eliminate the need for a separate strut or spoke support structure which attaches the hydrofoil to a central hub. This could simplify the structural design and shorten the load path. This would possibly require a hydrofoil with a varied cross section/profile along its length as you will get different relative velocity depending on the radius at a particular point along the span - similar to how a wind turbine blade cross section varies with length. It is possible a similar approach could be used to improve average performance across a wider range of sea states, however might decrease performance in any one given sea compared to a straight hydrofoil. A simple example is presented in the image. | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/Parabolic-Hydrofoil.jpg |
| 26 | Uniform Radius Hydrofoil (along span) | | Hydrofoil | | The idea would simply be that the hydrofoil would operate at a uniform radius across its entire length. That is - the radius of action at any given location along the hydrofoil is constant. This does not mean the radius is not variable in time (for control purposes), simply that any given part of the hydrofoil always acts at the same radius as all other parts at a snapshot in time. In the ideal operating environment of regular waves with perfect alignment (90 degrees head on) then you should be able to use a hydrofoil with a uniform profile as the relative velocity and angle of attack would be constant across the length of the hydrofoil. For example - all of the CycWEC systems use this approach. | No | |

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| Entry ID | Idea title | Idea champion | Idea scope | 'Other' details | Idea description | Idea is possibly patentable | File Upload |
|---|---|---|---|---|---|---|---|
| | | | | | The example on the front of the proposal used this approach, even though it theoretically had a variable radius for control purposes. | | |
| 27 | Vaning system for orientation | | Whole system, Control | | For compliance structure it is important to ensure the hydrofoil system is always correctly orientated to the wave direction. An idea would be to use a rotational platform to orient the hydrofoil. Using a radar system to forecast the direction of the wave. | Yes | |
| 28 | Use generator torque control to act as modifying inertia | | Hydrodynamics, Control | | Use generator torque control to act as modifying inertia - so achieving the same effect as changing inertia through torque control. | | |
| 29 | Synthetic lines for mooring | | Whole system | | Use synthetic lines for mooring solution in the case of a floating structure. Weight in transportation is advantageous, corrosion resistance. Has shown to reduce OPEX (less inspection required, fatigue strengh is better). | No | |
| 30 | Use of a 'free resources' to modify inertia | | Hydrodynamics, Control | | Use one or more of the following 'free resources' (no parasitic power) to realize the inertia modification:<br>- Springs<br>- Gravitational force<br>- Centrifugal force<br>- Buoyancy | | |
| 31 | Surface attachment buoy | | Whole system | | The idea is to have a buoy at the surface moored to the seabed that would act as attachment point for the LiftWEC device. The advantage of being able to remove the entire device for maintenance purpose and ease the installation. | No | |
| 32 | Use inertia modification to harvest energy | | Hydrodynamics, Control | | Use a subsystem to harvest the energy of moving the mass in a radial system. This could work nicely with a radial mass that is moved by outside forces (spring, gravity, centrifugal and buoyancy). | | |
| 33 | Share submerged mooring solution with fixed pile as anchor | | Whole system | | This would reduce the number of mooring lines attached to the seabed and thereby reducing envirnomental impact and cost. Similar to floating wind and floating PV. Multiple devices/modules can be connected at or below the surface. | No | |
| 34 | Preset inertia values with | | Hydrofoil, Control | | Inertia is only changed on long time scales (per day, month, season) to a few preset values - between locked positions. | | |

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| | locked position | | | | | | |
| 35 | Fixed Rotational Axis | | Hydrodynamics, Hydrofoil | | Very simply, this idea intends that the rotational axis is fixed in place (no compliance in x, y or z) and thus should not move with wave action. | | |
| 36 | Chevron configuration for ease of maintenance | | Marine operations | | The chevron configuration would create a calmer water space or moonpool type behind the device to increase weather window and ease maintenance. | No | |
| 37 | Compliant Rotational Axis | | Hydrodynamics, Hydrofoil | | This idea would simply be that the rotational axis about which the hydrofoil spins is complaint, or free to move in some manner, perhaps as a result of wave action or to allow us to try to increase the relative velocity by having the hydrofoil rotate and the axis of rotation move in tandem somehow. | | |
| 38 | Telecospic cantilever to connect rotational center and hydrofoil | | Control, Load transmission | | This is a method to change the rotational radius for control purpose. | Yes | |
| 39 | Use the inertia modifier as the primary PTO mechanism | | Hydrodynamics, Control | | Use moving mass in the radial direction as part of primary PTO mechanism.<br>Could even do this by moving hydrofoil radially and use this as part of primary PTO mechanism (lift working with you). | | |
| 40 | Secondary Generator Mounted on Hydrofoil | | Hydrofoil, Power train, Reaction source | | This idea involves mounting one, or more, smaller turbine style generators on the hydrofoil such that power can be extracted through these generators instead of at the hub. So in essence the rotational mechanism of the LiftWEC is free from any power conversion equipment. This might greatly simplify the power train and make the system quite 'modular'. As an example, google the 'Minesto Kite' which uses this approach. You could also use this approach to match the hydrodynamics to the wave climate, thus obtain the ideal velocity of the LiftWEC hydrofoils, but try to increase the velocity of the fluid running through the generator by placing them at a larger radius from the axis than the hydrofoil. Using an approach similar to this Minesto get a much higher velocity through their generator than a traditional tidal horizontal axis turbine and so can generate a similar level of power with a much smaller generator unit. | | |
| 41 | Play with surface | | Hydrodynamics, Hydrofoil | | Use of 'shark skin varnish', surface types, roughness elements to reduce drag components | | |

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| | roughness to reduce drag on hydrofoils | | | | | | |
| 42 | Eccentric mass to counteract torque | | Whole system, Reaction source, Marine operations | | Provide reaction torque through an eccentric mass below the rotor to counteract the torque of the rotor. It can be associated with a surface piercing spar or not.<br>A possibility of an active swinging keel system could be contemplated.<br>installation method to be looked at in the field of floating wind spar => possibility of low draft during towing if ballastable.<br>Survivability: the new idea can contemplate submergence of the rotor/device to limit wave loads in extreme sea states | Yes | |
| 43 | Keep angle of attack at optimal value | | Hydrodynamics, Hydrofoil | | Keep angle of attack at optimal value - through:<br>- pitch control<br>- foil morphing<br>- actuated external flaps<br>- internal foil morphing<br>- internal actuators<br>- pressure regulation | | |
| 44 | (Whale inspired) tubercles on hydrofoils to reduce drag | | Hydrodynamics, Hydrofoil | | (Whale inspired) tubercles on hydrofoils to reduce drag | | |
| 45 | Change from LIFTwec to DRAGwec - amplify the harm til it becomes a benefit | | Hydrodynamics, Hydrofoil | | Change from LIFTwec to DRAGwec - amplify the harm til it becomes a benefit. Basically, use a Savonius type turbine | | |
| 46 | Use a central hub and eliminate the endplates, and use | | Hydrodynamics, Hydrofoil | | Use a central hub and eliminate the endplates, and use winglets to limit drag | | |

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| | winglets to limit drag | | | | | | |
| 47 | Passive survival mode | | Whole system | | The survival mode should be a passive fail safe system. The main focus is to minimise load on the structure and on the PTO mechanism for survival purposes. Two approaches have been retained. The first one involves having a passive break on the rotor itself and let the hydrofoils pitching freely around their axes so that they can passively feather to minimise generated lift and drag. This approach is analogous to what is done for wind turbines. The free pitching motion of the foils should be nevertheless passively damped to avoid over spin. The second approach involves reducing passively the radius of the rotor to minimise lever arm of the foils and therefore minimise loads.<br>An important aspect common to those two approaches is that these mechanisms should be passive, failsafe and not reliant on active control. | Yes | |
| 48 | The number of optimal configuration | | Whole system, Control | | The LiftWEC should have 2-3 optimal working configurations to response to the different weather conditions<br>These configurations are determined by submerged depth and active radius<br>The device should be destined to have 2-3 working forms and work stable in them. | Yes | |
| 49 | Flexible material for trailing of the hydrofoil to produce additional torque, reduce drag and passive load control | | Hydrofoil | | Introducing flexible material for the trailing edge of the hydrofoil. Benefits to that:<br>1. Introducing passive loading control to offload in highly/extreme loading conditions;<br>2. Introducing passive flapping motion excited by vortex shedding, which can increase the torque and hence power output;<br>3. Potential noise mitigation due to the cancellation of shedding noise. | No | |
| 50 | Contra-Rotating LiftWEC | | Power train | | Using two rotors, each spins in opposite directions with one connected to the 'stator' of the generator and the other to the 'rotor' of the generator. In doing so this reduces the generator capacity, increase the generator speed (and could smoothen torque ripple in irregular sea states). Will introduce hydrodynamics problems as there is an optimum direction of rotation. | Yes | https://liftwec.com/wp-content/uploads/vfb/2020/05/LiftWEC-Counter-rotating.png |
| 51 | Passive & active hybrid radius | | Whole system, Hydrodynamics, Hydrofoil, Power train, Control, | | Fail save mode: this is the mode that the system react towards any system failures, that the system will return passively to zero/minimum radius to survive the extreme conditions. This is also will be used during the installation and transportation.<br>Normal operating mode: this is the mode that the system operates under the power | Maybe | |

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| | control and momentum control | | Load transmission, Installation | | generation condition. The radius of the device can be extended and retracted according to the incoming wave.<br>Preliminary idea is to use tubular electric magnetic clutches located at operational different radii to control the radius and hence momentum of inertia. The extension motion is driven passively by centrifugal force and the retraction motion will be actuated by a air spring or other mechanical systems (energy storage systems needed, EG, accumulator, capacitor, rubber; open for suggestion). | | |
| 52 | Single point V shape mooring and loading transmission system | | Marine operations | | The idea involves two potential solutions: 1. twin point tensioned mooring using V shaped mooring in the front and Y shaped mooring at the back. Y shaped mooring will allow some directional compliance so that the system can face towards the incoming wave. The system is positively buoyant to introduce the tension and hold the system upright. The mooring lines can use ropes.<br>2. Negatively buoyant system using two steel tubes to the single point mooring bearing (torrent) and a shoe to transmit and spread the downward forces to the seabed. The tube can be used as additional ballast for floatation in transit. | Maybe | https://liftwec.com/wp-content/uploads/vfb/2020/05/Vshaped-mooring.png |
| 53 | Minesto-Type PTO | | Power train | | Instead of employing a large diameter magnetic drive one or multiple turbines are attached to the foils or other parts of the external hub.<br>The position of the turbines relative to the foil is open: on top, below, trailing, in front of or attached to the sides of the foils. | Maybe | |
| 54 | Single Wing | | Hydrofoil, Load transmission | | Nacelle should not require support but be part of the supporting structure. In aircrafts wings are centrally supported through wingbox. The wing itself becomes the structure supporting multiple smaller generators which could enable weigh and cost saving. | Yes | |
| 55 | Jack-up Strut Supports | | Load transmission, Reaction source, Marine operations, Installation | | This idea involves supporting the LiftWEC through the use of 4 (or more, or less) jack-up style (telescopic) supports. These would ideally allow for the height of the system to be modified, and would act as the primary means by which the system is deployed and recovered. So if we had 4 legs, they could be jacked-up (so shortened) and perhaps folded in along the length (or span) of the device. This would mean the device could be towed around with relative ease. Then, when you are at your deployment location you could fold out the 'legs' and extend them. The bottom of the legs could be located to pre-fitted foundations (piles, gravity foundations etc). This would ideally make marine operations a little less tricky. The idea is taken from the most recent version of the CycWEC which is outlined in a paper by Siegel, 2019. There is a description and a picture in the paper (see attached). | Maybe | https://liftwec.com/wp-content/uploads/vfb/2020/05/Siegel-2019-Numerical-benchmarking-study-of-a-Cycloidal-Wave-Energy-Converter.pdf |
| 56 | Separate Struts for Hydrofoils and Turbines | | Power train | | Small turbines are attached to struts shifted 90Â° along circumference relative to hydrofoil struts. This might have negative impact on fatigue but less interaction of foils and turbine expected.<br>This might improve O&M and increase operability since small turbines can more easily be replaced and energy production is maintained (at lower rate) if only single turbine fails.<br>Good availability of components since Minesto already uses a similar concept. | Yes | |

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| 57 | High-Speed Fly Wheels | | Hydrofoil | | Large variations of inflow direction are expected. Employing high speed fly wheel motor generators as done in Formula 1 will lead to smoother motion. Deep water deployment is likely to lead to dominance of long wave periods making fluctuations less likely. | Maybe | |
| 58 | Use of 2 opposing hydrofoils | | Hydrodynamics, Hydrofoil, Control | | The idea involves the use of a single pair of rotating hydrofoils. The two hydrofoils would be placed 180 degrees apart. If perfect wave prediction and control could be achieved, the use of two hydrofoils would allow the generation of both the wave crest and trough phase of the radiated wave, thus improving potential wave cancellation and therefore performance (from a far field hydrodynamics perspective). In addition, the use of two hydrofoils at opposing points suggest that both can be operated at the point of least sensitivity to angle of attack (if only small phase deviations occur). This might reduce the severity of the influence of pitch control but probably requires some phase correction control. It will however mean that one foil will have to operate 'ahead' of the wave velocity and one foil 'behind' the wave which may double the non-tangential loads generated. | No | |
| 59 | Flow attaching devices | | Hydrodynamics, Hydrofoil | | Due to inflow fluctuations separation of flow along foils is likely to separate. Flow attaching devices might improve performance. | Maybe | |
| 60 | Passive radial motion | | Control | | Use a spring in combination with the centrifugal forces and a clever pitch of the foil. The sum of radial forces has to be evaluated with respect to the relation between lift force and centrifugal force. If they are of the same order of magnitude, it could use less energy than moving radially. | Maybe | |
| 61 | Taking learning from tidal energy in terms of fixed platform design | | Reaction source | Detachable module | Various solutions have already been developed in tidal energy that allow the generation system to be detachable from the platform and we should focus on the detachable module such will allow remote O&M<br>Base platform can be variable in design depending on soil conditions<br>Detachable winch within structure<br>One connection point<br>Remote O&M<br>HydroQuest example (https://www.hydroquest.net/marine-current-turbine/) | Maybe | |
| 62 | Pitch Control through local hydrofoil forces | | Hydrodynamics, Hydrofoil, Control | | A longitudinally split hydrofoil is used (as in air crafts) using force differences on pressure and suction side to passively adjust hydrofoil shape. A rubber load/spring is used to move hydrofoil back to original shape at zero loading. | Yes | |
| 63 | Induction based energy transmission | | Power train | | Instead of using slip rings to transfer power from generator to shore-cable a rotary transformer in shaft is used (it may not exist). | Yes | |

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| 64 | Slack Moored system | | Reaction source | | Counterweight or buoyancy stabilised<br>Single point/Turret moored - wave vaning around central point<br>Orbital  Marine Power type configuration (https://orbitalmarine.com/)<br>Lower WEC from surface or fixed below platform<br>Multiple rotors on structure<br>Can tow the device<br>Can be ballasted<br>Surface piercing<br>One big WEC or multiple WECs depending on  cost benefit | Maybe | |
| 65 | Hydrodynamic Reaction of Substructure | | Load transmission, Reaction source | | The substructure is equipped with components inducing a hydrodynamically enhanced reaction to foil induced shaft moment, e.g. through drag plates.<br>Self-reacting nature of substructure should be used to minimize load transmission to sea-bed. | Maybe | https://liftwec.com/wp-content/uploads/vfb/2020/05/Whiteboard7-01.png |
| 66 | Central Hub and Spoke Structure | | Load transmission | | This is simply the use of a central hub (most likely aligned along the axis of rotation) and spoke layout to support the hydrofoils. This simply means the hydrofoils are supported on cantilevered 'spokes' which are attached to the central hub. The lift force on the hydrofoil would drive the foil which in turn would drive the spoke and thus the central hub which would probably be attached to some sort of generator and mounted at each end by bearings. This system is exampled in the mock-up image in the LiftWEC proposal document. | No | |
| 67 | Hydrofoil Manufacturing Ideas | | Other | Manufacturing | The hydrofoils could be manufactured in two ways to prevent internal residual stresses from welding<br>a. Aluminium welded using linear friction welding using a bobbin<br>b. Super plastic formed + diffusion bonding to prevent joints | No | |
| 68 | Shaft-Based Generator | | Power train, Load transmission | | This is very simply the use of a system where the rotational motion is transferred to the generator via a solid shaft - for example this system would make sense if the configuration employs a central hub and spoke system - then the shaft can be taken from the central hub and into the generator. | No | |
| 69 | Variable WEC submergence | | Whole system | | Suitable for Semi sub type structure<br>Ballasting and de-ballasting  to adjust the depth of submergence for different wave conditions and survivability<br>Accessible generator through legs of semi sub<br>Multiple WECs possible<br>Rotor exposed area limited which is favourable from an extreme force perspective | Maybe | |
| 70 | Radial Generator (alternative to shaft- | | Power train, Load transmission | | This is an alternative to the use of a shaft-based transmission of rotational energy into the generator. This approach would use a radial generator - which is basically a generator that uses a larger diameter rotor and stator. A good exampl eof this in the marine industry would be the Openhydro type through-flow tidal turbine. | No | |

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| | based generator) | | | | | | |
| 71 | Low-energy radial actuator | | Control | | Limit the amount of energy used to run the radial actuator by limiting the number of times it is activated. Use the radial actuator only after certain time-intervals when a specified threshold is reached to set the system up for certain detected sea state change. | Maybe | |
| 72 | Generator Mounted in Nacelle(s) | | Power train | | This idea involves the mounting of some form of generator unit within the end-nacelle(s) of the LiftWEC device. This is similar to the approach taken by Atargis in their most recent version of the CycWEC device (see Siegel, 2019). | No | |
| 73 | Wave-driven radial motion | | Hydrodynamics, Control | | Under the assumption that the radial motion is not needed every rotation/very often: Perform the radial motion just at times where external force is acting in the necessary direction and use brakes to maintain the gained distance. Implement a radial force sensor to be able to detect these situations. Predict necessary changes in radial position based on environmental forecast adequately ahead of time. | Maybe | |
| 74 | Reduce impact on seabed from mining/piling | | Installation | | Floating should be worse than fixed because of cables sweeping the seafloor.<br>Use of micro piles to reduce damage on seafloor and organisms and possibly reduce noise from activities. | No | |
| 75 | Reduce impact on seabed from mining/piling | | Installation | | Floating should be worse than fixed because of cables sweeping the seafloor.<br>Use of micro piles to reduce damage on seafloor and organisms and possibly reduce noise from activities. | No | |
| 76 | Hydrofoil Radius of rotation variation to tune to wave height and period and maintain optimal angle of incidence | | Hydrodynamics, Hydrofoil | optimising radius to maintain phase coupling with wave | Methods to change the radius of rotation along the length of the hydrofoil.<br>Stepped profile, parabolic profile generated by hydraulic rams at the blade ends, hinged segmented blade; all three to change shape span wise | Maybe | |
| 77 | Reduce harm to | | Other | | The probability of encounter should be minimal and is mostly associated with larger animals (e.g., dolphins). | Maybe | |

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| | orgainsms from encounter with equipment n/pressure fields | | | | Use protective screens to blades that can harm/kill the organisms upon collision. Ways of temporary shut-down should be considered when marine mammals are observed in the area. Also, the device should be able to be stopped quickly in case of observing marine mammals. | | |
| 78 | Reduce impact from EMFs and noise | | Installation, Other | | EMFs and especially noise that may compromise the behaviour of fish and mammals should be minimized during activities and during the device operation.<br>Noise can possibly be reduced by soft start (â€˜ramp upâ€™) of activities. Attenuate the produced sound using bubble curtains, confined bubble curtains, bubble sleeves, hydro sound dampers or de-watered cofferdams | Maybe | |
| 79 | Reduce impact on seabed from mining/piling 2 | | Installation | | Reduce the seabed area to be cleared;<br>Eco-efficient surface mining, by establishing a limit depth to mine or creation of pits;<br>Usage of silt screens, to limit the dispersion of suspended sediments;<br>If possible, the various types of anchors (rock, latching and stabilization) should be chosen based on a minimum practical depth into the sediment, thus limiting the volume of drill cuttings discharged to the environment and the seabed morphology disruption | Maybe | |

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