LiftWEC

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

Deliverable D2.7

Report on Synthesis of Design Knowledge

Deliverable Lead	Queen’s University Belfast
Delivery Date	3rd June 2021
Dissemination Level	Public
Status	Final
Version	2.0

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.

Document Information

Project Acronym	LiftWEC
Project Title	Development of a new class of wave energy converter based on hydrodynamic lift forces
Grant Agreement Number	851885
Work Package	WP2
Related Task(s)	T2.6
Deliverable Number	D2.7
Deliverable Name	Report on Synthesis of Design Knowledge
Due Date	31st May 2021
Date Delivered	3rd June 2021
Primary Author(s)	Matt Folley (QUB)
Co-Author(s)	Paul Lamont-kane (QUB)
Document Number	LW-D02-07

Version Control

Revision	Date	Description	Prepared By	Checked By
0.1	20 May '21	Release for internal review	MF	PLK
1.0	31 May '21	Release for publication	MF	PLK
2.0	02 June '21	Repaired broken references in text	MF	PLK

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.

EXECUTIVE SUMMARY

This document constitutes Deliverable 'D2.7 Report on Synthesis of Design Knowledge' 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 a rotating hydrofoil that generates lift as the primary interaction with the incident waves. This report is intended to provide a foundation of the knowledge required to undertake the design of LiftWEC configurations in the project and is a natural extension of D2.1, Preliminary Report on Synthesis of Design Knowledge.

In this document the design knowledge is separated into the four fundamental design categories together with their sub-divisions used in the Preliminary Report (D2.1): hydrodynamics, structure, power train and marine operations to support cross-referencing if desired, plus a cross-cutting category that captures design knowledge that does not naturally fall into one of the original four categories. In each case the design knowledge provided in the Preliminary Report is first summarised and then additional Design Knowledge added.

TABLE OF CONTENTS

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.

1 INTRODUCTION

This document constitutes Deliverable 'D2.7 Report on Synthesis of Design Knowledge' 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 a rotating hydrofoil, 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 purpose of this document is to review and update the synthesis of design knowledge in the LiftWEC project. Thus, this document continues the process of identifying the design decisions that must be taken by the project consortium in developing such a novel and innovative system, which was started in Deliverable D2.1. Consequently, this document builds on the construction of a knowledge framework that can be used to; (1) support potential design decisions, (2) present arrays of options available, (3) track decisions made, and (4) consider the potential implications of the decisions in a whole-system assessment. In summary, this document should assist with ensuring end-of-project LiftWEC system(s) have been produced as a result of structured, logical, and robust design decisions made in light of good science and consortium-wide experience.

1.3 STRUCTURE OF THE DOCUMENT

This document is divided into seven sections, including this introductory section. Section 2 describes the structure of the design knowledge that has been developed both within and outside of the LiftWEC project to date. Section 3 discusses design knowledge and options available regarding the fundamental hydrodynamic processes the system seeks to exploit. Section 4 discusses the options available for implementation of a system exploiting the hydrodynamics in terms of the mechanical structure required. Section 5 describes design knowledge acquired and options available with regards to the extraction of energy through the system Power Train. Section 6 describes existing design knowledge acquired and options available with regards to Marine Operations such as installation, operation, maintenance etc. Finally, Section 7 contains design knowledge that is cross-cutting and so does not naturally exist in any one of the above sections. Following these sections, a bibliography is provided that lists the project documents that have been used in the production of this report on design knowledge and where further details may be obtained. All of these project documents are publicly available and may be downloaded from the project website or upon request.

Note that the structure of design knowledge is fluid and was expected to vary as design knowledge increased. However, it has been found that the structure of the design knowledge that was identified at the start of the project, and described in D2.1, remains valid, except for the additional of a section of cross-cutting design knowledge. Thus, this structure has been retained for the presentation of this synthesis of the design knowledge, helping to facilitate the relationship of this new knowledge with the preliminary design knowledge provided in Deliverable D2.1.

2 STRUCTURE OF DESIGN KNOWLEDGE

Although the structure of design knowledge should not be considered as a static framework, but rather as a flexible mechanism that can be manipulated to support the design process, the structure of the design knowledge identified in the Preliminary Report (D2.1) remains appropriate with the addition of a category to contain cross-cutting knowledge. As such, the structure to the design knowledge remains being based on the work-packages that have been identified in the proposal. Thus, the core design aspects of the LiftWEC concept are shown in Figure 1.

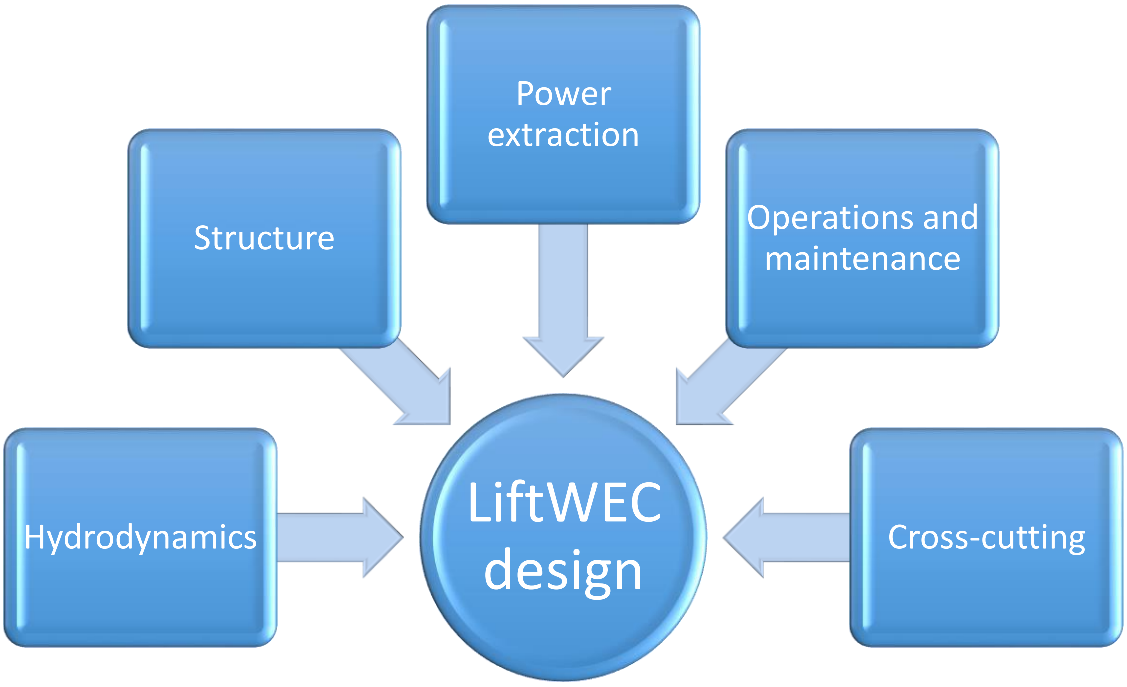

Figure 1: Core design elements of the LiftWEC concept design

The design knowledge associated with each of these core design aspects is covered in a separate Section of this document. The core design aspects and associated key elements provides a structure for the LiftWEC design knowledge as shown in Figure 2.

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.

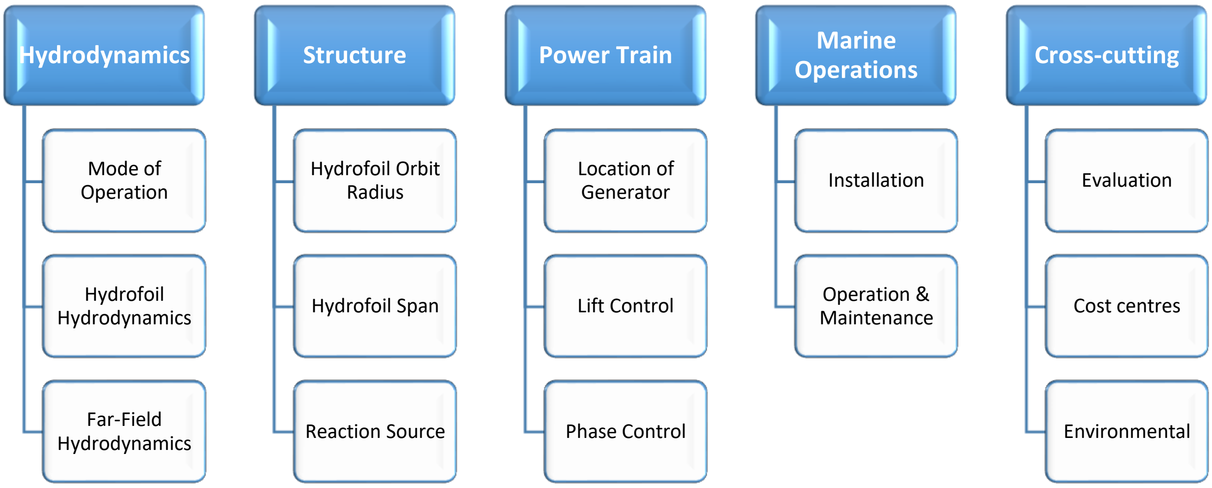

Figure 2: Key aspects of the core design elements

It will be noted that some of the design knowledge contained in this report may not appear to have a direct impact on differentiating between the current preliminary LiftWEC configurations, and as such may appear to be superfluous. However, this knowledge has been included as it may become relevant for future configurations, or its relevance may only become apparent when the LiftWEC configurations have been developed further.

3 HYDRODYNAMICS

Hydrodynamic design is taken as the specification and conceptualisation of the main operating principles of the system. Taken as an aside to practical implementation, the hydrodynamics are initially considered prior to the specific of mechanical elements, with the option for subsequent iterative reconsiderations to be made if later found to be necessary or preferable. Thus, the hydrodynamic design is associated with defining the underlying fundamentals of *how* the LiftWEC system might operate in terms of its exploitation of driving fluid motions. The hydrodynamic design will consider what fundamental wave-based hydrodynamic processes exist which could be exploited in an attempt to generate lift, and then how would an ideal system operate which might seek to exploit the hydrodynamic processes identified.

3.1 MODE OF OPERATION

The preliminary report on design knowledge identified that a phase-locked rotation (where the hydrofoil rotates with a phase of approximately ±90° to the wave-induced velocity) is expected to have a higher potential power capture, but places significant demands on the control system to maintain the optimum phase. Conversely, phase-independent rotation would be expected to require a less demanding control system but may be associated with a reduction in the potential power capture. Other aspects to consider are that in a phase-independent rotation the force on the hydrofoil may sometimes be centripetal and sometimes centrifugal, which suggests that the hydrofoil should be symmetrical (about the curved path of the hydrofoil). However, a phase-locked rotation can mean

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.

that the force on a hydrofoil should always act in the same direction and so there would be some advantage in using asymmetrical hydrofoil profiles. Furthermore, a phase-locked rotation would imply the use of 1 or 2 hydrofoils (to achieve the ±90° phase relationship), which a phase-independent rotation could have 3+ hydrofoils. In general, the hydrofoils may rotate either in the same direction as the wave-induced water particle motions, or contra-rotating. If rotating against the wave-induced water particle motions, then the positive pressure lifting surface on each hydrofoil will have to reverse an average of four times each rotation and thus passing through a point of zero lift four times each rotation. This is expected to significantly limit the maximum power capture. However, in the case that a contra-rotating hydrofoil is considered then the hydrofoil profile should be symmetrical as the force will be continually varying between centrifugal and centripetal.

An indication of the potential performance of a hydrofoil with phase-independent rotation can be inferred from the performance of a Voith-Schneider propeller. Essentially a Voith-Schneider propeller consists of one or more hydrofoils that rotate about an axis parallel to the span of the hydrofoil (as LiftWEC) and adjust their pitch to obtain a unidirectional thrust. At a primary level this is similar to LiftWEC, but operating in reverse, that is the force generated is used to extract energy rather than require energy for propulsion. Research into Voith-Schneider propellers indicate that efficiencies of up to 70% can be achieved in the conversion of shaft power to propulsion and thus it may be expected that phase-independent rotation can achieved similar levels of efficiency provided that the velocity and pitch of the hydrofoil can be controlled appropriately.

In addition, the performance of phase-independent rotation can also be inferred from research into the Wave Harrow wave energy converter. The Wave Harrow is a four-hydrofoil device that has been developed at the Technical University of Hamburg. It was found that the peak 2D efficiency of the Wave Harrow is about 25%, when the rotational speed of the rotor is about 40% of the wave frequency. For the optimal configuration of the Wave Harrow identified the efficiency increased with wave height so that the largest efficiencies occurred in the larger sea-states, see Figure 3. However, ideally the largest efficiencies should occur in the smaller sea-states as in the larger sea-states the power will be limited by the plant rating making the higher efficiency superfluous.

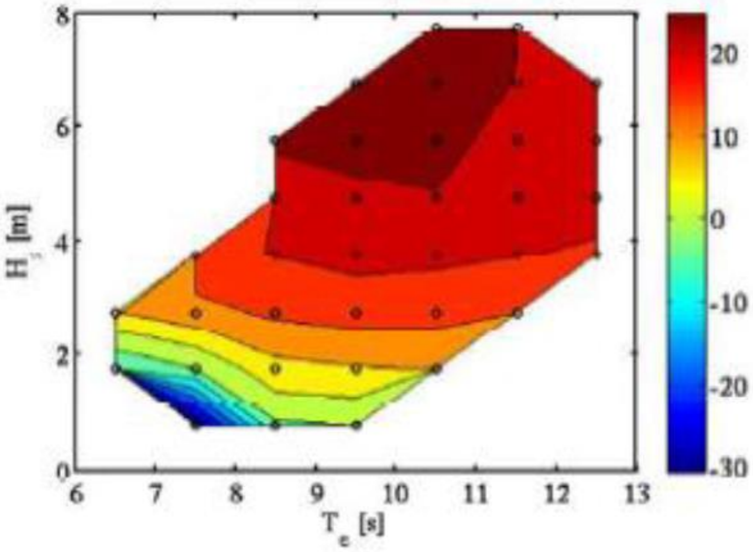

Figure 3: Wave Harrow efficiency matrix

Although a pair of contra-rotating hydrofoils may result in a reduction in the required hydrofoil reaction torque, it has already been noted that the performance is likely to be reduced because one of the hydrofoils will have to swap the positive pressure lifting surface an average of four times per wave cycle. Furthermore, the reduction in hydrofoil reaction torque is not expected to have a significant impact because the loads that this induces are typically expected to be much smaller than the loads associated with the fundamental reaction. In addition, a pair of contra-rotating hydrofoils may represent an increased risk to marine fauna due to a scissor motion between the hydrofoils as they pass each other and may also experience an increase in fatigue damage as the turbulence generated as the hydrofoils pass each other may cause additional cyclic loads.

An analysis based on potential flow theory on the CycWEC indicates that where a single hydrofoil is used there will be a larger loss of energy in radiated wave harmonics, which can be significantly reduced by using a pair of hydrofoils. Single hydrofoil will also result in a larger unbalanced load that rotors with multiple hydrofoils suggesting that two or more hydrofoils should be used. A useful reference for the design of LiftWEC is that CycWEC has a rotor diameter of 12m, containing two hydrofoils with a chord length of 5.0m and a total span of 60.0m.

3.2 HYDROFOIL HYDRODYNAMICS

The preliminary report on design knowledge identified that the hydrofoil profile influences the peak lift coefficient as well as the bandwidth where the lift to drag ratio is high. In general, it is necessary to compromise between these two characteristics, with the optimum depending on the control system's ability to maintain an optimum angle of attack. An improved ability to maintain an optimum angle of attack suggests that a higher peak / narrower bandwidth hydrofoil profile should be used, whilst a larger range of potential angles of attack suggest the use of a lower peak / broader bandwidth hydrofoil profile. It is possible that some spanwise variation of the hydrofoil profile may be beneficial (e.g. for self-starting) but this advantage is expected to be relatively small.

As noted, the hydrofoil profile should be chosen appropriately depending on the desired characteristics. Although the specific characteristics of each hydrofoil profile is unique, some general hydrofoil characteristics can be used that can help in identifying a suitable profile for a particular LiftWEC configuration. In general, it has been identified that thicker hydrofoils usually have a less abrupt flow separation than more slender hydrofoils suggesting that they are also likely to have a broader bandwidth. It is also expected that hydrofoils with blunt leading edges (more typical of thicker hydrofoils) are likely to reduce harm and mortality to marine fauna following collision. Testing undertaken by Atargis on the CycWEC has also indicated that a hydrofoil curved to follow the circular path may be expected to have a 3 – 5% increase in power capture. Finally, when considering the characteristics of the hydrofoils it is important to recognise that the transition point where flow separation occurs is dependent on the free-stream/incident turbulence, which is expected to be high as each hydrofoil effectively moves in the wake of another hydrofoil, and this may affect the lift and drag coefficients of the turbine.

For a phase-locked hydrofoil operating at a fixed radius it has been found that hydrofoil efficiency will initially increase with wave height as the lift force becomes larger relative to the drag force. The efficiency will then reach a peak before beginning to decline in large waves as the lift force is limited to avoid excessive wave radiation. An example of the 2D hydrofoil efficiency is shown in Figure 4. It can be seen that the peak efficiency is about 70% and over 30% for a large range of conditions.

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.

However, Figure 4 also shows that the efficiency is less than zero for smaller waves, indicating conditions when no power would be generated.

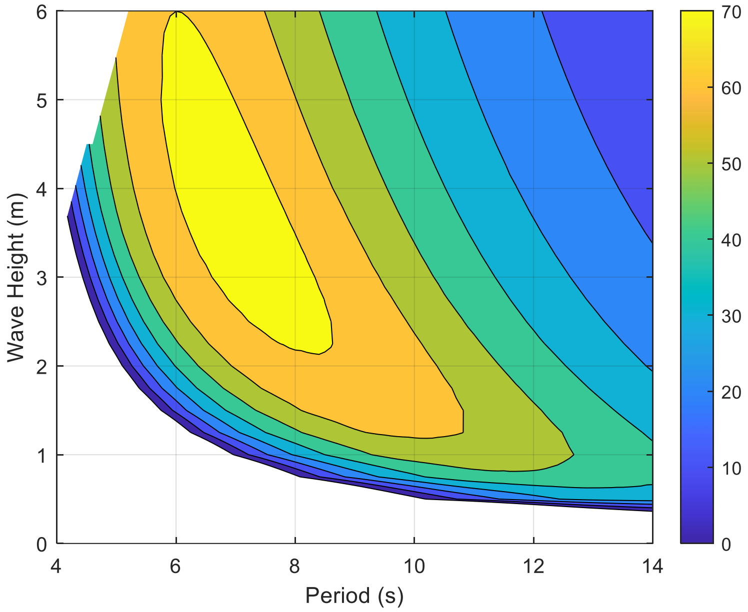

Figure 4: Peak efficiency for a pair of wave-driven, rotating hydrofoils with a 7m fixed operational radius

Figure 4 is for a hydrofoil that can pitch to maximum power capture; however, modelling suggests that there is not a very significant reduction in the power capture for a fixed pitch hydrofoil provided that the correct phase with the incident waves can be maintained. Similar analysis shows that the reduction in power capture is relatively modest even the optimum pitch and/or phase is not achieved as shown in Figure 5.

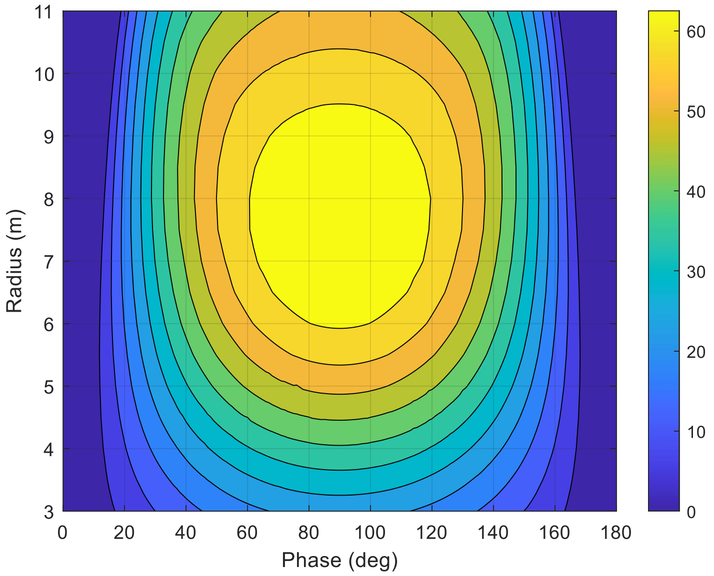

Figure 5: Peak hydrodynamic efficiency for a pair of wave-driven, rotating hydrofoils operating in a regular sea with T=10s, H=2m

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.

In general, it may be expected that the coupling of the hydrofoil with the waves, and associated maximum power capture, will improve as it approaches the wave surface. This has typically been found to be the case except where the hydrofoil is very close to the surface when there appears to be a reduction in the lift force, which is a phenomenon that has been observed for other hydrofoils used in high-speed craft.

3.3 FAR-FIELD HYDRODYNAMICS

The preliminary report on design knowledge identified that consideration of the far-field hydrodynamics suggests that optimum operating characteristics for lift-based wave energy converters (WECs) should be no different from other WECs. This implies that there is an optimum lift-force that needs to be generated (for a particular motion of the hydrofoil) and generating too much lift can reduce the net power capture, due to increased radiated waves, as well as too little lift, due to a lack of energy transfer from the waves. The far-field analysis also suggests the power absorber effect should improve performance and because the hydrofoil will interact in both heave and surge modes then the maximum capture width for a small device is approximately half a wavelength (3λ/2π).

It has been shown that the optimisation of a phase-locked fixed-radius LiftWEC configuration has a similar characteristic to a "traditional" wave energy converter except that in this case the lift force has to be optimised rather than the amplitude of motion. In particular, it is shown that the maximum 2D efficiency reduces in a similar fashion in that

$$\eta = 2\zeta(1-\epsilon) - \zeta^2$$

Where

η	2D efficiency
ζ	proportional of optimum lift force
ϵ	drag to lift ratio

Thus, in the ideal case of no drag ($\epsilon = 0$), the maximum efficiency is 100% and reducing from this peak as a quadratic function. Thus, a 10% error in the optimum lift force would result in an approximately 1% reduction in the efficiency. This helps to explain the relative insensitivity to the operating conditions described in the previous section. This equation also shows that as the drag-to-lift ratio increases the efficiency reduces.

It has been found, using the Haskinds Relation, that although in deep water the optimum path of a 2D hydrofoil (to a first-order approximation) is circular, if the hydrofoil has a finite span the optimum path becomes elliptical. This occurs because the radiation pattern associated with the wave-induced water particle surge motion is a dipole, whilst for the heave motion is a monopole. Because the lift-forces are similar for these two cases (for waves propagating orthogonally to the axis of the hydrofoil rotation) then Haskinds Relation can be used to show that the radiation damping coefficient is surge is smaller than that in heave. This is then used to show that the optimum motion in surge is larger than the optimum motion in surge, which results in an optimal hydrofoil path that is elliptical, with the ellipticity proportional to the ratio of the radiation damping coefficients. If the hydrofoil span is small relative to the wavelength, then the radiation damping coefficient in surge will be half that of the heave coefficient and so the major horizontal axis of the ellipse will be twice that of the major vertical axis. At the other extreme, for a very large span the radiation damping

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.

coefficients will be approximately the same and the optimum path will be circular, as expected from a 2D analysis.

An estimate of the ratio of damping coefficients can be made by assuming a particular lift distribution along the hydrofoil. Assuming that the lift force does not vary along the span of the hydrofoil, then the optimum ellipticity varies as shown in Figure 6. Thus, even when the span is approximately equal to half a wavelength (*kS* = 3 or 75m for a 10 second wave) the optimum ellipticity is over 1.6. This suggests that finite span effects need to be considered in the optimisation of the LiftWEC hydrodynamics. However, significantly the same analysis suggests that the maximum capture width ratio can be greater than unity suggesting that finite span hydrofoils may be hydrodynamically more efficient than that based on 2D assumptions (where the maximum capture width ration is one).

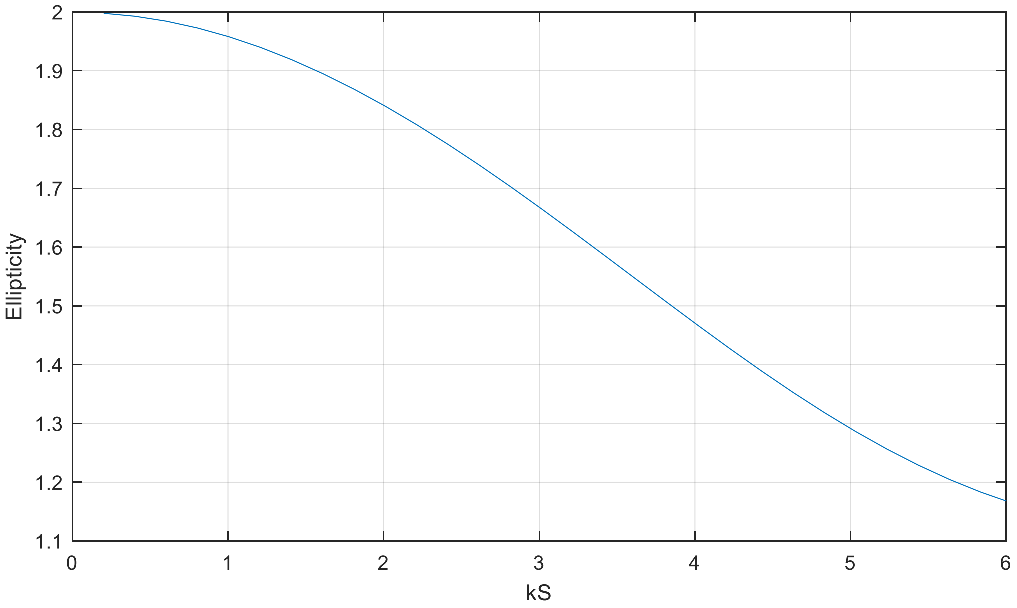

Figure 6: Optimum ellipticity for hydrofoil in deep water

However, if finite water depth is considered then the wave-induced motion of the water particles is no longer circular but elliptical, where there is more horizontal motion that vertical motion. This means that the lift force in surge is larger than that in heave and so will also have a larger radiation damping coefficient. This ratio of horizontal to vertical wave-induced water particle velocities is shown in Figure 7. Conveniently this increase in surge motion of the wave particles in finite depth water can be used to compensate for the required ellipticity for a finite span hydrofoil so that for a particular span and water depth the optimum hydrofoil motion is circular. Of course, in general the optimum path will only be circular for one wave period; however, if this wave period is typical for the chosen site, then the loss of potential performance due to the non-circular optimum hydrofoil path should be minimised.

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.

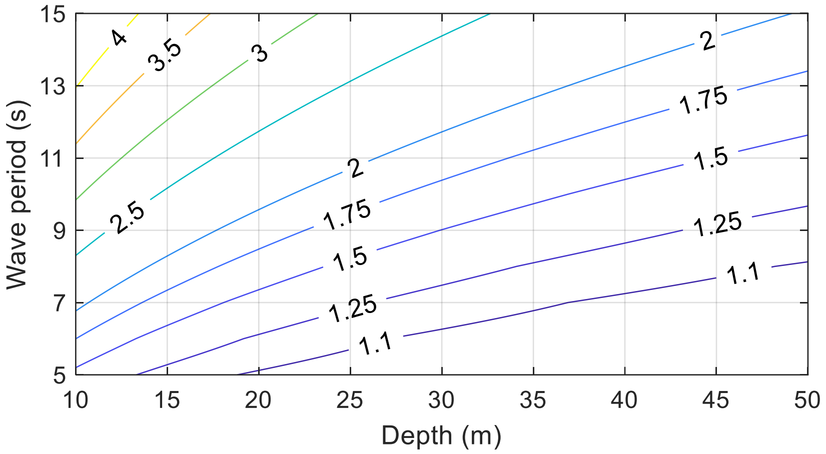

Figure 7: Ratio of horizontal to vertical wave-induced water particle velocities at mid-depth

4 STRUCTURE

The mechanical structure required by any LiftWEC concept needs to transmit the wave forces generated on the hydrofoils to the electrical generator and to a reaction source for the electrical generator. The radius of the rotor's orbit would be expected to be an important consideration in the structural requirements of all LiftWEC concept configurations. Similarly, the span of the hydrofoil (previous termed 'length', but span is considered to be a better, less ambiguous, term) would also be expected have a significant impact on structural requirements. From a more global perspective, the demands on the structure will be affected by ultimate reaction source against which the hydrofoils need to react to extract energy from the waves.

4.1 HYDROFOIL ORBIT RADIUS

The preliminary report on design knowledge identified that a fundamental consideration of loads suggests that the structural task (the product of force and the distance that force must be transmitted) increases with the hydrofoil orbit radius at a rate that is faster than any associated increase in power capture. This would suggest that a small hydrofoil orbit radius is desirable. However, wind turbines also have the same relationship between structural task and power with increasing size (the structural task increases more rapidly that the power capture as the wind turbine diameter increases) but this does not appear to influence the reduction in levelized cost of energy (LCoE) with increasing turbine diameter, at least for turbines rated up to about 10 MW. This suggests that the structural task is not a strong determinant of the total cost as the reduction in costs with size dominate over the increasing structural task per unit of power generation.

Linear potential flow models indicate that the optimum radius to maximise power capture is approximately 1/6th of a wavelength (e.g. 25m for a 10s wave period). However, the inclusion of drag in the model results in a smaller optimum orbit radius, with the optimum radius increasing with the wave height and wave period. In addition, the optimum operational radius reduces with the hydrofoil chord length as the required lift force can be generated with a smaller relative velocity. A typical optimum radius to maximise power capture for the North Atlantic wave climate is expected to be between 6 and 12 metres.

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.

A structural analysis of the demands of the structure required to support the hydrofoil indicates that the loads are relatively undemanding. Two potential configurations have been investigated – spoke and disk supports. It has been found that spoke provide a resilient support structure and are expected to have a lower cost than for disks. A potential advantage of disks is that the drag losses may be smaller than for spokes due to smoother flow conditions (this effect can be seen in racing bicycle wheels where solid wheels are used in time-trials to reduce drag; however, it should also be noted that they attract larger side loads, which is why they are less commonly used in road racing).

4.2 HYDROFOIL SPAN

The preliminary report on design knowledge identified a similar relationship for the relationship of structural task for the hydrofoil span as for the orbit radius. That is, the structural task will increase faster than the increase in power capture. However, similarly the increasing size of wind turbine suggests that this is not a critical contributor to the total cost and the structural task is not a key determinant of the optimum hydrofoil span.

Two different support configurations have been considered, a centrally (cantilever) and distally (beam) supported. The most appropriate support has been found to depend on the distribution of the loading on the hydrofoil. In the case of a uniform load along the hydrofoil the beam support is structurally more efficient, whilst if the load increase linearly from zero at the edge of the hydrofoil to a maximum in the centre of the span the cantilever support is more structurally efficient. Figure 8 shows a stress analysis for a steel NACA0012 hydrofoil. It can be seen that the stress increasing quadratically with the span and decreases with the chord length due to both an increase in the width and thickness of the hydrofoil. Clearly, using a thicker hydrofoil section (e.g. NACA0015) would reduce the maximum stresses in the hydrofoil. In addition, CycWEC proposes the use of glass-fibre for the hydrofoil, which may be more appropriate depending on the particular loading conditions.

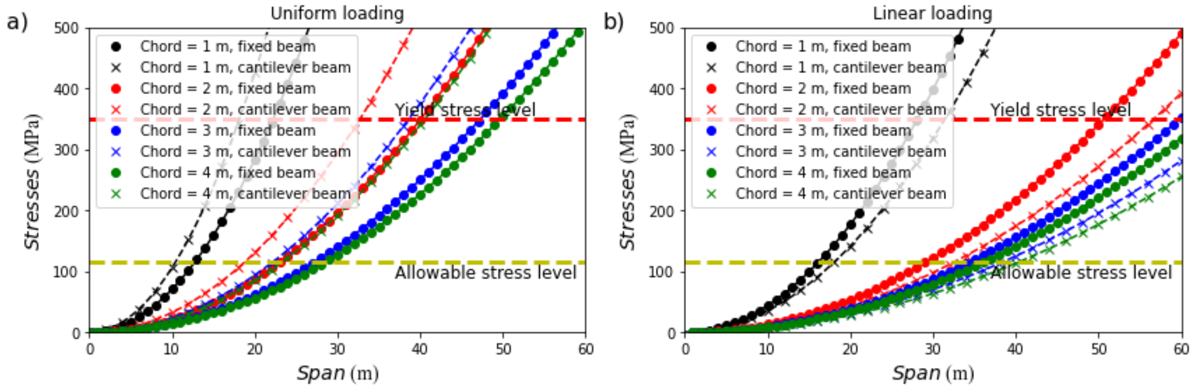

Figure 8: Stress analysis for hydrofoil

In addition to the structural requirements the hydrofoil span will also affect the power capture. Although it can be reduced it may be expected that there will be some loss of lift and additional induced drag at the ends of the hydrofoils, which will be more significant for shorter spans. Longer hydrofoil span will experience a more rapid reduction in lift from oblique waves as the wave-induced velocity will vary along the hydrofoil span. However, this reduction may not be very significant, with an estimated 10% reduction in lift for oblique waves at 20° when the hydrofoil span is equal to half a

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.

wavelength. Conversely, hydrofoils with larger spans will benefit less from the "point absorber effect" and the CycWEC is calculated to have the highest capture width ratio with a span of about 40m.

4.3 REACTION SOURCES

The preliminary report on design knowledge identified that to extract power, it is necessary to provide a reaction, which for LiftWEC can be separated into two types: a Fundamental Reaction and a Hydrofoil Reaction. The Fundamental Reaction provides a reference against the lift force, which oscillates in Cartesian space and can be provided by the seabed, phase diversity, and/or an inertia. The Hydrofoil Reaction provides a reference against the drive torque, which is primarily unidirectional and can be provided by the seabed, buoyancy/weight, and/or the surrounding water (although the use of surrounding water is expected to reduce power capture as it is likely to generate waves and thus be an additional loss of energy). Preliminary calculations suggest that the Fundamental Reaction will be much larger than the Hydrofoil Reaction, which means that if the seabed is used for the Fundamental Reaction, then it should also be used for the Hydrofoil Reaction. Phase diversity for the Fundamental Reaction requires that there be at least half a wavelength between hydrofoils, and that to provide a reaction against heave would require at least three hydrofoils as phase diversity from two hydrofoils would result in pitching (although a viable reaction would be provided in surge). Where inertia is used to provide a reaction, this could be either from a large body or an "inertia plate" providing a large added inertia. Preliminary calculations for the size of weight/buoyancy required to provide the Hydrofoil Reaction suggest that this should not be too demanding with a 1 MW plant requiring a reaction of 200 kN (20 Tonnes) at a distance of 5m.

The reaction source will potentially have a significant impact on the "survival strategy" that will be used in extreme waves. Although Atargis expect the loads during storms to be no larger than loads during normal operation, due to the longer wave periods, the CycWEC is also designed to increase its submergence to reduce loads during storms. Three options for the LiftWEC support structure have been analysed for deployment in a water depth of 50 metres. These indicate that the support structure compared to a floating structure would require twice as much steel if an A-frame support structure is used and three times as much steel for a monopile. These results are consistent with the requirements for offshore wind turbines, where in 50 metres of water it is expected that a floating wind turbine is most economic, whilst a lattice frame would be next cheapest followed by a monopile, which is generally considered to be only suitable for relatively shallow water.

As well as the structure, the water depth for deployment will also influence the incident waves. In general, there is minimal energy loss in North Atlantic waves provided the water depth is more than about 20m. In addition, there are potential advantages in shallower water as depth-induced refraction will tend to reduce the directional spread of the waves, resulting in less phase diversity along the length of the hydrofoil and a reduced advantage in weathervaning to maximum power capture.

It has also been identified that the type of reaction source may have an environmental impact with the use of mooring lines being a potential hazard for entanglement of diving birds and gravity and suction anchors being preferable to piles because of less disruption during installation, although gravity anchors are likely to cover more of the seabed to provide the same anchor loads. However, if mooring lines are used it is considered that it is preferable that they are synthetic as their use may reduce the required size of the installation vessels because they are much lighter than traditional mooring chains. In the case of a floating device, it is recognised that it may be preferable to have two

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.

electrical umbilical cables, one at each end of the hydrofoil to minimise yaw loads on the floating structure.

5 POWER TRAIN

The power train design is assumed to consist of those elements of the system which are most directly related to the extraction of useful energy from the LiftWEC system. Thus, it consists of the generator and associated control of the power flow using lift and/or phase control.

5.1 LOCATION OF GENERATOR

The preliminary report on design knowledge identified that there are two fundamental locations for the generator have been identified, either at the hub of the hydrofoil and on the hydrofoil itself. The hub generator is expected to have a low rotational speed, which typically means a more expensive generator, whilst a hydrofoil generator can be small and have a much higher rotational speed, but its efficiency is expected to be lower.

The use of a hydrofoil-mounted turbine has been identified as a potential hazard to marine fauna as a result of the relatively high speed of the turbine blades. It is also considered that a hydrofoil-mounted turbine may reduce lift and increase fatigue loads due to turbulent flow in the wake of the turbine.

An initial estimate of costs indicates that the generator and associated parts will be 15 – 20% of the total costs of the system, which must be considered when selecting the location of the generator. For example, halving the cost of the generator by using a smaller hydrofoil-mounted turbine would only be economically justified if there is less than a 10% reduction in the annual energy production.

5.2 LIFT CONTROL

The preliminary report on design knowledge identified that in general, the hydrofoil needs to be controlled to provide the optimum lift force, whilst maximising the lift/drag ratio (minimising the drag force). This can be achieved by controlling the pitch angle, the relative velocity and/or the phase of body rotation, where because there are two requirements of the control this implies that ideally at least two control parameters are required. Specifically, it is noted that the optimum pitch to provide the correct lift force will generally not result in the maximum lift/drag ratio for a fixed radius but can be achieved if the orbit radius is also controlled. However, changing the orbit radius of the hydrofoils will also change their moment of inertia and tend to cause a change in the hydrofoil speed.

It is claimed by Atargis that with knowledge of the incoming waves it is possible to achieve similar capture efficiencies in irregular waves as are achieved for regular wave; however, how this is achieved is considered to be proprietary know-how by Atargis. Moreover, it is not clear what impact limited knowledge or measurement uncertainty of the incoming waves may have on the power capture. A further point to consider is that a particularly aggressive control strategy that included rapid changes in lift force could result in an increase in fatigue loads and thus a more expensive structure. To minimise the required size of generator it would be expected that the lift could be controlled to limit the power generated at the plant rating (as for wind turbines).

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.

An analysis of the effect of angle of attack on the drive torque indicates that below an angle of attack of about 3° then the drive torque is negative and so either the hydrofoil rotation will slow down, or power is required to maintain its speed. A small angle of attack can occur if the hydrofoil is moving too fast relative to the wave-induced water particle velocities and the hydrofoil is not capable of pitch to compensate for this effect.

5.3 PHASE CONTROL

The preliminary report on design knowledge identified that for phase-locked rotation there is also an optimum phase for the hydrofoil rotation relative to the wave. This can be achieved using full-quadrant control of the generator (so that it can also be used as a motor) but there will be a loss of energy when running as a motor, with the amount of energy loss depending on the efficiency of the motor as well as the required change in kinetic energy. An alternative would be to modify the torque applied to the hydrofoil to best maintain the optimum phase, but never working the generator as a motor. A final option would be to modify that moment of inertia of the hydrofoil rotor so that the rotational speed changes due to conservation of momentum. It is noted that this last option requires less energy cycling than for a system with a constant moment of inertia but requires an additional actuator and associated cost.

6 MARINE OPERATIONS

The main phases of marine operations that are generally considered to be required for wave energy converters (and indeed all marine structures) are installation, operations & maintenance (O&M) and decommissioning. Decommissioning is not considered because discounted costs mean that it only makes a small contribution to the cost of energy, although it is typically simply the reverse of the installation process with approximately about 80% of the installation costs (but discounted because this cost in only incurred at the end of the project, typically after 25 years).

6.1 INSTALLATION

The preliminary report on design knowledge identified that there is a limited amount of information on marine operations for wave energy due to the limited number of deployments. Experience from the installation of Oyster was that the installation of 2 large rather than 4 smaller piles was preferable as although this configuration is structurally less efficient the cost was lower due to the dominant cost of the jack-up barge used to install the piles. It is also considered that using non-specialist, readily available, vessels are preferable as their costs tend to be more competitive (less driven by limited supply and demand).

Analysis of other wave energy converters indicates that installation may be expected to represent 8 – 17% of the total CAPEX. Preliminary analysis of a monopile system suggests that the installation could be about 1700 €/kW, whilst for a floating structure the installation cost would be about 1000 €/kW. The largest parts of the installation costs would be the foundations for the monopile and seabed preparation for the floating structure. These installation costs assume an operational limit of 2.0m significant wave height. However, if the limit can be increased to a significant wave height of 4.0m, then the installation costs may reduce by about 40%. This is because a large part of the costs would be spent whilst the vessels are on hire, but in port due the significant wave height being too large for

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.

operations. This situation can be particularly acute if heavy lift vessels are required because they are typically much more expensive that towing vessels and can only operate in relatively calm waters.

The proposed method of transporting the CycWEC to site is by towing, with the support struts hinged to reduce the towing loads (as well as reduce fuel consumption, which has environmental benefits). The towing loads are expected to increase approximately with the square of the towing speed. That is doubling the towing speed with quadruple the loads. Notwithstanding, the cost of vessel hire is expected to represent the largest proportion of the installation costs and so a higher towing load could be justified by a reduction in the duration for hire. A simple analysis of publicly available data indicates that hire costs increase approximately linearly with the maximum tug pull as shown in Figure 9, although the variability of this price can be very high as there can be a factor of four change in prices depending on the demand from the oil and gas industry.

An analysis of the stresses on the structure whilst being towed indicate that they are expected to be small relative to operational loads, including when being towed in waves of significant wave height of up to 4.0m. Similarly, the loads on the hydrofoil are acceptable when held down using straps from transport and if a crane-lift is required then the rotor should be lifted with the hydrofoils aligned vertically to minimise stresses.

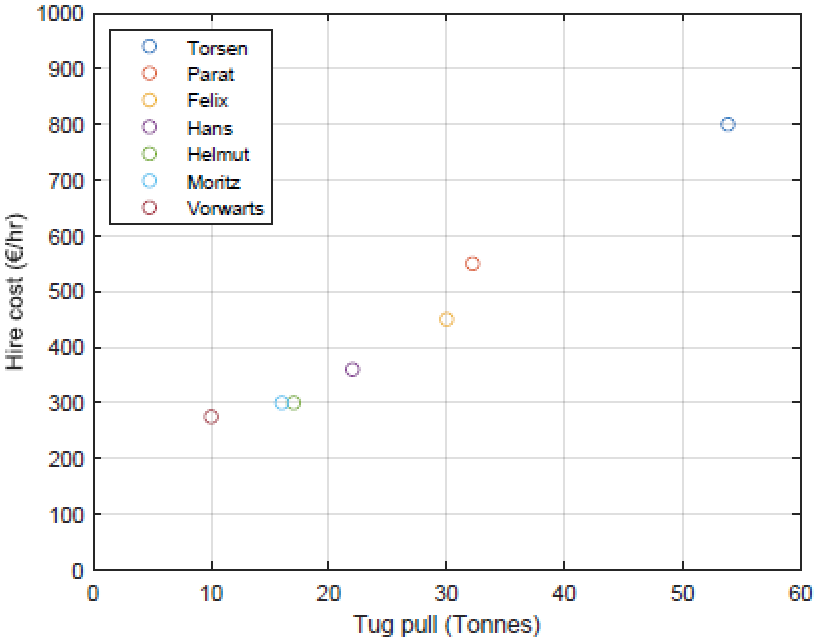

Figure 9: Change in hire costs with maximum tug pull (tug name in legend)

Changing the number of devices that need to be installed will obviously change the total installation duration; however, the effect is not linear because a significant amount of time is spent in port waiting for appropriate deployment conditions. Modelling indicates that halving the number of WECs to install would reduce installation duration by 15%, whilst doubling the number of units would increase installation costs by about 20%. However, how this translates into to a change in cost of installation will depend on how the vessel hire costs may vary with the size of the WECs.

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.

6.2 OPERATION AND MAINTENANCE

The preliminary report on design knowledge identified that it is important to ensure that the design considers the impact of time and access, which can significantly reduce the O&M costs. Related to this is that to achieve a similar accessibility for wave energy converters in the North Atlantic as offshore wind turbines it is necessary that they can be access with significant wave heights up to 3.5 metres. This suggests that human intervention in offshore O&M is not feasible and the use of ROVs and a return-to-base maintenance policy is preferable.

Analysis of other wave energy project and offshore wind indicates that annual operations and maintenance costs (OPEX) are typically between 1 and 10% of CAPEX costs; offshore wind projects it is typically 3 – 4.5%. This translates into a lifetime cost that is from one third to the equivalent of the CAPEX costs, depending on the expected life and financial discount rate. However, the actual OPEX costs are likely to be highly device specific and can be significantly reduced by careful design. Indeed, it is recognised that optimisation of O&M has the greatest potential for reducing the cost of energy in the short term. Factors that should be considered in the design for O&M are:

- Use of local available vessels where possible,
- ensuring that the WEC is designed for retrieval as well as deployment,
- multiple sensors for redundancy,
- application of fault tolerant design,
- potential for entanglement of mooring lines,
- submerged structures are more expensive, especially if they require diver access.

In general, it is recommended to minimise the requirement for personnel to access the WEC whilst deployed. Crew access to fixed structures is normally limited to significant wave heights of 1.5 – 2.0m, whilst the use of a special access gangway can increase this limit to 2.5 – 4.0m. Moreover, it is generally not recommended to require personnel to access a floating WEC, not only because of the difficulty in boarding, but also because of the difficult operating conditions present in a moving structure. The maintenance strategy for the CycWEC is to jack the structure out of the water.

As with installation, the major item of O&M costs is the vessel hire and so there is significant benefit in minimising the required size of the vessel. Access is also critically important, and modelling has confirmed that a significant wave height limit of 1.0 or 2.0m would mean that there are long periods, especially during the winter, when the plant could not be serviced with a significant impact on the plant availability. In this respect a floating structure is generally considered to be more accessible with a resultant reduction in O&M costs of up to 50%.

Specific technological solutions that have been identified as possible routes to the reduction in O&M costs for LiftWEC include the use of flooded water-gap generators (removing the need for a nacelle seal which requires maintenance to avoid leakage), remote control shackles (removing the need for crew to access connection shackles and so allowing operations to occur in larger sea-states with a potential reduction in costs of 10 – 30%) and acoustic cleaning for removal of biofouling (removing the need for divers). Other more general routes to a reduction in O&M costs are:

- increasing reliability,
- modularisation of components,
- simplification of access,

- use of specialist vessels,
- intelligent predictive maintenance,
- remotely operated vehicles (ROVs) and autonomous vehicles.

The proposed hierarchy for an O&M strategy is to first use fault-tolerant design to minimise the potential for critical failures. If that is not possible then to design so that maintenance operations can be undertaken at sea in most weather conditions. Then, in the final case the WEC should be easily recoverable, again in most weather conditions, for repair/maintenance in port.

It is finally worth noting that there are some apparent contradictions in the design of an O&M strategy that require some consideration as they depend on context. For example, a specialist vessel should be avoided where possible if considering a single prototype as this can be very expensive to mobilise. However, this could be an appropriate solution for a wave farm where the specialist vessel would be used regularly to justify its cost.

7 CROSS CUTTING

Cross-cutting knowledge is typically associated with the whole plant and it cannot easily be allocated to a specific aspect but considers the relative significance of all factors associated with the LiftWEC design. Although the evaluation criteria developed in Deliverable D2.2 are primarily designed to be applied after the LiftWEC configurations have been generated, they can also provide an indication of what is important in the design and thus provide design knowledge on where additional effort should be undertaken. Similarly, the distribution of the costs into cost centres can help to identify the potential benefit in improve specific aspects and thus where design effort would be most productively spent. For example, at this early technology performance level (TPL) there is little reason to spend a lot of effort on an aspect that at best will have a 1% impact on the cost of energy. Finally, the environmental category captures all the knowledge that is potentially important regarding how environmental considerations may influence the LiftWEC design.

7.1 EVALUATION

The evaluation of LiftWEC configurations has been separated into 16 primary categories that cover the aspects of energy production, survivability, affordability, acceptability and developability. These categories are relatively standard for the evaluation of wave energy converters, but for LiftWEC they have also been weighted based on feedback from partners within the LiftWEC consortium. These weightings were done in Month 10 of the project when partners were already relatively familiar with the potential challenges of LiftWEC and so represents the opinion of a well-informed expert group. The results of this weighting are shown in Figure 10.

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.

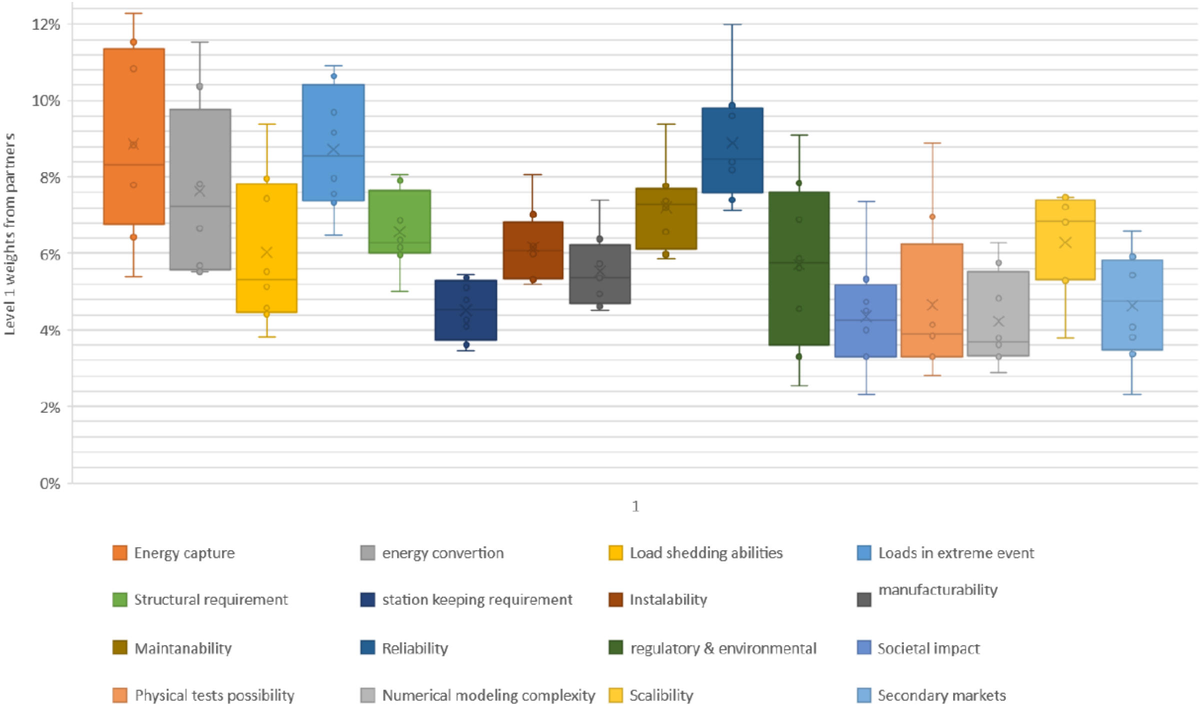

Figure 10: Weightings proposed for LiftWEC evaluation criteria.

As would be expected good energy capture and conversion are considered to be very important for LiftWEC, as well as the loads in extreme events. However, in addition the two related factors of reliability and maintainability were also identified as being important in the design of LiftWEC. This implies that these factors, which are often not explicitly considered at low Technology Readiness Levels, should be a major focus in the configuration design – including providing differentiation between designs that would otherwise be considered equivalent.

At the other end of the range, the station keeping, numerical modelling, physical modelling and societal impact are not considered to be significant factors in determining a promising LiftWEC configuration. The low racking of numerical and physical modelling suggests that the challenges in modelling a particular configuration should not be used as a measure of whether a particular configuration deserves further investigation. It is likely that the low value for societal impact is because of the potential for it to be both negative (reduction in fishing grounds) as well as positive (increase in employment) impacts. Finally, the low ranking of station keeping suggest that movement of the device around a typical watch circle of maybe 50 – 100 metres is not considered significant, which is likely to be associated with its deployment in deep water where movements of this magnitude are generally not considered to be an issue.

7.2 COST CENTRES

A typical breakdown of the costs of a wave farm into specific cost centres is shown in Figure 11. This shows that the major contributors to the total cost are the structure and O&M and so these should be the focus of the design effort.

The power take-off (generator) is also identified as a relatively significant proportion of the total costs and so deserved further focus; however, it is important to keep this in perspective. Because it only represents about 1/5th of the total costs then there is a five-fold ratio in relation of efficiency to cost. That is a 5% increase in average efficiency would justify a 25% increase in PTO costs, and conversely, a 25% decrease in PTO costs would only be justified if this resulted in a less than 5% reduction in average efficiency. Some guideline figures for the PTO are 300 €/kW for a direct-drive generator, 800 €/kW for a hydraulic PTO and 1400 €/kW for a mechanical mechanism. The efficiencies of these three types of PTOs may be similar and so this suggests that a direct-drive generator is most attractive, although clearly it need to be suitable for the operating conditions.

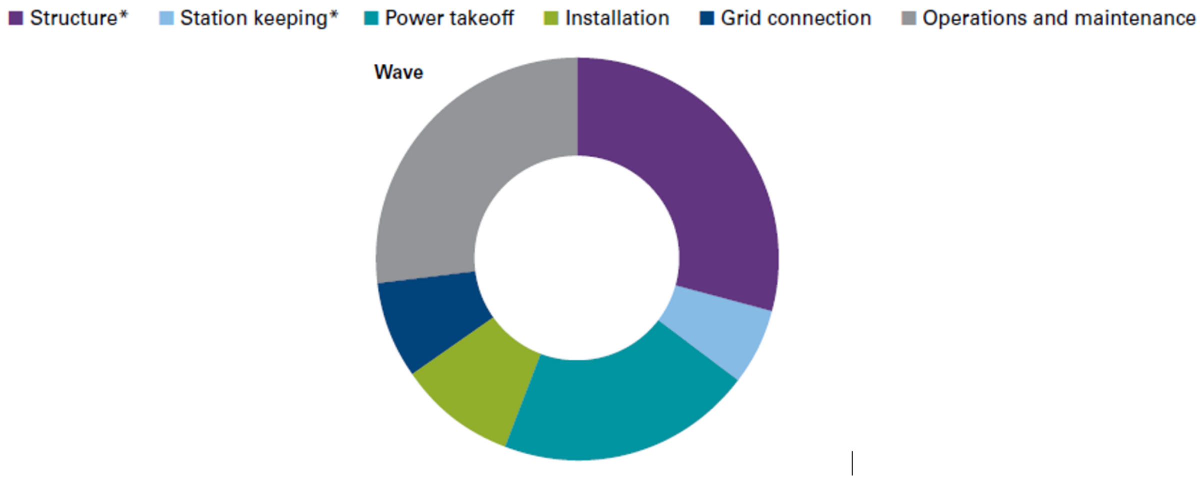

Figure 11: Breakdown of typical costs by cost centres

A calculation of the target CAPEX and OPEX for LiftWEC indicate that the CAPEX should be less than 4000 €/kW and the OPEX less than 270 €/kW/year. For example, a 1 MW device should have a CAPEX of less than 4 M€ and an annual OPEX of less than 270 k€.

7.3 ENVIRONMENTAL

The environmental aspects of design are regularly overlooked, and this can lead to issues when they need to be resolved at a later stage of the technology development. In general, these environmental concerns do not easily fall into one of the other categories as they must deal with the technology in its entirety. The environmental considerations can be separated into two categories, those that can be directly linked to an aspect of technology and those that can be considered as part of a process.

Environmental considerations for the technology include ensuring that any anti-fouling paints used are environmentally-friendly, the electrical cables should be deployed to minimise the effect of EMF radiation, the area of the wave farm should be minimised to limit the impact on access to fishing grounds and that the turbulence should be minimised to avoid a significant impact on water quality.

Environmental considerations for the process include avoiding the introduction of non-native species, avoid working during the tourism season (if appropriate) to minimise impact on the local economy and to consider the potential visual impact, although this is anticipated to be small due to the expected distance from the coast.

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.

8 PROJECT DESIGN KNOWLEDGE BIBLIOGRAPHY

Document code	Document title
LW-D09-01-1x0	Identification of potential technology stressors and environmental receptors of the LiftWEC technology
LW-D03-01-1x0	Uncoupled Model of LiftWEC for preliminary concept assessment
LW-D03-02-1x1	Preliminary assessment of computational capability report
LW-D04-01-2x0	Design of 2D scale model
LW-D05-01-1x0	Determination of performance function parametric structure
LW-WP01-AE-R01-8x0	The Control Problem for LiftWEC
LW-D06-01-1x3	Extreme Event LiftWEC ULS Assessment
LW-D06-02-1x3	Transportation and Maintenance LiftWEC ULS Assessment
LW-WP06-AAG-T01-1x2	A methodology for the structural design of LiftWEC a wave bladed cyclorotor
LW-D07-01-2x0	Operational Design Considerations
LW-D07-02-1x2	Operations and maintenance model development
LW-D07-03-1x2	Assessment of Preliminary Configurations
LW-D08-01-1x3	Cost database
LW-WP08-AT-N02-1x0	Progression to meet the mid-project LCoE KPI
LW-WP05-AE-T02-1x0	Development of an analytical model for a cyclorotor wave energy device
LW-WP10-JFC-R01-1x0	A Parametric Cost Model for the Initial Techno-Economic Assessment of lift-based Wave Energy Converters
LW-D02-01-2x0	Preliminary Report on Synthesis of Design Knowledge
LW-WP06-AAG-N02-1x2	Effect of water depth on support structure of Config 2
LW-D02-02-1x0	Identification of evaluation criteria
LW-D02-03-1x2	Review of current Lift-based WEC concepts and specification of preliminary configuration
LW-D02-04-1x2	Specification of Design and Evaluation Support Software Tools
LW-D02-05-1x0	Beta Version of Design and Evaluation Support Software Tools

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.

Document code	Document title
LW-WP02-MF-N24-1x0	Effect of radiation pattern on optimum hydrofoil motion
LW-WP02-MF-N25-1x1	Approximating far-field hydrodynamics for finite length hydrofoils
LW-WP10-MF-R01-1x0	Optimum water depth for lift based wave energy converters
LW-WP02-PLK-P01-1x0	Preliminary investigations into the hydrodynamic performance of lift based wave energy converters
LW-WP02-MF-N28-1x0	Configuration review - shallow water
LW-WP02-MF-N30-1x0	Configuration review - wing-mounted turbine
LW-WP02-MF-N31-1x0	Configuration review - contra-rotated turbine
LW-WP07-MF-N01-1x0	Cost of tug hire

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.