LiftWEC

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

Deliverable D2.8

Specification of Baseline Configurations

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EXECUTIVE SUMMARY

This document constitutes Deliverable 'D2.8 Specification of the Baseline 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 a rotating hydrofoil that generates lift as the primary interaction with the incident waves. This report defines the specifications of the Baseline Configurations that will be analysed in Phase 3 (Detailed investigations into LiftWEC configurations) of the project.

The process of the identification of the Baseline Configurations is described, which was centred around a two-day workshop with active involvement and contributions from all members of the consortium, together with a member of the LiftWEC Advisory Board who was able to attend the second day. Prior to the workshop all work packages and members of the consortium had identified the promising and unpromising Preliminary Configurations, desirable tangible features, and key design findings. These contributions were presented at the workshop and reviewed by the other workshop attendees. The Preliminary Configurations were also assessed using the LiftWEC Evaluation Tool described and refined in deliverables D2.2, D2.4, D2.5 and D2.6.

All of this information was used to generate a set of prospective Baseline Configurations. These prospective Baseline Configurations were generated in small groups in the workshop, where the membership of each group was chosen to provide a diverse range of perspectives. These prospective Baseline Configurations were then presented in a Plenary session and discussed, refined, and augmented until four Baseline Configurations were identified by consensus. The justification for the selection of the four Baseline Configurations, which were the basis of the consensus, are provided in this report. The consensus was that, except for some small refinements, the hydrofoil rotor and its control would be essentially the same for all configurations with the difference being in the implementation of the reaction and station-keeping requirements. The four Baseline Configurations cover the full range of promising implementations, which are considered to be

1. a tower,
2. a tension leg platform (TLP),
3. a semi-submersible, and
4. a spar buoy.

More detailed specifications of these four Baseline Configurations, including drawings, were produced following the workshop based on the discussions at the workshop and further input from consortium members. These specifications have been formatted as a Basis of Design for each Baseline Configuration that is consistent across all of the configurations. The agreed Baseline Configuration Basis of Designs are included as appendices of this document.

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1 INTRODUCTION

This document constitutes Deliverable 'D2.8 Specification of Baseline 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 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 primary purpose of this document is to provide the specifications of the Baseline Configurations that will be analysed in detail during Phase 3 of the project. The additional purposes of this document are to describe the process of the identification of the Baseline Configurations and to provide the justification for their choice. By providing this additional information the specifications of the Baseline Configurations can be understood in the context of their identification and selection. Providing this context means that the fundamental expectations of the Baseline Configurations can be used in subsequent refinements of their specifications, which is a natural and essential part of the design process. In summary, this document, together with the synthesis of design knowledge provided in deliverable D2.7, provide a solid basis for Phase 3 of the LiftWEC project.

1.3 STRUCTURE OF THE DOCUMENT

This document is divided into three Sections and nine Appendices, including this Section (Introduction). Section 2 describes the process by which the Baseline Configurations were identified. This includes the additional information from deliverable D2.7 used as the basis to support the choice of the Baseline Configurations. Furthermore, this section provides the justification of the choice of the four Baseline Configurations, including where appropriate the choice of dimensions used in the specifications. Section 3 describes the four Baseline Configurations that have been identified. Finally, Appendices A – E contain further information about the workshop, including the presentations and raw outputs, whilst Appendices F – I contain the detailed specifications of each of the Baseline Configurations, where the specification is structured as a Basis of Design document.

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2 BASELINE CONFIGURATION IDENTIFICATION PROCESS

The process for the identification of Baseline Configurations was based around a two-day workshop, which was attended by all primary researchers in the project as well as many other employees of the consortium members that may have only had a peripheral role in the project. Importantly, all of the technical work packages contained within the project were represented. Those attending the workshop were asked to submit prior to the workshop; (1) their views on which of the Preliminary Configurations were promising and unpromising, (2) tangible design features that a good configuration should have, and (3) the key design findings from their work package.

This pre-workshop production of information ensured that all participants were thinking critically about the LiftWEC configurations. An outline of the workshop agenda is provided in Table 2.1 below, with the full agenda, together with a list of participants, reproduced in Appendix A. Further details on each of these activities are provided in the sub-sections below.

Table 2.1: Outline agenda for Baseline Configuration Identification workshop

Day 1 Session 1	**Identification of promising Preliminary Configurations** **Identification of unpromising Preliminary Configurations**
Day 1 Session 1/2	**Desirable differentiating tangible features**
Day 1 Session 2	**Key differential design findings**
Day 1 Session 3	**Evaluation of Preliminary Configurations**
Day 2 Session 1	**Generation of Baseline Configurations (in small groups)**
Day 2 Session 2	**Selection of Baseline Configurations (plenary session)**

2.1 IDENTIFICATION OF PROMISING/UNPROMISING PRELIMINARY CONFIGURATIONS

Each member of the consortium was asked to identify what they believed to be the most promising and most unpromising configuration from the Preliminary Configurations based on their own perspective. As would be expected there was a range of different opinions on the most promising / unpromising configurations, including cases where what one member of the consortium considered to be promising, another member of the consortium considered to be unpromising. A summary of the promising / unpromising configurations is provided in Table 2.2 below and the presentations of the promising/unpromising configurations provided at the workshop are available in Appendix B.

Table 2.2: Promising/unpromising configurations identified by the consortium members

Entry ID	Configuration	Promising	Unpromising
2	Jack-up CycWEC	1	
4	LiftWEC proposal configuration	2	
6	Adaptable - Reconfigurable WECs	1	1
7	Twin-moored buoyant structure		1
8	Spar buoy with phase free rotor	3	
9	Parabolic with flaps and stiff single-point V-mooring		1
10	Phase-locked contra-rotating	1	3
12	Tethered mono-hydrofoil with wing mounted turbine		3

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Entry ID	Configuration	Promising	Unpromising
14	Slack moored LiftWEC semi-sub with multiple rotors	2	
15	Hydraulic PTO on main rotational shaft		
17	Radius Control Focused Config		
18	Planetary Gear End Plates		

Each member of the consortium explained the reasoning behind their choices, and this was discussed during the workshop. It became evident in these discussions that the differences in choice were largely based on assumptions of what can be achieved with future development. For example, Configuration 6 is considered promising by some because of the anticipated high potential power capture and unpromising by others because of the anticipated low reliability of complex systems in an open ocean environment. This difference of opinion is not unique to the LiftWEC project but reflects the differences of opinion in wave energy development in general.

Notwithstanding the cases where there was a difference of opinion, the process helped to identify some configurations that were universally considered to be promising (Configurations 2, 4, 8 and 14) and those universally considered to be unpromising (Configurations 7, 9 and 12). Equally importantly, the discussions of promising and unpromising configurations provided a forum where the design of LiftWEC could be discussed. This provided the opportunity for the deepening the understanding of the consortium members, which ultimately supported the identification of the Baseline Configurations.

2.2 Desirable Differentiating Tangible Features

As the design of LiftWEC progresses from initial concepts (Preliminary Configurations) to more concrete embodiments (Baseline Configurations) it is necessary to move from more abstract features of configurations to more tangible features. For example, an abstract feature could be easy to install, whilst a more tangible feature would be that it can be towed to site for installation using a small vessel and connected within 1 hour of arriving on site. A focus was also made that the features should be differentiating, that is they may be included in some configurations, but not others. A feature such as the desirable characteristics of the seabed electrical cable is expected to be the same for all configurations and so is not a feature that could be used to differentiate configurations. Thus, although these features may be important, they are not considered useful in the identification of the baseline configurations. Moreover, including these features would reduce the focus on differentiating features, which is why they were excluded from the analysis.

To encourage the identification of desirable differentiating tangible features, all members of the consortium were invited to submit and present up to three desirable differentiating tangible features at the workshop. Twenty-two features were identified and presented at the workshop. These desirable features can be separated into the four areas of Design Knowledge previously identified in Deliverables D2.1 and D2.7. The desirable features are categorised below in Table 2.3 and the presentation slides of each of these desirable features are provided in Appendix C.

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Table 2.3: Desirable Differentiating Tangible Features of LiftWEC

Design Knowledge	Feature
Hydrodynamics	End effectors & fins to reduce induced drag
Hydrodynamics	Phase independent rotor
Hydrodynamics	Phase free rotor
Structure	Compliance
Structure	Multi-bladed rotor
Structure	Doubly supported foils
Structure	Multiple rotors/Segmented span
Structure	Structure made in concrete
Power Train	Variable submergence control
Power Train	Variable radius to reduce ‘cut-in’ condition
Power Train	Pitch and rotational velocity control (phase free)
Power Train	Pitch control
Power Train	Submergence control
Power Train	Hydrofoil radius control
Power Train	Control of the submerged depth
Power Train	Control of the submergence of the rotor
Power Train	Pitch control
Marine Operations	Moorings
Marine Operations	Collapsible device
Marine Operations	Synthetic moorings
Marine Operations	Synthetic mooring lines
Marine Operations	Tow out Installation & O&M
Cross-cutting	Reduce blades speed
Cross-cutting	Single point mooring
Cross-cutting	Protective screens/temporary device shutdown
Cross-cutting	Can be installed in all water depths

It can be seen that there a number of common themes within the desirable differentiating tangible features. This is encouraging because it indicates that there is a degree of convergence within the consortium with respect to the desirable features and, by induction, the likely specifications of the Baseline Configurations.

2.3 Key Design Findings

Although a comprehensive catalogue of the LiftWEC design knowledge was produced in Deliverable D2.7, the presentation of key design findings by the Work Packages ensured that all workshop participants were updated with their status and given a further opportunity to interrogate the design findings to further deepen their understanding of their implications. Furthermore, the presentation of Key Design Findings provided workshop participants an explicit opportunity to share knowledge that had been generated between the submission of Deliverable D2.7 (on 31st May 2021) and the Identification of Baseline Configurations Workshop (held on the 28/29th September 2021).

A total of seventeen Key Design Findings were presented and discussed at the workshop, which are listed by Work Package in Table 2.3 below and the presentations reproduced in Appendix D.

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Table 2.4: Key Design Findings presented at Workshop

Work package	Key Design Finding
WP2 – Concept Development	Optimal water depth for finite span hydrofoil
WP2 – Concept Development	Fundamental reaction source options
WP2 – Concept Development	Phase diversity from multiple rotors
WP2 – Concept Development	Induced drag dominance for finite span hydrofoil
WP2 – Concept Development	Improved hydrodynamic performance with phase locking
WP3 – Numerical modelling	Phase-lock in irregular waves not possible
WP3 – Numerical modelling	Performance = f(Rotor Vel/Wave Ind Vel) in basic control
WP3 – Numerical modelling	Wave termination does not mean 100% conversion efficiency
WP3 – Numerical modelling	Foil behaviour different to straight flight
WP3 – Numerical modelling	Vortex structures possibly of minor importance
WP5 – Control Strategy	Radius control does not increase the generated power
WP5 – Control Strategy	Phase free rotation (Variable rotational velocity)
WP6 – Structural Design	Radius to span ratio should optimise power extraction
WP6 – Structural Design	Design is dictated by operational loads
WP6 – Structural Design	Power enhancement through single-foil heaving compliance
WP7 – O&M	Weather window restrictions (lifting & surface access)
WP8 – Cost of Energy	Target 4000EUR/kW in CAPEX and 210 EUR/kW/year in OPEX

2.4 Assessment of Preliminary Configurations

During the workshop the Preliminary Configurations were assessed using the Evaluation Tool developed within the LiftWEC project and described in deliverables D2.2.D2.4, D2.5 and D2.6. This Evaluation Tool is based on an Excel spreadsheet, where each configuration is evaluated on the numeration of 35 parameters in 16 categories. Unfortunately, time restrictions meant that it was not possible for all Preliminary Configurations to be assessed by all workshop participants. To compensate for this an Evaluation of the Atargis WEC (Configuration C02) was provided as a reference evaluation to minimise the variance in interpretation of the evaluation scores. In addition, rather than assessing the Preliminary Configurations individually as originally envisaged, each configuration was evaluated by a small team of three workshop participants, that would be expected to produce an evaluation with less variability than may be expected from an individual.

Level 1	Energy capture	energy convertion	Load shedding abilities	Loads in extreme event	Structural requirement	station keeping requirement	Instalability	manufacturability	Maintanability	Reliability	regulatory & environmental	Societal impact	Physical tests possibility	Numerical modeling complexity	Scalibility	Secondary markets	Totals	Team
C14: Slack Moored Semisub Multiple Rotors	6.0	2.8	7.3	6.7	4.8	7.0	8.4	6.4	8.1	7.7	8.0	8.0	4.0	6.0	8.0	7.0	**6.6**	Blue
C6: Adaptable, reconfigurable	8.4	2.8	10.0	10.0	2.4	5.0	7.8	4.9	5.7	5.7	8.0	8.0	7.0	7.0	7.0	5.0	**6.6**	Purple
C17: Radius control focused	5.7	2.8	7.3	9.3	3.5	5.0	6.4	6.5	7.2	6.3	8.0	8.0	7.0	8.0	7.0	5.0	**6.4**	Red
C10: Phase locked contra-rotating	5.9	2.9	7.0	9.3	3.3	5.0	5.5	5.9	5.5	7.7	7.0	7.0	6.0	7.0	7.0	6.0	**6.2**	Blue
C2: Jack up CycWEC	5.6	2.8	7.0	9.3	3.8	2.0	6.3	5.7	5.8	6.3	8.0	8.0	7.0	8.0	7.0	5.0	**6.1**	QUB
C8: Spar buoy, phase free	5.8	2.8	7.7	7.7	3.4	1.0	7.2	7.1	5.8	6.3	6.0	6.0	4.0	4.0	8.0	7.0	**5.7**	Green
C7: Twin moored buoyant structure	4.4	2.3	5.0	5.3	4.6	5.0	7.0	5.4	5.9	8.0	6.0	9.0	5.0	5.0	8.0	6.0	**5.7**	Green
C9: Parabolic with flaps and single point V mooring	3.1	2.8	4.0	9.3	5.0	1.0	6.3	5.3	5.9	6.0	6.0	6.0	7.0	6.0	7.0	5.0	**5.4**	Purple
C4: LiftWEC Proposal	5.7	2.8	7.3	4.3	4.5	1.0	4.7	5.7	3.8	6.7	8.0	8.0	5.0	7.0	7.0	3.0	**5.3**	Red

Figure 2–1: Evaluation scores for Preliminary Configurations

Figure 2–1 shows the evaluation scores for the Preliminary Configurations. The relatively early stage of development of the Preliminary Configurations means that in a number of cases the evaluation had to be undertaken based on an assumed performance, which clearly has the potential to be

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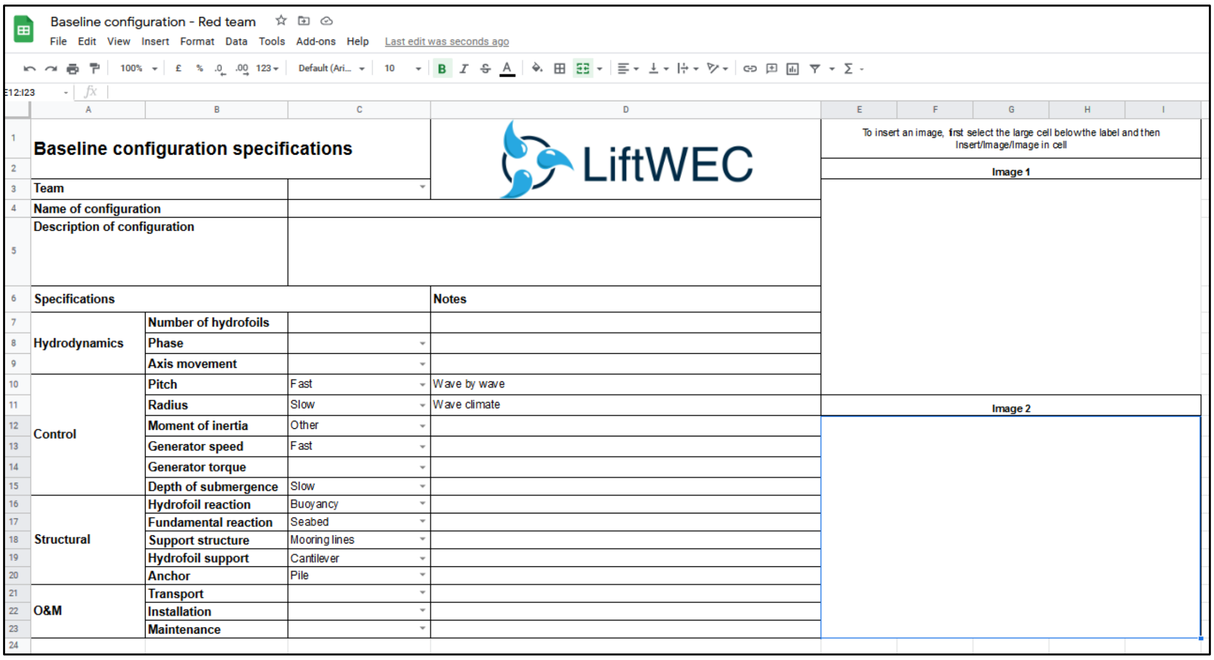
different between teams for the same fundamental concept. Notwithstanding the limitations associated with evaluating early-stage WEC concepts due to limited information and subjective assumptions, the evaluation of the Preliminary Configurations provided a useful tool to discuss the different Preliminary Configurations, which was done in a Plenary session following their evaluation. Equally importantly, the use of the Evaluation Tool by the workshop participants provided a direct reminder of the factors that are important in the identification of the promising wave energy converter. Thus, workshop participants entered the Baseline Configuration identification process with a heightened awareness of all the factors that need to be considered in design and not just those with which they are most familiar.

2.5 GENERATION AND SELECTION OF BASELINE CONFIGURATIONS

The generation and selection of the Baseline Configurations was undertaken as a two-phase process. In the first phase, three small groups were asked to produce detailed specifications for one or two Baseline Configurations. The groups were chosen to have a range of knowledge and experience in each group to help to ensure that the Baseline Configurations proposed were specified with consideration from a wide range of different perspectives. The Specifications Sheet used to record the configuration is shown in Figure 2–2. This sheet was produced using GoogleSheets©, which means that all members of the team could edit the specifications simultaneously. This made the recording of the proposed Baseline Configurations more time-efficient because it was not necessary for all of the writing to go through one person filling in the Specifications Sheet. In addition, it also meant that ideas for specifications could be directly entered by the person with the idea, without the need to dictate these ideas, but still allowing other people to modify the specifications, building on what another person had written. In general, this multiple-user synchronous production of the proposed Baseline Configurations was very successful. The Specification Sheets produced by each group are provided in Appendix E.


Baseline configuration - Red team

Baseline configuration specifications			
Team			
Name of configuration			
Description of configuration			
Specifications			Notes
Hydrodynamics	Number of hydrofoils		
	Phase		
	Axis movement		
Control	Pitch	Fast	Wave by wave
	Radius	Slow	Wave climate
	Moment of inertia	Other	
	Generator speed	Fast	
	Generator torque		
	Depth of submergence	Slow	
Structural	Hydrofoil reaction	Buoyancy	
	Fundamental reaction	Seabed	
	Support structure	Mooring lines	
	Hydrofoil support	Cantilever	
	Anchor	Pile	
O&M	Transport		
	Installation		
	Maintenance		

To insert an image, first select the large cell below the label and then Insert/Image/Image in cell
Image 1
Image 2

Figure 2–2: Baseline Configuration specification sheet

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The second phase of the Baseline Configuration Specification process involved a Plenary session that started with each small group presenting the potential Baseline Configurations that they had identified, with a total of 5 potential Baseline Configurations being identified by the three groups. During the presentations it became clear that two configurations, a semi-sub and spar buoy, were proposed by more than one group; a monopile/tower configuration was proposed by a single group. However, in addition, it was agreed that an additional configuration, a tension-leg platform configuration, is also promising and it was agreed to include it as a Baseline Configuration. It was also noted and agreed that the fundamental difference between the proposed Baseline Configurations was in the method of providing station-keeping and reaction sources; the design of the rotor and associated power take-off was essentially the same for all configurations. Thus, a total of four Baseline Configurations were identified, which are given the names of Tower LiftWEC, TLP LiftWEC, Semi-sub LiftWEC and Spar LiftWEC; these Baseline Configurations are described in Section 3 below.

2.6 JUSTIFICATION OF THE BASELINE CONFIGURATIONS

The Design Knowledge that has been developed in the LiftWEC project indicates that the fundamental differentiating aspects of the LiftWEC design, where a design compromise needs to be achieved, is in the method of supporting the hydrofoil rotor. The four Baseline Configurations that have been identified represent four fundamentally different ways in which the hydrofoil rotor can be supported. Each of these four Baseline Configurations contain characteristics that favour it over the other configurations, but further analysis is required to assess which of these Baseline Configurations is most promising from a whole system perspective. In particular, the factors of CAPEX, OPEX and hydrodynamics, including uncertainty, can be used to characterise and justify the selection of the four different Baseline Configurations.

The Tower LiftWEC Baseline Configuration represents a design that provides the highest rigidity to the hydrofoil rotor axis and is consequently expected to have the best and more predictable hydrodynamic performance. As such, it is a low-risk configuration as there are minimal unknowns with respect to hydrodynamic performance. However, the use of a rigid tower to support the hydrofoil rotor has been shown to have a higher structure requirement compared to floating configurations and is also expected to be more costly with respect to operations and maintenance (although some design elements of the configuration are proposed to minimise this additional cost). A further factor to consider for this configuration is that it may have additional dependence on local bathymetry compared to the other configurations, which may reduce its market potential. Thus, the inclusion of this Baseline Configuration is justified on the basis of it having a low hydrodynamic uncertainty, although its costs may be higher and market potential lower.

The TLP LiftWEC Baseline Configuration represents a design that can maintain a relatively stable axis of the hydrofoil rotor, which should ensure a relatively low uncertainty in the hydrodynamic performance, but with an expected reduction in the costs when compared to the Tower LiftWEC configuration. The use of the spread TLP moorings should reduce the cost of the installation, although the operations and maintenance may remain complex. Thus, the inclusion of this Baseline Configuration is justified on the basis of it having a relatively low hydrodynamic uncertainty and with a reduction in costs relative to the Tower LiftWEC configuration.

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The Semi-sub LiftWEC Baseline Configuration represents a design where the axis of the hydrofoil rotor may have significant movements, but this is compensated for by a reduction in the operational and maintenance costs. For this configuration the reduced dependence on local bathymetry is likely to increase its market potential due to more potential sites as it is essentially independent of water depth. It is currently unclear the extent to which the movement of the hydrofoil rotor axis may affect power performance, although this is being further investigated, especially in Work Package 6 and deliverable D6.3. It is currently expected that movement of the hydrofoil rotor axis will reduce the power capture, but it is possible that there is a design of the semi-sub that minimises any reduction in power capture and even offers the potential that the motion enhances the power capture. Thus, the inclusion of the Semi-sub LiftWEC Baseline Configuration is justified on the basis that it may be a relatively low cost solution, but further analysis is required to assess whether these lower costs are accompanied by an acceptable power performance.

The Spar LiftWEC Baseline Configuration represents a design where the axis of the hydrofoil rotor may have significant movements, but this is compensated for by a potential reduction in costs, similar to the Semi-sub LiftWEC configuration. However, the dynamics and design of a Spar LiftWEC is very different to those of a Semi-sub LiftWEC and so may be considered as an alternative, potentially attractive configuration. Thus, the inclusion of the Spar LiftWEC Baseline Configuration is justified on the basis that it may be a relatively low cost solution and is a commonly proposed solution for floating offshore wind turbines. However, further analysis is required to assess whether these lower costs are accompanied by an acceptable power performance, where these costs and performances may be different to those of the Semi-sub LiftWEC configuration.

As noted above, the four Baseline Configurations have been selected based on differences in their methods of supporting the hydrofoil rotor and associated hydrodynamic performance and costs. This leaves the subject regarding the design of the hydrofoil rotor unresolved. However, the Design Knowledge that has been developed in the LiftWEC project with respect to the hydrofoil and rotor design has led the consortium to the view that there is a single optimal design of the rotor and associated bearings, PTO, etc. that can be used in all of the Baseline Configurations. This rotor is expected to have a span of about 30 metres and operate on a fixed diameter of approximately 12 metres and with a chord length of 6 metres. The analysis of cost of energy indicates that the rating of LiftWEC should be as high as possible and this is achieved by maximising the hydrofoil span. Conversely, the structural analysis of the hydrofoil indicates that the maximum span of the hydrofoil is expected to be about 30 metres and so this is the chosen span of the hydrofoil.

The analysis of the hydrofoil control has also shown that increasing the diameter of the rotor also increases the average power capture and a diameter of 12 metres is considered to be the maximum achievable rotor diameter based on expected structural requirements of the rotor. In addition, maximising the size of the hydrofoil chord has been found to increase the power capture, although a limit of approximately half the rotor diameter is considered to represent a sensible geometric constraint. It has also been identified that power capture is maximised with a rotation that is sympathetic to the wave frequency, but not rigidly phase-locked. Finally, the use of two opposing hydrofoils is considered to be the most attractive option so that both hydrofoils can have a good phase relationship with the incident waves, which is not possible to achieve simultaneously for all hydrofoils if there are more than 2 hydrofoils, and the use of a single hydrofoil would require a significantly increased operational radius to achieve similar performance.

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Notwithstanding this definition of a standard rotor that applies to all Baseline Configurations, there remains significant potential for refining the design of the rotor. In particular, it is noted that the hydrofoil profile can be further optimised as well as the control strategy and the geometric design required to minimise tip-losses. However, in all cases, these improvements in rotor performance are expected to be relevant to all of the Baseline Configurations. Thus, whilst improving the performance of the hydrofoils remains a key element of the LiftWEC project, it is not currently considered to be a determining factor in the relative performance of the Baseline Configurations.

3 BASELINE CONFIGURATION SPECIFICATIONS

Summaries of the four Baseline Configuration specifications are provided in the sub-sections below. Their full specifications are provided in Appendices F - I. Some of the configurations have variants, which are described in the detailed specifications of the Appendices. These are considered to be variants rather than different configurations because the fundamental design does not differ between the variants, but the variants provide alternative methods of providing the same functional requirements to the configuration. It is anticipated that the detailed investigations that will be completed during Phase 3 of the project will identify which of the variants is most promising, which may depend on particular deployment circumstances.

Each configuration is given a unique code to facilitate its identification. To distinguish them from the Preliminary Configurations, the code starts with 'CB' and is followed by a two digit number starting at 01 for the first configuration. Variations on each of these configurations are identified by adding a letter to the end of the configuration code. For example, the section variant of the third Baseline Configuration has the code CB03B.

3.1 CONFIGURATION CB01: TOWER LIFTWEC

The Tower configuration consists of a two-hydrofoil rotor set atop a previously installed jack-up strut via a self-aligning transition piece as shown in Figure 3–1. The jack-up strut is mounted atop a monopile foundation. The rigid foundation and support structure provide a fixed axis of rotation for the rotor. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator, and pitch control mechanisms. The combined rotor/stator unit is referred to as the power-capture-unit and is affixed to the jack-up strut via a transition piece that permits ease of device deployment/recovery as well as yaw control. The jack-up strut is used both during deployment/recovery activities and to provide submergence control of the rotor. Power Take Off (PTO) is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the monopile occurs through the use of a jack-up platform and installation of the jack-up strut is achieved using a heavy-lifting vessel. Transport of the rotor/stator section is achieved through the attachment of temporary buoyancy tanks and the use of tug units. At the point of deployment, the transition piece self-aligns atop the extended jack-up strut, requiring de-ballasting of only a few metres worth of

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draft to permit rigid attachment of the power-capture-unit to the jack-up strut, after which temporary buoyancy tanks can be removed and the device submerged.

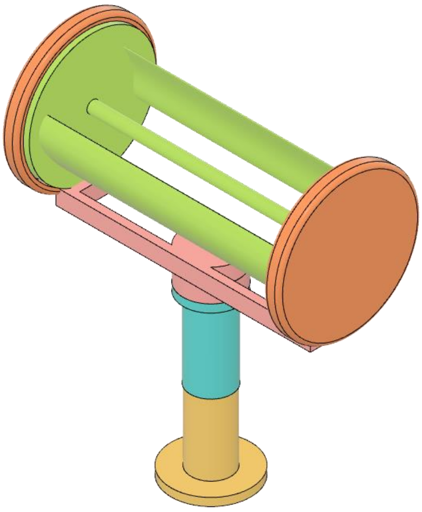

Figure 3–1: LiftWEC Tower configuration

3.2 Configuration CB02: TLP LiftWEC

The LiftWEC TLP configuration consists of a two-hydrofoil rotor held in place by 4 tension leg mooring cables as shown in Figure 3–2. Each cable is reacted by a micro-piled footing structure. This semi-rigid station-keeping system provides a near-fixed axis of rotation for the rotor. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator, tension leg winch and pitch control mechanisms as well as the permanent reactive buoyancy tanks required to maintain mooring tension. The combined rotor/stator unit is referred to as the power-capture-unit. Yaw control may or may not be possible through intelligent control of the tension leg winch system. The tension leg mooring winch system is used both during deployment/recovery activities and to provide submergence control of the rotor. Power take-off is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the micro-piled footings and tension leg mooring cables occurs through the use of micro-piling assets, and light weight lift vessels. Transport of the power-capture-unit (i.e. the combined rotor/stator section) is achieved using tug units. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the 4 corners of the power-capture-unit. The nacelle-mounted winching mechanisms then submerge the device to the desired depth for operation.

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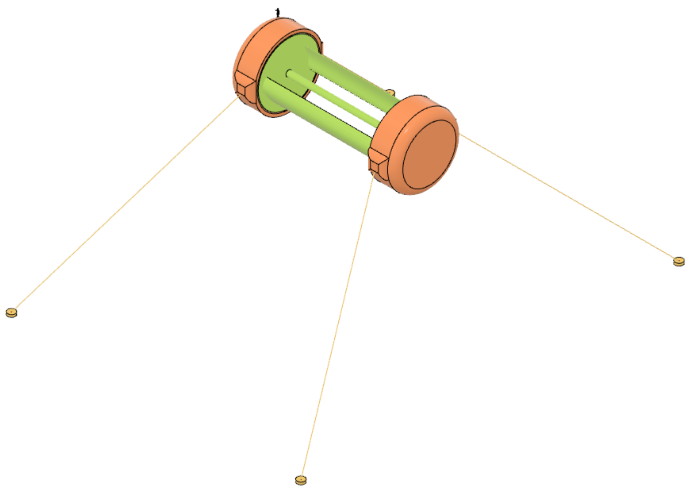

Figure 3–2: LiftWEC TLP configuration

3.3 Configuration CB03: Semi-sub LiftWEC

The LiftWEC semi-sub configuration consists of a two-hydrofoil rotor held in place by a 3-float semi-submersible as shown in Figure 3–3. The 3 floats are arranged in a triangular planform pattern. The semi-submersible is held in place by 3 catenary mooring cables, one attached to each of the three floats. The 3 catenary moorings may be anchored to the seabed either through micro-piled footings (variant CB03A), drag anchors (variant CB03B) or gravity foundations (variant CB03C), where it is recognised that the choice may depend on water depth, bathymetry and benthic conditions. The mooring arrangement allows for reasonable motion of the device, including the axis of rotation for weather-vaning to the dominant wave direction, in all 6 traditional degrees of freedom. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator, and pitch control mechanisms. The combined rotor/stator unit is referred to as the power-capture-unit. The power-capture-unit is suspended between the two front floats. Submergence control is achieved through ballasting/de-ballasting of the semi-submersible floats. Power take-off is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the anchor and station-keeping system will depend on the anchor system selected. Transport of the semi-submersible, including the power-capture-unit, for deployment is achieved using tugs. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the 3 floats of the semi-submersible. The semi-submersible is then ballasted using sea-water to achieve the desired submergence depth of the rotor.

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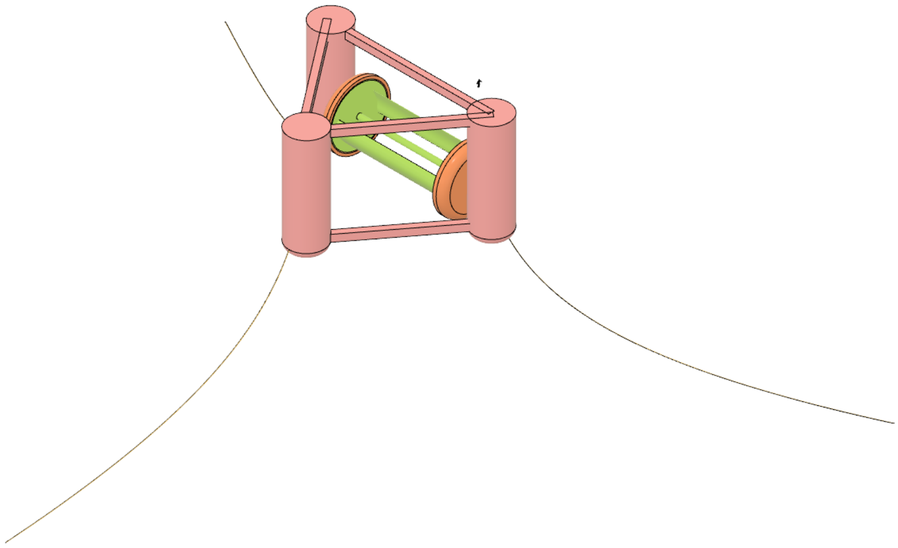

Figure 3–3: LiftWEC Semi-sub configuration (waves are incident from the right-side of the WEC)

3.4 Configuration CB04: Spar LiftWEC

The LiftWEC Spar configuration consists of a two-hydrofoil rotor held in place by a twin-tower spar-buoy float as shown in Figure 3–4. The two towers of the spar buoy are rigidly attached by a cross bar towards the bottom of the structure. The structure is held in place by a single point mooring sinking to a 3 catenary mooring cabled anchor system. The single point mooring is attached to each tower of the two-tower spar buoy structure. The 3 catenary moorings may be anchored to the seabed either through micro-piled footings (variant CB04A), drag anchors (variant CB04B) or gravity foundations (variant CB04C). The mooring arrangement allows for reasonable motion of the device, including the axis of rotation, in all 6 traditional degrees of freedom. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator, and pitch control mechanisms. The combined rotor/stator unit is referred to as the power-capture-unit. The power-capture-unit is suspended between the two towers of the spar-buoy structure. Submergence control is achieved through ballasting/de-ballasting of the spar-buoy floats. Power take-off is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the anchor and station-keeping system will depend on the anchor system selected. Transport of the spar-buoy structure, including the power-capture-unit, for deployment is achieved using tug units and ballasting/de-ballasting activities which reorientate the spar buoy onto a horizontal plane to permit ease of towing. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the towers of the spar-buoy unit. The spar-buoy is then ballasted using sea-water to achieve the desired submergence depth of the rotor.

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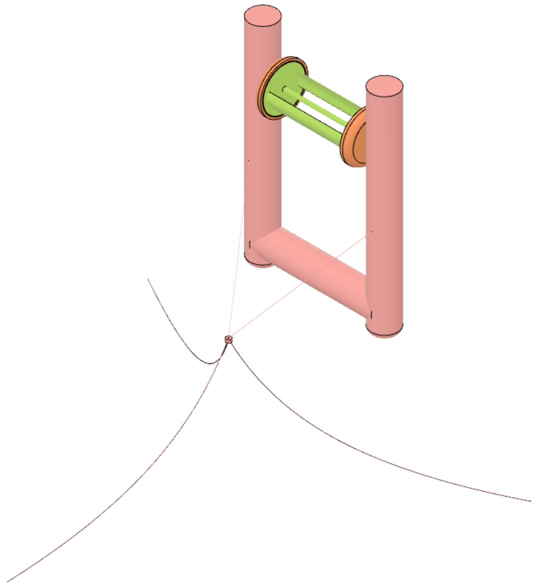

Figure 3–4: LiftWEC Spar configuration (waves are incident from the left-side of the WEC)

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Appendix A BASELINE CONFIGURATION IDENTIFICATION WORKSHOP

A.1 WORKSHOP AGENDA

Dates: 9:00 – 16:00 BST (10:00 – 17:00 CEST) 28 – 29 September 2021

Location: Zoom

https://us06web.zoom.us/j/84267496759?pwd=N3VDcGE2aDY3WEJ3ZlNUTFYyU0FPQT09

Meeting ID: 842 6749 6759 Passcode: 095511

Day/time	Dur.	Content	Resp.
		Day 1	
Session 1 9:00 – 11:00 BST 10:00 – 12:00 CEST	10’ 50’ 60’	Workshop introduction Promising/unpromising configuration presentations Desirable/undesirable differentiating tangible features 5’ per person or WP / 1’ changeover	MF All All
BREAK	**45’**		
Session 2 11:45 – 13:15 BST 12:45 – 14:15 CEST	90’	Key differential design findings by work package 10’ per work package / 5’ changeover	All
BREAK	**45’**		
Session 3 14:00 – 16:00 BST 15:00 – 17:00 CEST	10’ 30’ 80’	Revision of evaluation tools Atargis evaluation example/reference 4 small groups (3 configurations / group) ~20’ per configuration	RP PLK All
		Day 2	
Session 4 9:00 – 11:00 BST 10:00 – 12:00 CEST	10’ 10’ 10’ 90’	Feedback on configuration evaluations Discussion on configuration evaluations Introduction to Baseline configuration tools 4 small groups identification of 2 Baseline configurations	MF MF MF All
BREAK	**45’**		
Session 5 11:45 – 13:45 BST 12:45 – 14:45 CEST	20’ 100’	Feedback from small groups of Baseline Configurations Plenary to define specifications for Baseline Configurations	MF All
BREAK	**45’**		
Session 6 14:30 – 16:00 BST 15:30 – 17:00 CEST	15’ 30’ 45’	Introduction to wave-tank model design Identification of wave-tank testing objectives Identification of wave-tank model specifications	GP All All

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A.2 WORKSHOP PARTICIPANTS

Day 1	Day 2
Matt Folley (QUB)	Matt Folley (QUB)
Paul Lamont-Kane (QUB)	Paul Lamont-Kane (QUB)
Gerrit Olbert (TUHH)	Gerrit Olbert (TUHH)
John Ringwood (MU)	John Ringwood (MU)
Andrei Ermakov (MU)	Andrei Ermakov (MU)
Gregory Payne (ECN)	Gregory Payne (ECN)
Abel Arredondo-Galeana (SU)	Abel Arredondo-Galeana (SU)
Julia Chozas (JCC)	Julia Chozas (JCC)
Kim Nielsen (AAU)	Kim Nielsen (AAU)
Brian Flannery (UCC)	Brian Flannery (UCC)
Pedro Vinagre (WavEC)	Pedro Vinagre (WavEC)
Trevor Whittaker (QUB)	Allan Thomson (Advisory Board)

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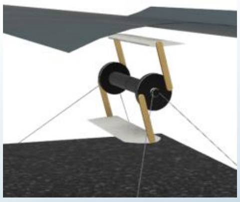
Appendix B PROMISING/UNPROMISING CONFIGURATIONS

LiftWEC **Promising configuration**

04 **LiftWEC proposal configuration** Matt

- Maximisation of power capture through control variables
- No evidence of significantly higher costs

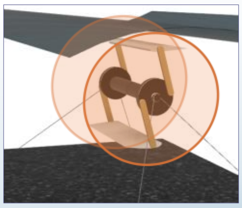


7

LiftWEC **Promising configuration**

04 **LiftWEC proposal configuration** Paul

- Floating configuration – easier & cheaper installation, recovery, O&M
- Include end effectors - reduce induced drag (increase performance)
- Two phase locked hydrofoils provides maximum power capture.
- Flexibility of foundation mechanisms – multi-WEC spine? Submergence control increases performance.
- Also like spar buoy – depending on impact of pitch due to large radial force.

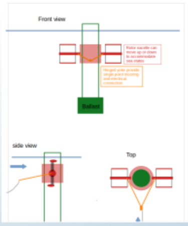


8

LiftWEC **Promising configuration**

08 **Spar buoy with phase free rotor** Abel

- Allows installation in deep water locations
- Possible reduction in installation costs due to less structural material for support structure
- Phase free rotation reduces control complexity
- Ease of towing for installation and maintenance
- Knowledge transfer from floating wind spar buoy array (Hywind Tampen)



9

LiftWEC **Promising configuration**

06 **Reconfigurable WECs (without radius control!)** Andrei

- Phase independent rotor
- Pitch, rotational velocity and submergence control
- the radius control does not increase the rotors performance

10

LiftWEC **Promising configuration**

14 **Phase-free, multi-rotor, multi-foil floating device with control of pitch, speed and sub control** Gerrit

- Design allows for limited span length, which allows to change blade pitch on short-term basis
- Good accessibility and opportunity for quick detachment of device
- Multi-foil allow to smoothen out power peaks
- Ptich and speed control have been shown to increase performance significantly
- Floating device allows submergence control

11

LiftWEC **Promising configuration**

02 **Jack-up CycWEC** Pedro

- Collapsible (reduce O&M requirements/impacts)
- Forecasting waves, prevent leaks of lubricants or hydraulic fluids caused by damage
- Submergence control, reduce damage, positioning according to most frequent/abundant organisms

12

LiftWEC **Promising configuration**

10 **Phase-locked contra-rotating** Kim

- One pile to seabed
- Contrarotation as reaction
- rotors on both side of monopile
- can adjust to incoming wave direction
- could also compensate for tidal range

13

LiftWEC **Promising configuration**

08 **Spar buoy with phase free rotor** Ben

- Having the capacity to store energy, by the ability of the spar angle to vary, is a valuable tool
- The single point mooring in the front will limit possible disruption to other marine activities
- A key O&M advantage is the single point mooring that this configuration contains
- The configuration represents the lowest level of probable environmental or social stresses

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LiftWEC **Promising configuration**

08 Spare buoy with phase free rotor — Greg

- phase lock seems difficult in realistic random waves
- Spare buoy is well establish technology

15

LiftWEC **Promising configuration**

14 Slack moored LiftWEC semisub with multiple rotors — Julia

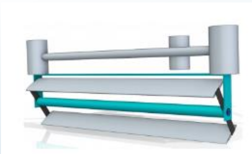
- floating, hence targets a higher number of locations to be installed
- normally less amount of station keeping material, hence, lower costs
- normally, easier to access than submerged structure

16

LiftWEC **Promising configuration**

7, 8, 9, 14 Float out Configs — Brian

- Cheaper Installation Prep needs AH Tugs, conventional vessels
- Standard vessels=better availability & cost
- Cheaper O&M can tow back @ larger Hs limit
- Quick connection & disconnection a la Pelamis
- Config#2 not quite equivalent as ballasting needed (not quick plug & play)

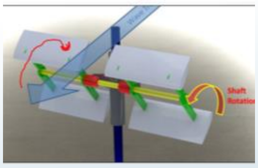


17

LiftWEC **Unpromising configuration**

10 Phase-locked contra-rotating — Matt

- Hydrofoil reaction small relative to fundamental reaction
- Reduced power performance of contra-rotating hydrofoil

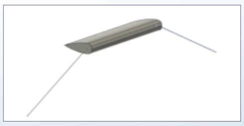


18

LiftWEC **Unpromising configuration**

12 Tethered mono-hydrofoil with wing mounted turbine — Paul

- Implementation of control will be needlessly difficult
- No apparent performance improvement despite additional complexity
- Design and use of tether technology very challenging (Minesto)
- Wave-body relative phase control may be extremely challenging
- Difficulty to provide sufficient buoyancy if control fails -> snag/snatch loads



19

LiftWEC **Unpromising configuration**

06 Adaptable - Reconfigurable WECs — Abel

- Increased likelihood of failure due to more degrees of freedom to actively control
- Increased control complexity

20

LiftWEC **Unpromising configuration**

09 Parabolic flap rotor — Gerrit

- Variation of inflow angle over span with no/limited pitch control option -> lift forces cancel out
- Radius required for torque -> either strong curvature (low eff) or large span (no control) needed

21

LiftWEC **Unpromising configuration**

07 Twin moored buoyant structure — Kim

- Minesto PTO not suited i think
- To slow relative speed to drive Minesto PTO
- drawing missing
- Moored system
- too large footprint

22

LiftWEC **Unpromising configuration**

10 Phase-locked contra-rotating — Ben

- It may have a greater environmental impact that other configurations
- Being mounted to the seabed can negatively impact the environment and other activities
- Installation, maintenance and decommissioning may require greater economic resources
- Size and speed of the rotors may pose a threat to wildlife

23

LiftWEC **Unpromising configuration**

12 Tethered mono-hydrofoil with wing mounted turbine — Julia

- big challenge that tether (which provides tension) is also mooring line & electrical cable
- tether is also a challenge for Minesto. to be fully developed
- seems very complicated to control in irregular (real) sea

24

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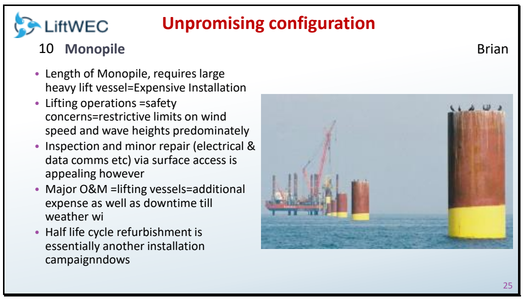
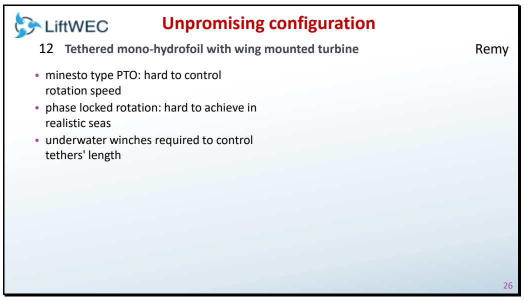

LiftWEC
Unpromising configuration
10 Monopile
Brian
Length of Monopile, requires large heavy lift vessel=Expensive Installation
Lifting operations =safety concerns=restrictive limits on wind speed and wave heights predominately
Inspection and minor repair (electrical & data comms etc) via surface access is appealing however
Major O&M =lifting vessels=additional expense as well as downtime till weather wi
Half life cycle refurbishment is essentially another installation campaignndows
25


LiftWEC
Unpromising configuration
12 Tethered mono-hydrofoil with wing mounted turbine
Remy
minesto type PTO: hard to control rotation speed
phase locked rotation: hard to achieve in realistic seas
underwater winches required to control tethers' length
26

Appendix C DESIRABLE DIFFERENTIATING TANGIBLE FEATURES

Desirable feature

Moorings — Matt

The structure should be moored, rather than connected to the seabed through a structure, whilst using buoyancy and lift control to ensure the moorings remain in tension

- Moorings simplify installation/retrieval
- Moorings are low cost relative to a rigid structure

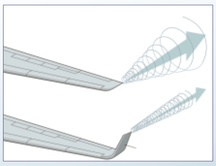
28

Desirable feature

End effectors & fins to reduce induced drag — Paul

Induced drag can significantly reduce potential power capture. Reduce induced drag by reducing tip vortices and spanwise flow.

- End effectors reduce formation of tip vortices
- End effectors may be discs, winglets or even holes (?)
- Mid foil fins reduce spanwise flow



29

Desirable feature

Variable submergence control — Paul

The effect of submergence depth can have a very significant impact on power capture (2-3m result in 33% increase in power).

- Keep device as close to surface as possible
- Use ~90 degree phase to minimise breaches
- Beware of surface proximity loss of lift

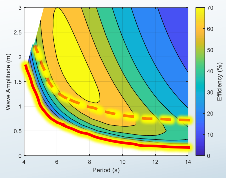
30

Desirable feature

Variable radius to reduce 'cut-in' condition — Paul

In small seas the extreme drag dominance means the device does not function at all. Radius reduction seems to alleviate issue.

- Reduced radius can reduce drag & radiation
- Allows device to operate in smaller seas
- NOTE – significance may be reduced - induced drag



31

Desirable feature

Pitch and rotational velocity control (phase free) — Andrei

- Simulations have shown the significant increase of power

32

Desirable feature

Compliance — Abel

Structure should have some degree of movement through elastic mooring lines, yaw should be restrained.

- Versatility to operate in different water depths
- Possible reduction in support structure installation and maintenance costs

33

Desirable feature

Multi-bladed rotor — Abel

Rotor equipped with more than two blades

- Can help coping with cyclic loading and reduce structural fatigue
- Redundancy

34

Desirable feature

Doubly supported foils — Abel

Hydrofoils supported at both ends rather than supported in the middle

- Reduction in bending moments, assuming uniform loading (large spans >= 30 m).

35

Desirable feature

Pitch control — Gerrit

The pitch of the foils relative to the motion path is adjustable by either applying a moment at the pivot point or by applying a force close to the trailing edge

- High impact on rotor performance whether done on wave-wave basis or on sea state basis
- May be used to start rotor by using foils as drag bodies
- Experience in pitch control of foils available from tidal, wind, VSP etc
- Expected variations of pitch moment allow to reduce required actuator force

36

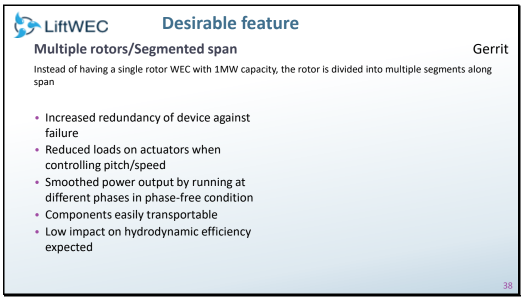
Desirable feature

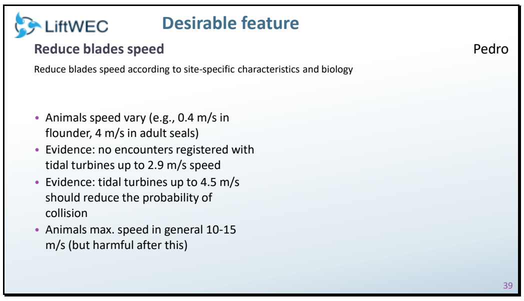
Submergence control — Gerrit

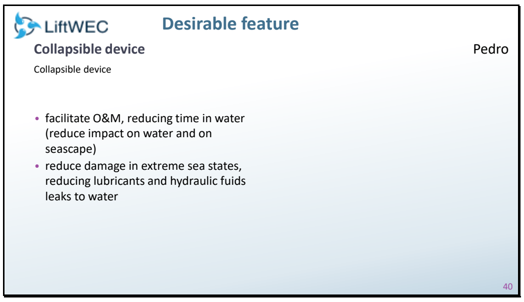
The submergence of the device can be changed

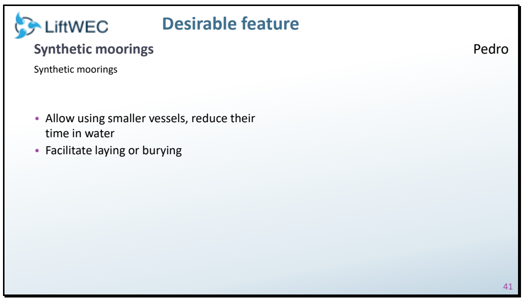
- Direct impact on cut-in wave height
- Operation in storms possible without increased loads

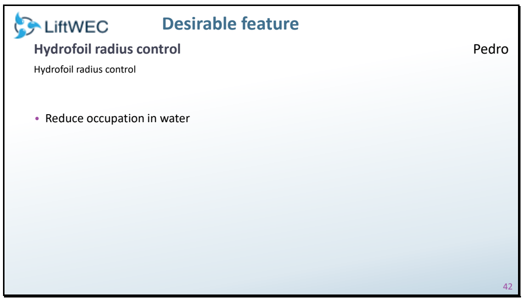
37

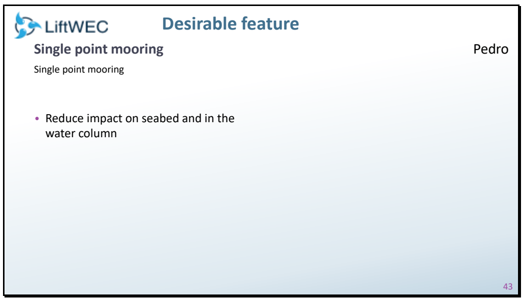


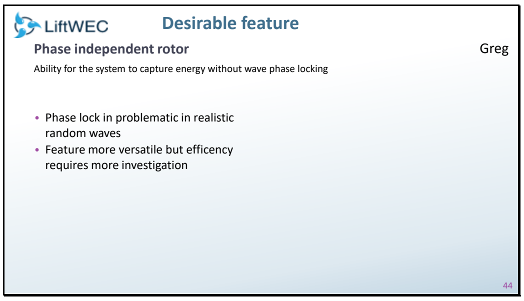


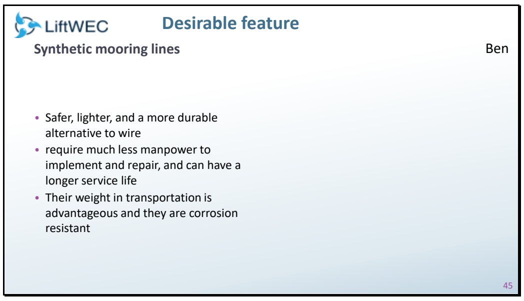


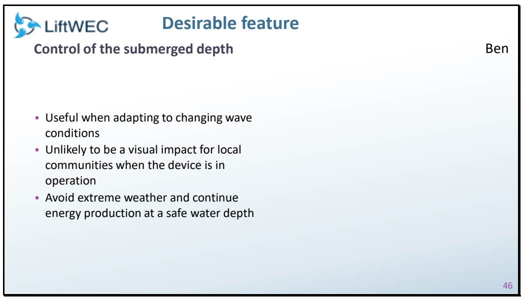


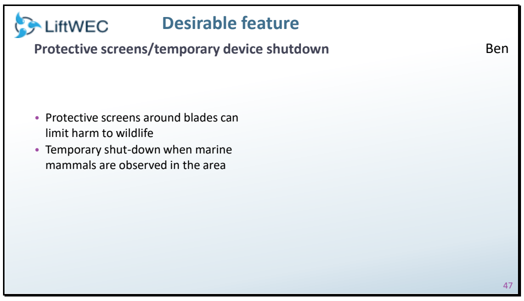












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LiftWEC **Desirable feature**

structure made in concrete Julia

- steel price is very high compared to concrete
- It is the trend in the wave energy sector

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LiftWEC **Desirable feature**

can be installed in all water depths Julia

water depth >= 30 m

- avoid shallow waters; hence limited locations
- avoid pb that offshore wind is having now - competitive advantage

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LiftWEC **Desirable feature**

Tow out Installation & O&M Brian

The ability to tow the device for installation using conventional vessels: quick release and reconnect for O&M

- Conventional vessels much cheaper than heavy lift
- Better availability, not entering the busy Summer chartering market
- Ability to operate in larger Hs conditions
- Quick (dis)connection for cheaper onshore maintenance
- Less fuel consumption

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LiftWEC **Desirable feature**

phase free rotor Remy

the rotor control is not focused on being phase locked

- Phase locking is ill defined in realistic seas, which will make it hard to achieve
- Phase locking will impose 2 foils at max on rotor
- phase free rotor are less constrained in term of dimensions

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LiftWEC **Desirable feature**

Control of the submergence of the rotor Remy

The concept allows the control of the submergence of the rotor for different sea states

- it allows to operate the rotor as close as possible to the water surface
- it can decrease exposure for survival
- it can control exposure, therefore ease PTO dimensioning

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LiftWEC **Desirable feature**

pitch control Kim

Feature to adjust the blade angle relative to the incoming flow of water

- This feature can help maximize the lift and thrust force on the blade in normal sea states
- This feature can help minimize the lift and thrust force on the blade i.e. under extreme waves
- This feature is useful as the waves are irregular
- This feature is useful to reach a defined power curve / matrix

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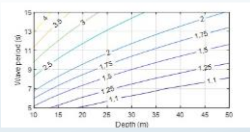
Appendix D DESIGN FINDINGS

LiftWEC Design finding

Optimal water depth for finite span hydrofoil WP2

A circular optimal path can be achieved by balancing the ellipicity of the wave particles with the ellipicity of the radiation damping

- More power is available coupling with surge than heave water velocities
- More power requires greater velocity for same force
- Water particle velocities are elliptical in shallow water
- Force is greater in surge than heave direction



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LiftWEC Design finding

Fundamental resource source options WP2

Gravity, pile, drag anchor and micropiles have been reviewed as reaction sources. Only micropiles appear attractive

- Gravity is too expensive with high CO2 content
- Pile is not possible from jack-up as limited operating conditions
- Drag anchors can move leading to progressive failure
- Micropiles are cheap, can be installed w/o jack-up and fixed

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LiftWEC Design finding

Phase diversity from multiple rotors WP2

Multiple rotos can provide reaction through phase diversity, but bending moments in structure similar to those to seabed

- Phase diversity allows a slack mooring to be used
- Rotors need to be separated by half wavelength
- High bending moments between rotors

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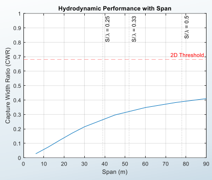
LiftWEC Design finding

Induced drag dominance for finite span hydrofoil WP2

"Induced drag" due to downwash (tip vortices) significantly reduces hydrodynamic performance of finite span (3D) hydrofoil. 3D not simple expansion of 2D.

- Induced drag reduces performance by 50%-85% for reasonable spans
- Induced drag coefficient 300%-5000% larger than section drag
- Caused by downwash behind hydrofoil resulting from tip vortices
- Existence of induced drag alters the fundamental hydrodynamics
- Use of end effectors may reduce influence of induced drag



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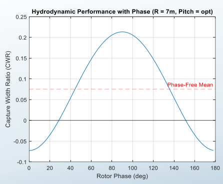
LiftWEC Design finding

Improved hydrodynamic performance with phase locking WP2

Use of phase locking significantly increases achievable power capture (x2/x3). Atargis suggest irregular 'phase-locking' achievable. Need upstream wave measurement.

- Phase-free power capture typically reduced by 60-70+%
- Significantly less fatigue loading
- Much simpler & slower pitch control than phase-free
- No more difficulty in estimating control required
- Appears achievable based on work of Atargis (>80% accuracy)



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LiftWEC Design finding

Phase-lock in irregular waves not possible WP3

The properties of "phase-locked" operation like low fluctuation of AoA cannot be maintained in irregular waves by matching rotor rate to a specific wave frequency

- Large number of simulations of two-foil rotor in JONSWAP sea states with random seeding
- Strong fluctuation of wave induced velocity vector, due to superposition
- Normal distribution of angle of attack on both sides
- Leads to constant change of pressure and suction side, unless fast pitch control (still likely)

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LiftWEC Design finding

Performance = f(Rotor Vel/Wave Ind Vel) in basic control WP3

When only slow-control actuators are assumed, the power capture of a cyclorotor is a direction function of the velocity ratio since it determines AoA-range

- AoA in irregular seas is distributed normally with mean at 0°
- Magnitude mainly determined by wave height
- Standard deviation is determined by velocity ratio
- only limited range of angles provides power -> std determines efficiency

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LiftWEC Design finding

Wave termination does not mean 100% conversion efficiency WP3

Contrary to early suggestions, radiation of 180° shifted wave (same height&period) often leads to low energy conversion due to increased drag

- Extension of original design goal by at least one boundary condition required
- Still relevant when considering up- and downwave wave radiation
- Applicability/Relevance in irregular wave conditions not yet fully understood

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LiftWEC Design finding

Foil behaviour different to straight flight WP3

The lift/drag-ratio of symmetric profils projected to curved path is much lower than their straight equivalents

- Lift is generated at zero pitch and no wave induced velocity
- Stall occurs much earlier than for symmetric profiles in straight flight
- Relative inflow angle varies over foil -> pressure distribution different
- Zero-ptich moment position likely to be different (not at 0.25c)
- New set of foils optimized for this application might be recommendable

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LiftWEC Design finding

Vortex structures possibly of minor importance WP3

Vortex structures due to flow separation or reattachment seem to dissipate rather quickly in foil wake in experiment

- Low impact of highly transient&local vortices on next foil passage
- Good reliability of "simple" models which neglect this influence
- 3D effects (tip vortices) are not yet considered in this finding

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LiftWEC **Design finding**

Radius control does not increase the generated power WP5

Our preliminary study has shown that the radius control does not increase the rotors performance and we must select the maximum possible constant value of the rotors radius.

- Constant value of the rotors radius

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LiftWEC **Design finding**

Phase free rotation (Variable rotational velocity) WP5

It has been shown analytically that the variable rotational rate can significantly increase rotors performace

- PTO or Velocity control

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LiftWEC **Design finding**

Sizing of rotor WP6

Radius to span ratio should optimise power extraction and keep hydrofoil bending stresses bellow allowable treshold

- Radius to span ratio of 0.8 was found to be optimum for regular wave test case (EWTEC paper)
- There is an optimum radius for which power extraction is maximised in regular waves
- Increasing the span will increase the maximum bending moments in hydrofoils

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LiftWEC **Design finding**

Design is dictated by operational loads WP6

Non-operational loads are generally lower than operational loads but still need to be carefully assessed

- Stresses are low for typical rotor when towed with axis of hydrofoil allowed to towing direction
- Drag increases with squared of velocity
- Stresses due to towing are still acceptable with Hs = 4 m
- Transport and lifting loads do not produce excessive stresses
- Rotor should be lifted with hydrofoils aligned vertically

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LiftWEC **Design finding**

Power enhancement through single-foil heaving compliance WP6

Single foil heaving compliance enhances power extraction of rotor

- Passive heaving of one foil in a two-foil configuration enhances power extraction
- Passive control could be used as an alternative to active control

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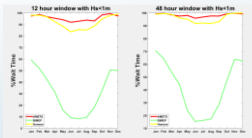
LiftWEC **Design finding**

Weather window restrictions (lifting & surface access) WP7

The HOMERE site has limited availability of weather windows of Hs=1m. Threshold is relevant for ops where safety is a concern: mainly lifting large device & allowing crew transfer

- Configs needing cranes for O&M=undesirable
- Lifting & Access restricted to Summer months
- Fixed platforms (access @1.5m) slightly better than floating
- Tow out configs preferable with quick (dis)connection



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LiftWEC **Design finding**

Cost of energy WP8

Cost effective LCOE should Target 4000EUR/kW in CAPEX and 210 EUR/kW/year in OPEX

- Cost centers to CAPEX; WEC Structure & Primer Mover (33%), PTO (15%) and station keeping (15%)
- Foundation and mooring design are dependent on the design conditions and concept principle
- Material has a high impact in CAPEX - offshore steel, 3400 EUR/ton - concrete,250 EUR/ton
- Cost of : Monopile, 724 ton/ 2.5 MEUR - v-frame, 500ton/1.7 MEUR - floating, 276 ton/0.95 MEUR
- The unit cost of the PTO varies from 800 EUR/kW - 1400 EUR/kW the unit cost should be revisited

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Appendix E POTENTIAL CONFIGURATION SPECIFICATION SHEETS

Baseline configuration specifications

Team		Blue	
Name of configuration		Single rotor semi-sub	
Description of configuration		A single rotor is supported between two semi-sub floats with a small surface-piercing area. The rotor will have a fixed radius of about 6 metres and a span of 30 metres. The typical depth of submergence would be kept as close and possible to the surface for operation and the depth modified by changing the ballast in the semi-sub. The offset of the third floating will be used to provide additional stability and reaction - an initial estimate of the offset of the float is 20 metres. The moorings are not intended to provide any reaction, and the device should be compliant to minimise anchoring loads. Multiple mooring lines are used to provide redundancy.	
Specifications			**Notes**
Hydrodynamics	Number of hydrofoils	2	
	Phase	Phase-optimal	
	Axis movement	Other	Minimal, but some from movement of semi-sub
Control	Pitch	Fast	
	Radius	Other	No radius control
	Moment of inertia	Other	None
	Generator speed	Slow	
	Generator torque	Fast	
	Depth of submergence	Slow	Through balasting of the semi-sub
Structural	Hydrofoil reaction	Buoyancy	Torque applied to offset float
	Fundamental reaction	Inertia	and some buoyancy (possibly)
	Support structure	Other	Semi-sub support using three bodies, using reinforced concrete, catenary lines
	Hydrofoil support	Beam	Supported by two side floats
	Anchor	Drag anchor	One or more for redundancy
O&M	Transport	Tow	Main tug plus stabilitising aft tug
	Installation	Vessel(s)	Connection to in-situ mooring lines
	Maintenance	Primarily RTB	Except for simple replacements

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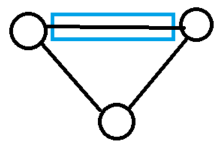

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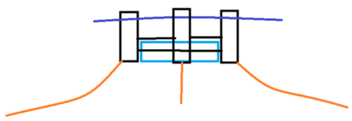

Baseline configuration specifications

Team		Blue	
Name of configuration		Double spar buoy configuration	
Description of configuration		A rotor will be held beween two spars, with two additional rotors cantilevered from the sides of each spar. The centre rotor will have a radius of about 6 metres and a span of 30 metres. The side rotors will have a similar radius and a span of 15 metres	
Specifications			**Notes**
Hydrodynamics	Number of hydrofoils	2	
	Phase	Phase-optimal	
	Axis movement	Other	Minimal, but some from movement of spar
Control	Pitch	Fast	
	Radius	Other	No radius control
	Moment of inertia	Other	None
	Generator speed	Slow	
	Generator torque	Fast	
	Depth of submergence	Slow	Through balasting of the spar? Need of a system that does not create big variations in moori
Structural	Hydrofoil reaction	Weight	
	Fundamental reaction	Inertia	
	Support structure	Other	Twin spar
	Hydrofoil support	Other	Cantilever for the side rotors and beam for the central rotor
	Anchor	Drag anchor	One or more for redundancy
O&M	Transport	Tow	Main tug plus stabilitising aft tug
	Installation	Vessel(s)	
	Maintenance	Primarily RTB	Time consuming to switch from vertical to horizontal

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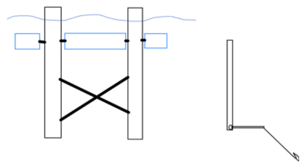

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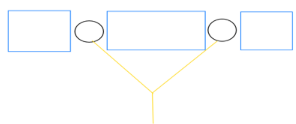

Baseline configuration specifications

Team		Green	
Name of configuration		Monopile with self jackup and float over installation facility	
Description of configuration		Support structure connects to foundation via transition piece (like in offshore wind?) with single point of connection. Foundation is a permanent, subsea self jack up monopile which allows for ease of installation and also allows submergence control. Installation via tug vessels which locate device on pre-existing jackup pile. May require some additional ssets to assist with installation and location of transition piece on pile but plan is to avoid requirement for heavy lift vessel.	
Specifications			**Notes**
Hydrodynamics	Number of hydrofoils		2 - composite material production. Chord length 6-7m. Fins for minimiseing spanwise flow.
	Phase	Phase-optimal	This has littel bearing on the rest of the configuration. Chose an alternative if you wish.
	Axis movement	Fixed	
Control	Pitch	Fast	
	Radius	Other	Fixed - hope to achieve smaller seas through depth of submergence. 6-7m radius.
	Moment of inertia		None
	Generator speed	Fast	
	Generator torque	Fast	
	Depth of submergence	Slow	Variable through transition piece - allows for
Structural	Hydrofoil reaction	Seabed	Monopile provides. Hydrofoil ~30-35m span. 6m chord,
	Fundamental reaction	Seabed	30m-50m depth assumed, Monopile provides
	Support structure	Monopile	Additonal structure to support generators, end effectors and foils. Support structure likely made of steel. Monopile is steel, expect roughly 5m (?) diameter, maybe 20-25m (?) depth of pile beneath seabed.
	Hydrofoil support	Beam	Supported by disc shaped ends which contain direct drive generators and act as end effectors to reduce induced drag.
	Anchor	Pile	Permanent pile with jack up facility to raise pile towards surface for ease of installation.
O&M	Transport	Tow	Standard tug
	Installation	Other	Float over. Self installation via transition piece on to extended jack up pile which is then submerged. Similar to Aquamarine pile attachement with additonal jackup facility (ref. Trevor).
	Maintenance	Primarily RTB	Is this return to base? We will return to base and in farm config have 2/3 spare units for a 100 unit farm to replace during maintenance.

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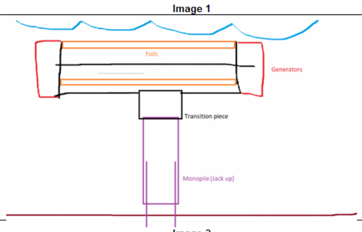

Image 2

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Baseline configuration specifications

Team		Red	
Name of configuration		(based on 14) Single-rotor semisub.	
Description of configuration		Structure modified from proposal 14 to lower complexity and fit to purpose. 3 Vertical semisub towers at each end point of the triangle. Rotor at the back, with hydrofoils supported at both ends. Allows weather vane.	
Specifications			**Notes**
Hydrodynamics	**Number of hydrofoils**	2	3 blades (or more) could be investigated
	Phase	Other	Perhaps phase modulated
	Axis movement	Moving	
Control	**Pitch**	Fast	wave by wave
	Radius	Slow	sea state basis. Changing the radious to have control on the mean hydrofoil velocity whtough
	Moment of inertia	Other	nice to have, if possible
	Generator speed	Slow	on sea state basis, to achieve as close to a fixed rotational velocity as necessary
	Generator torque	Fast	to keep the generator speed close to constant
	Depth of submergence	Other	not practical
Structural	**Hydrofoil reaction**	Buoyancy	hydrostatic stiffness of the device
	Fundamental reaction	Other	buoyancy
	Support structure	Mooring lines	single point mooring to front (free) column and rotor on the back. Allows weather vaning.
	Hydrofoil support	Beam	material to be defined based on ecomonics
	Anchor	Other	depends on location, but single point mooring so it can weather vane
O&M	**Transport**	Tow	
	Installation	Vessel(s)	
	Maintenance	Primarily RTB	ROV if possible (minor interventions & inspection), otherwise going back to base. avoid diver

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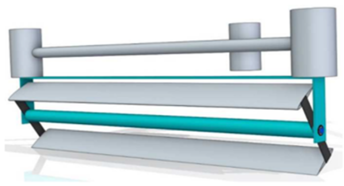

Image 2

Baseline configuration specifications

Team		Red	
Name of configuration		Spar-buoy (based on number 8 with modifications in rotor location)	
Description of configuration		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) but the initial proposal is having 2 foils. As the spar is hollow, the rotor will be located at the centre of the spar. 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. Rack& pinion system for example can be used to activate vertical movement. The rotors submergence could also be	
Specifications			**Notes**
Hydrodynamics	**Number of hydrofoils**	2	
	Phase	Other	perhaps phase modulated
	Axis movement	Moving	
Control	**Pitch**	Fast	wave by wave
	Radius	Slow	sea state basis. Changing the radious to have control on the mean hydrofoil velocity whtough
	Moment of inertia	Other	nice to have, if possible
	Generator speed	Slow	on sea state basis, to achieve as close to a fixed rotational velocity as necessary
	Generator torque	Fast	to keep the generator speed close to constant
	Depth of submergence	Slow	sea state per sea state basis
Structural	**Hydrofoil reaction**	Weight	the spar is providing it
	Fundamental reaction	Inertia	
	Support structure	Other	parallel truss with buoyancy apex with ballast at the bottom
	Hydrofoil support	Beam	
	Anchor	Other	single point mooring connected to either ballast or the truss (can be investigated). Will allow
O&M	**Transport**	Tow	
	Installation	Vessel(s)	
	Maintenance	Primarily RTB	ROV if possible (minor interventions & inspection), otherwise going back to base. avoid diver

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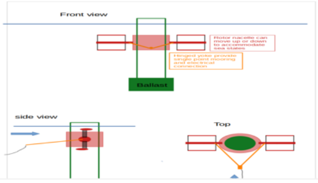

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Appendix F CB01 LiftWEC Tower Basis of Design

F.1 Outline Description

The LiftWEC Tower configuration consists of a two-hydrofoil rotor set atop a previously installed jack-up strut via a self-aligning transition piece. The jack-up strut is mounted atop a monopile foundation. The rigid foundation and support structure provide a fixed axis of rotation for the rotor. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator and pitch control mechanisms. The combined rotor/stator unit is referred to as the power-capture-unit and is affixed to the jack-up strut via a transition piece that permits ease of device deployment/recovery as well as yaw control. The jack-up strut is used both during deployment/recovery activities and to provide submergence control of the rotor. Power take off is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the monopile occurs through the use of a jack-up platform and installation of the jack-up strut is achieved using a heavy lift vessel. Transport of the rotor/stator section is achieved through the attachment of temporary buoyancy tanks and the use of tug units. At the point of deployment, the transition piece self-aligns atop the extended jack-up strut, requiring de-ballasting of only a few metres worth of draft to permit rigid attachment of the power-capture-unit to the jack-up strut, after which temporary buoyancy tanks can be removed and the device submerged.

F.2 Rotor Design & Operation

F.2.1 Brief description of rotor section

The rotor section of the device consists of two curved hydrofoil elements, capped by circular endplates and orbiting a rigid cylindrical strut. The rotor component of the radial direct drive generators is set behind the endplates and the entire rotor section is located within the bearing structure of the radial direct drive generator (i.e. the radial direct drive generator also acts as the bearing mechanism).

F.2.2 Rotor/hydrofoil operating principles

The rotor operating condition is defined as ‘Phase Optimal’, meaning that real time control should be used to maximise the hydrodynamic performance of the device.

F.2.3 Axis of rotation compliance (should this be in stator section?)

The axis of rotation is fixed per the rigid foundation and support structure arrangement. There should be no significant compliance of the axis of rotation under wave, current or other environmental loading experienced by the structure.

F.2.4 Number & layout of hydrofoils

The rotor incorporates two opposing hydrofoils, set 180° apart.

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F.2.5 Hydrofoil primary dimensions

Span: 30m. Chord length: 6-7m. Operational radius: 6m.

F.2.6 Hydrofoil cross-section properties

The hydrofoil cross-section has not yet been specified. Where appropriate, assume a NACA 0012 profile.

F.2.7 Hydrofoil materials and manufacturing

Hydrofoils will be of composite construction, similar to wind turbine blades.

F.2.8 Linear speed of hydrofoils

- Linear speed in 4s waves: 9.4m/s (expected maximum speed – very rare occurrence)
- Linear speed in 10s waves: 3.8m/s (expected typical mean speed)
- Linear speed in 15s waves: 2.5m/s (expected minimum speed – rare occurrence)

F.2.9 Other hydrofoil design considerations

None.

F.2.10 Description of hydrofoil support/mounting structure

Hydrofoils are rigidly mounted via two solid/perforated endplates. The radius of the end plates should be approximately 1-2m greater than the distance from the axis of rotation to the outermost point of the hydrofoil at the point of greatest radial extension due to pitch. The primary function of these end plates is to stop the flow of water around the ends of the hydrofoil, which would result in the formation of tip vortices and induced drag. Hence, it is important that perforation of the endplates for the purposes of inertial considerations does not significantly increase the formation of tip vortices. A balance of these issues will be required. Where possible, perforation in the end plates should be countered through the use of endplate proximity of the stator structural section, thus still eliminating the potential for the formation of tip vortices.

Pitch control of the hydrofoils is achieved via rotation of a local, circular section of the endplate at the point of hydrofoil attachment. Mounting of these local sections on bearing mechanisms and activation by hydraulic actuators set behind the endplates permits absolute termination of the hydrofoil span ends on the endplate structures without concerns for pressure leakage. If this arrangement is not feasible for structural reasons, it is possible a through-plate rotary bearing with solid shafts extending from the hydrofoil ends could be used instead.

The entire rotor structure is stiffened by the positioning of a 1.5m diameter cylindrical section mounted between the two endplates at the axis of rotation.

F.2.11 Hydrofoil support/mounting structure materials and manufacturing

The rotor endplates and cylindrical strut are of steel construction.

F.2.12 Additional rotor components

Hydraulic pitch control mechanisms are positioned on the rear face of the endplate sections.

F.2.13 Attachment to generator element

The rotor sections of the radial direct drive generators are attached to the rear face of the rotor endplates.

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F.2.14 Attachment to the bearing mechanism

The rotor is permitted rotational motion by means of the bearing mechanism inherent within the radial direct drive generators.

F.2.15 Rotor torque reaction source (aka hydrofoil reaction source)

The torque generated by the rotor, which is resisted by the direct drive generators, is ultimately reacted at the seabed through the monopile foundation. A rigid structural path is therefore required from the generator units to the seabed via the generator housing/nacelle, the power-capture-unit support structure, transition piece, jack-up strut and monopile.

F.2.16 Fundamental reaction source

The oscillatory loads generated by the rotor are ultimately reacted at the seabed through the monopile foundation. A rigid structural path is therefore required from the bearing elements to the seabed, via the generator housing/nacelle, the power-capture-unit support structure, transition piece, jack-up strut and monopile.

F.2.17 Other rotor design considerations

None.

F.3 Control Design & Operation

F.3.1 Hydrofoil pitch control: function, design & implementation

Pitch control is on a wave-by-wave basis (fast pitch control). Pitch control of each hydrofoil is achieved through linear hydraulic actuators set behind the endplate and attached to the locally rotating point of hydrofoil attachment.

F.3.2 Rotor/Hydrofoil phase control: function, design & implementation

Real time rotor phase control (fast rotor phase control) is achieved through torque control applied via the two direct drive generators.

F.3.3 Moment of inertia control: function, design & implementation

None.

F.3.4 Hydrofoil radius control: function, design & implementation

None.

F.3.5 Rotor submergence control: function, design & implementation

Control of the rotor submergence depth is achieved on a sea-by-sea basis (slow submergence control) via the jack-up strut.

F.3.6 Yaw control: function, design & implementation

Yaw control is applied on a sea-by-sea basis (slow yaw control) via hydraulic actuation of a turntable element contained within the transition piece of the stator structural section.

F.3.7 Additional control systems

None.

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F.3.8 Other control considerations

Control system implementation will require upstream wave measurement.

F.4 Stator/Support Structure Design & Operation

F.4.1 Brief description of stator section

The stator section of this configuration includes the power-capture-unit support structure, the transition piece and the two nacelle units places at either end of the rotor section. These nacelle units hold the radial direct driver generator stators, ancillary power electronics and braking mechanisms. The transition piece incorporates a hydraulically actuated turntable to permit yaw control of the device.

F.4.2 Hydrodynamic motion/compliance of stator section

The entire stator section is fixed per the rigid foundation and jack-up strut system. There is no significant compliance of the stator section under wave, current or other environmental loading. This ensures the fixed axis of rotation for the rotor element of the configuration.

F.4.3 Stator section components & functionality

The radial direct drive generator stator sections provide the mounting and bearing facilities for the rotor of the device. Power take-off and phase (torque) control of the rotor is achieved through the two direct drive generators. The direct drive generators act as the bearing mechanisms which permit free rotation of the rotor section. Braking mechanisms are affixed to the direct drive generator stator.

The direct drive generators are set within the generator housing units/nacelles, which shelter the generators and other ancillary power electronics from the marine environment. These housings have attachment points for the temporary buoyancy tubes/tanks which are used during transport of the power-capture-unit.

The power-capture-unit support structure rigidly connects the two nacelle units, and provides attachment to the jack-up strut via the transition piece. The transition piece serves two primary functions; (1) self-alignment and ease of attachment via quick connect/disconnect during deployment and recovery operations, and (2) yaw control of the device by means of a hydraulically actuated turntable set at the top of the transition piece.

F.4.4 Stator section structural design, materials & manufacturing

The nacelle units each incorporate a generator housing formed of structural steel.

The power-capture-unit support structure is of trusswork structural steel construction.

The transition piece will be of cast-iron construction with a hydraulically actuated turntable and locating facilities/mechanisms.

F.4.5 Other stator section details/considerations

None.

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F.5 Power Train Design & Operation

F.5.1 Brief description of power train

Hydrodynamic power is captured by the rotor section and converted into unidirectional rotary motion (kinetic energy). This kinetic energy is converted directly into electrical energy by the radial direct drive generators set at either end of the rotor section.

F.5.2 Hydrodynamic rotor performance

Approx. 30% hydrodynamic efficiency (Capture Width Ratio) at the design point with 2m wave amplitude and 10s wave period.

F.5.3 Power train conversion efficiency

Direct drive generator efficiency assumed at 90%.

F.5.4 Generator type, size & rating

Two radial direct drive generators, each approx. 10-12m diameter, each with 750 kW rating. These could be replaced by a single, 1.5MW generator if preferable due to structural, cost and reliability considerations.

F.5.5 Energy storage mechanisms

None.

F.5.6 Power smoothing mechanisms

None.

F.5.7 Other relevant power train components & functionality

The direct drive generators are additionally used to provide phase control of the rotor.

F.6 Station-Keeping System Design & Operation

F.6.1 Brief description of station-keeping system

The station-keeping facility is provided by the jack-up strut component of the configuration.

F.6.2 Station-keeping system components & functionality

The jack-up strut is affixed to the top of the monopile foundation in a semi-permanent fashion. The jack-up strut is formed from two concentric cylindrical steel sections that house a series of rollers and hydraulic mechanisms. These mechanisms enable the strut to be jacked up and down, increasing or decreasing its apparent length respectively.

In terms of station-keeping, the jack-up strut is used to ensure adequate depth of submergence is maintained during operation. Jack-up operations will be in 1m increments, with a deadlock style holding system employed to maintain position between jack-up operations (similar to Seagen). Thus, the jack-up hydraulic mechanisms will not be used to hold the required position during operation or between jack-up activities.

The jack-up strut is capped with a cast-iron top-plate with locating elements for ease of positioning of the transition piece during deployment operations.

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F.6.3 Station-keeping system sizing, materials & manufacturing

The nominal diameter of the jack-up strut is 5m. At full extension, the jack-up strut has a nominal length of 27m. At full retraction, the jack-up strut has a nominal length of 17m. Thus the strut has a 10m permissible extension length.

The jack-up strut will be manufactured using 5m and 4.6m diameter circular steel hollow sections. The jack-up strut will incorporate a variety of locating, roller, guiding and hydraulic components to facilitate the jack-up operations. In addition, an internal deadlock system will lock the strut in place when the desired extension is reached. Lock points will be available every 1m extension.

F.6.4 Other station-keeping system details/considerations

None.

F.7 Anchor/Foundation/Grounding Design & Operation

F.7.1 Brief description of anchor system

The anchoring system is a single 5m diameter steel monopile with a cast iron top plate structure set atop the protruding length.

F.7.2 Anchor system components & functionality

A single monopile which provides grounding for all rotor torque and fundamental reaction forces.

F.7.3 Anchor system sizing, materials & manufacturing

The monopile is 5m diameter and approximately 28m in length, with 3-4m protrusion above the seabed. The monopile is made of steel. The monopile is capped by a cast iron top plate that permits semi-permanent attachment of the lower portion of the jack-up strut.

F.7.4 Other anchor system details/considerations

None.

F.8 Operations & Maintenance

F.8.1 Brief description of installation procedure & asset requirements

Note that installation refers to the placement and commissioning of the anchor and station-keeping systems. Placement of the power-capture-unit (i.e., the combined rotor/stator section) is referred to as '*Deployment*' and is described in a subsequent section.

Initially, a jack-up barge is used to install the 5m diameter monopile foundation and pile cap. Subsequently, a heavy lift vessel and ROVs are used to mount the jack-up strut atop the monopile foundation. The lower portion of the transition piece should already be set in place atop the jack-up strut at this time.

F.8.2 Brief description of power-capture-unit deployment procedure & asset requirements

The power-capture-unit (combined rotor/stator section) is towed to site using a conventional tug unit. Temporary buoyancy tanks/bags are used to provide sufficient uplift to ensure the device remains afloat during transport. At the point of deployment, the jack-up strut should be extended such that the top of the jack-up strut sits approximately 4m beneath the transition piece which is

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attached to the lower side of the power-capture-unit support structure. The self-aligning properties of the transition piece should be employed to permit ease of location. Deflation of the buoyancy tanks should permit lowering of the power-capture-unit onto the jack-up strut at which point the semi-permanent connection can be made. At this time, it is expected that approximately 4-6m of the power-capture-unit will remain surface piercing. Further deflation/ballasting of the buoyancy tanks until the point of their neutral buoyancy will permit their safe removal from the device. Finally, the jack-up strut is then used to submerge the power-capture-unit to the desired submergence depth. Deployment should be achievable within a 2 hour window (measured from arrival at deployment location) using 2 tug units, 2 shallow depth ROV units and standby divers in case of requirement.

F.8.3 Brief description of power-capture-unit recovery procedure & asset requirements

Recovery procedure for the power-capture-unit is as the reverse of the deployment procedure using the same procedures and assets.

F.8.4 Brief description of decommissioning procedure & asset requirements

Decommissioning of the system refers to the removal of the jack-up strut and the monopile foundation. Removal of the power-capture-unit is encompassed by the '*Recovery*' operations outlined in a previous section.

Removal of the jack-up strut will be through the use of ROVs and a heavy lift vessel. The monopile and pile cap may be left in place for re-use. Alternatively, the pile cap will be removed along with the jack-up strut and the pile will be cut off at the seabed and the top portion removed. The driven/drilled portion of the pile will remain in place due to the seabed disruption required to remove it.

F.8.5 Outline of maintenance strategy

Device maintenance will be primarily on a return-to-base (RTB) strategy for all but the simplest procedures. Tug boats will be used to recover individual power-capture-units as required according to the deployment/recovery procedures described above. In a station of 100 units, it is envisaged that 2-3 'spare' units would be kept in base for replacement of units brought in for maintenance, thus alleviating time pressures on O&M activities and reducing concerns over weather window availability. This is naturally dependent on the expected cost of energy implications.

F.8.6 Relevant farm-scale considerations

Deployment of a 100-unit farm would see placement of devices at approximately a 3x device span centre-to-centre spacing. For example, assuming a total device span of 42m (30m hydrofoil span + 6m nacelle length) would see a centre-to-centre device placement length of 126m, yielding a free spacing of 84m between devices. If asset sizing and operational area requirements permitted, this could be reduced to a 2 - 2.5x centre-to-centre spacing from a hydrodynamic perspective.

F.9 CONFIGURATIONS VARIANTS

F.9.1 Variant CB01A

This is the basic variant and is as described above.

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F.9.2 Variant CB01B

This variant is associated with the support structure. A variant of this configuration includes the fitting of permanent buoyancy tanks and ballast pumps within the nacelles of the device. This would eliminate the need for attachment and manipulation of temporary buoyancy tanks/bags during deployment and recovery operations.

F.9.3 Variant CB01C

This variant is associated with the power train design and operation. If the mass of the radial direct drive generator stator induces inertial issues that inference with performance/control, a smaller generator and gearbox arrangement could be used instead.

F.9.4 Variant CB01D

The variant is associated with the anchoring system. Variant CB01D of this configuration replaces the use of the monopile foundation with a micro-piled jacket structure. The envisaged benefit is a reduction in the cost and complexity of assets required to perform the foundation installation activities and improved re-use/recycling of the structural components following decommissioning.

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Appendix G CB02 LiftWEC TLP Basis of Design

G.1 Outline Description

The LiftWEC TLP configuration consists of a two-hydrofoil rotor held in place by 4 tension leg mooring cables. Each cable is reacted by a micro-piled footing structure. This semi-rigid station-keeping system provides a near-fixed axis of rotation for the rotor. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator, tension leg winch and pitch control mechanisms as well as the permanent reactive buoyancy tanks required to maintain mooring tension. The combined rotor/stator unit is referred to as the power-capture-unit. Yaw control may or may not be possible through intelligent control of the tension leg winch system. The tension leg mooring winch system is used both during deployment/recovery activities and to provide submergence control of the rotor. Power take off is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the micro-piled footings and tension leg mooring cables occurs through the use of micro-piling assets, and light weight lift vessels. Transport of the power-capture-unit (i.e. the combined rotor/stator section) is achieved using tug units. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the 4 corners of the power-capture-unit. The nacelle-mounted winching mechanisms then submerge the device to the desired depth for operation.

G.2 Rotor Design & Operation

G.2.1 Brief description of rotor section

The rotor section of the device consists of two curved hydrofoil elements, capped by circular endplates and orbiting a rigid cylindrical strut. The rotor component of the radial direct drive generators is set behind the endplates and the entire rotor section is located within the bearing structure of the radial direct drive generator (i.e. the radial direct drive generator also acts as the bearing mechanism).

G.2.2 Rotor/hydrofoil operating principles

The rotor operating condition is defined as 'Phase Optimal', meaning that real time control should be used to maximise the hydrodynamic performance of the device.

G.2.3 Axis of rotation compliance (should this be in stator section?)

The axis of rotation is near-fixed per the semi-rigid station-keeping system which is comprised of the combined action of the tension leg mooring cables and the reactance buoyancy tanks. It is currently unknown precisely how much compliance might exist in the axis of rotation under wave, current or other environmental loading experienced by the structure, however it is expected that motions

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should be designed to be small (i.e. more comparable to those of a fully fixed structure compared to those of a floating one).

G.2.4 Number & layout of hydrofoils

The rotor incorporates two opposing hydrofoils, set 180° apart.

G.2.5 Hydrofoil primary dimensions

Span: 30m. Chord length: 6-7m. Operational radius: 6m.

G.2.6 Hydrofoil cross-section properties

The hydrofoil cross-section has not yet been specified. Where appropriate, assume a NACA 0012 profile.

G.2.7 Hydrofoil materials and manufacturing

Hydrofoils will be of composite construction, similar to wind turbine blades.

G.2.8 Linear speed of hydrofoils

- Linear speed in 4s waves: 9.4m/s* (expected maximum speed – very rare occurrence)
- Linear speed in 10s waves: 3.8m/s* (expected typical mean speed)
- Linear speed in 15s waves: 2.5m/s* (expected minimum speed – rare occurrence)

* These values may increase slightly due to minor compliance/motions of the axis of rotation.

G.2.9 Other hydrofoil design considerations

None.

G.2.10 Description of hydrofoil support/mounting structure

Hydrofoils are rigidly mounted via two solid/perforated endplates. The radius of the end plates should be approximately 1-2m greater than the distance from the axis of rotation to the outermost point of the hydrofoil at the point of greatest radial extension due to pitch. The primary function of these end plates is to stop the flow of water around the ends of the hydrofoil, which would result in the formation of tip vortices and induced drag. Hence, it is important that perforation of the endplates for the purposes of inertial considerations does not significantly increase the formation of tip vortices. A balance of these issues will be required. Where possible, perforation in the end plates should be countered through the use of endplate proximity of the stator structural section, thus still eliminating the potential for the formation of tip vortices.

Pitch control of the hydrofoils is achieved via rotation of a local, circular section of the endplate at the point of hydrofoil attachment. Mounting of these local sections on bearing mechanisms and activation by hydraulic actuators set behind the endplates permits absolute termination of the hydrofoil span ends on the endplate structures without concerns for pressure leakage. If this arrangement is not feasible for structural reasons, it is possible a through-plate rotary bearing with solid shafts extending from the hydrofoil ends could be used instead.

The entire rotor structure is stiffened by the positioning of a 1.5m diameter cylindrical section mounted between the two endplates at the axis of rotation.

G.2.11 Hydrofoil support/mounting structure materials and manufacturing

The rotor endplates and cylindrical strut are of steel construction.

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G.2.12 Additional rotor components
Hydraulic pitch control mechanisms are positioned on the rear face of the endplate sections.

G.2.13 Attachment to generator element
The rotor sections of the radial direct drive generators are attached to the rear face of the rotor endplates.

G.2.14 Attachment to the bearing mechanism
The rotor is permitted rotational motion by means of the bearing mechanism inherent within the radial direct drive generators.

G.2.15 Rotor torque reaction source (aka hydrofoil reaction source)
The torque generated by the rotor, which is resisted by the direct drive generators, is ultimately reacted at the seabed through the micro-piled footing. A suitable structural path is therefore required from the generator units to the seabed via the generator housing/nacelle, the tension leg mooring cables and micro-piled footing.

G.2.16 Fundamental reaction source
The vertically downward facing components of the oscillatory loads generated by the rotor are ultimately reacted against the buoyancy provided by the buoyancy tanks contained within the nacelle units. Lateral and vertically upwards facing components of the oscillatory loads generated by the rotor are reacted at the seabed through the micro-piled footing. A suitable structural path is therefore required from the generator units to the seabed via the generator housing/nacelle, the tension leg mooring cables and micro-piled footing.

G.2.17 Other rotor design considerations
None.

G.3 Control Design & Operation

G.3.1 Hydrofoil pitch control: function, design & implementation
Pitch control is on a wave-by-wave basis (fast pitch control). Pitch control of each hydrofoil is achieved through linear hydraulic actuators set behind the endplate and attached to the locally rotating point of hydrofoil attachment.

G.3.2 Rotor/Hydrofoil phase control: function, design & implementation
Real time rotor phase control (fast rotor phase control) is achieved through torque control applied via the two direct drive generators.

G.3.3 Moment of inertia control: function, design & implementation
None.

G.3.4 Hydrofoil radius control: function, design & implementation
None.

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G.3.5 Rotor submergence control: function, design & implementation

Control of the rotor submergence depth is achieved on a sea-by-sea basis (slow submergence control) via winching of the tension leg anchor cables at the point of attachment to the power-capture-unit.

G.3.6 Yaw control: function, design & implementation

Yaw control may be able to be applied on a sea-by-sea basis (slow yaw control) via winching of the tension leg anchor cables at the point of attachment to the power-capture-unit. It is not currently clear if this is reasonably achievable or not.

G.3.7 Additional control systems

None.

G.3.8 Other control considerations

Control system implementation will require upstream wave measurement.

G.4 Stator/Support Structure Design & Operation

G.4.1 Brief description of stator section

The stator section of this configuration is broken into 2 separate structures, one at each end of the rotor section. Each section includes a single nacelle unit housing a single radial direct driver generator stator, ancillary power electronics, braking mechanisms and permanent buoyancy tanks. Each section also includes two winch elements and winding drums for the tension leg mooring cables.

G.4.2 Hydrodynamic motion/compliance of stator section

The entire stator section is near-fixed per the semi-rigid station-keeping system which is comprised of the combined action of the tension leg mooring cables and the reactance buoyancy tanks. It is currently unknown precisely how much compliance might exist in the axis of rotation under wave, current or other environmental loading experienced by the structure, however it is expected that motions should be designed to be small (i.e. more comparable to those of a fully fixed structure than compared to those of a floating one).

G.4.3 Stator section components & functionality

The radial direct drive generator stator sections provide the mounting and bearing facilities for the rotor of the device. Power take-off and phase (torque) control of the rotor is achieved through the two direct drive generators. The direct drive generators act as the bearing mechanisms which permit free rotation of the rotor section. Braking mechanisms are affixed to the direct drive generator stator.

The direct drive generators are set within the generator housing units/nacelles, which shelter the generators and other ancillary power electronics from the marine environment. These housings also hold the permanent buoyancy tanks which provide reactance and float buoyancy for the device.

The nacelle units also hold the winching and winding mechanisms used to vary the submergence of the device.

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G.4.4 Stator section structural design, materials & manufacturing
The nacelle units each incorporate a generator housing formed of structural steel.

G.4.5 Other stator section details/considerations
Inclusion of winching mechanisms for shortening of tension leg moorings.

G.5 Power Train Design & Operation

G.5.1 Brief description of power train
Hydrodynamic power is captured by the rotor section and converted into unidirectional rotary motion (kinetic energy). This kinetic energy is converted directly into electrical energy by the radial direct drive generators set at either end of the rotor section.

G.5.2 Hydrodynamic rotor performance
Approx. 30% hydrodynamic efficiency (Capture Width Ratio) at the design point with 2m wave amplitude and 10s wave period, assuming fully fixed rotor.

It is currently unknown how much impact small motions of the axis of rotation might have on performance.

G.5.3 Power train conversion efficiency
Direct drive generator efficiency assumed at 90%.

G.5.4 Generator type, size & rating
Two radial direct drive generators, each approx. 10-12m diameter, each with 750 kW rating. These could be replaced by a single, 1.5MW generator if preferable due to structural, cost and reliability considerations.

G.5.5 Energy storage mechanisms
None.

G.5.6 Power smoothing mechanisms
None.

G.5.7 Other relevant power train components & functionality
The direct drive generators are additionally used to provide phase control of the rotor.

G.6 Station-Keeping System Design & Operation

G.6.1 Brief description of station-keeping system
The station-keeping facility is provided by the 4 tension leg mooring cables.

G.6.2 Station-keeping system components & functionality
The 4 tension leg mooring cables are each attached to the seabed via a single, discrete, micro-piled structural steel footing. Winches and cable drums set in/upon the nacelle units are used to submerge the device and vary is depth of operation as desired (on a sea-by sea basis – i.e. slow submergence control).

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Uplift is provided in the form of two large buoyancy tanks. One buoyancy tank is set within each nacelle unit.

When the device is detached from the tension mooring cables, the cables are affixed to locating floats for ease of access and recovery as required.

G.6.3 Station-keeping system sizing, materials & manufacturing

The buoyancy tanks are of steel construction.

G.6.4 Other station-keeping system details/considerations

None.

G.7 Anchor/Foundation/Grounding Design & Operation

G.7.1 Brief description of anchor system

The anchoring system consists of 4 structural steel footing elements, each of which is independently micro-piled to the sea floor.

G.7.2 Anchor system components & functionality

Four independent foot elements which provide a seabed attachment point for the tension mooring cables. Steel micro-piles are used to rigidly affix the footing elements to the seabed.

G.7.3 Anchor system sizing, materials & manufacturing

Steel micro-piles are used to affix a small steel anchoring attachment to the seabed.

G.7.4 Other anchor system details/considerations

None.

G.8 Operations & Maintenance

G.8.1 Brief description of installation procedure & asset requirements

Note that installation refers to the placement and commissioning of the anchor and station-keeping systems. Placement of the power-capture-unit (i.e., the combined rotor/stator section) is referred to as '*Deployment*' and is described in a subsequent section.

Initially, a micro-piling asset and small lift vessel are used to install the footing elements with guidelines and marker buoys attached. Divers or ROVs are then used to connect the tension leg mooring cables which are similarly attached to locating floats for ease of access at the point of power-capture-unit deployment.

G.8.2 Brief description of power-capture-unit deployment procedure & asset requirements

The power-capture-unit (combined rotor/stator section) is towed to site using a conventional tug unit. At the point of deployment, the tension leg mooring cables are detached from the locator floats and attached to the power-capture-unit via the nacelle-mounted winch mechanisms. The winches are then engaged to submerge the device to the desired depth. Subsequently, the tension leg mooring cables are locked in position using a cable-lock and tension on the winch mechanisms is disengaged. Deployment should be achievable within a 2 hour window (measured from arrival at deployment location) using 1-2 tug units.

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G.8.3 Brief description of power-capture-unit recovery procedure & asset requirements

Recovery procedure for the power-capture-unit is as the reverse of the deployment procedure using the same procedures and assets.

G.8.4 Brief description of decommissioning procedure & asset requirements

Decommissioning of the system refers to the removal of the micro-piled footing elements and the tension leg mooring cables. Removal of the power-capture-unit is encompassed by the '*Recovery*' operations outlined in a previous section.

Removal of the tension leg mooring cables will be achieved using either diver or ROV intervention. Recovery of the micro-piled footing elements will be via ROV/diver extraction and light-lift vessel use. Recovery of the micro-piled footing elements may also require grout-breaking activities. Micro-pile elements will be left in situ due to the seabed damage that would be required for their removal.

G.8.5 Outline of maintenance strategy

Device maintenance will be primarily on a return-to-base strategy for all but the simplest procedures. Tug boats will be used to recover individual power-capture-units as required according to the deployment/recovery procedures described above. In a station of 100 units, it is envisaged that 2-3 'spare' units would be kept in base for replacement of units brought in for maintenance, thus alleviating time pressures on O&M activities and reducing concerns over weather window availability. This is naturally dependent on the expected cost of energy implications.

G.8.6 Relevant farm-scale considerations

Deployment of a 100-unit farm would see placement of devices at approximately a 3x device span centre-to-centre spacing. This allows for a 76m separation distance between adjacent device anchors. For example, assuming a total device span of 48m (30m hydrofoil span + 9m nacelle length) would see a centre-to-centre device placement length of 144m.

G.9 CONFIGURATION VARIANTS

G.9.1 Variant CB02A

This is the basic variant and is as described above.

G.9.2 Variant CB02B

This variant is associated with the power train design. If the mass of the radial direct drive generator stator induces inertial issues that inference with performance/control, a smaller generator and gearbox arrangement could be used instead.

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Appendix H CB03 LiftWEC Semi-sub Basis of Design

H.1 Outline Description

The LiftWEC semi-sub configuration consists of a two-hydrofoil rotor held in place by a 3-float semi-submersible. The 3 floats are arranged in a triangular planform pattern. The semi-submersible is held in place by 3 catenary mooring cables, one attached to each of the three floats. The 3 catenary moorings may be anchored to the seabed either through micro-piled footings (CB03A), drag anchors (CB03B) or gravity foundations (CB03C). The mooring arrangement allows for reasonable motion of the device, including the axis of rotation, in all 6 traditional degrees of freedom. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator, and pitch control mechanisms. The combined rotor/stator unit is referred to as the power-capture-unit. The power-capture-unit is suspended between the two front floats. Submergence control is achieved through ballasting/de-ballasting of the semi-submersible floats. Power take off is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the anchor and station-keeping system will depend on the anchor system selected. Transport of the semi-submersible, including the power-capture-unit, for deployment is achieved using tugs. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the 3 floats of the semi-submersible. The semi-submersible is then ballasted using sea-water to achieve the desired submergence depth of the rotor.

H.2 Rotor Design & Operation

H.2.1 Brief description of rotor section

The rotor section of the device consists of two curved hydrofoil elements, capped by circular endplates and orbiting a rigid cylindrical strut. The rotor component of the radial direct drive generators is set behind the endplates and the entire rotor section is located within the bearing structure of the radial direct drive generator (i.e. the radial direct drive generator also acts as the bearing mechanism).

H.2.2 Rotor/hydrofoil operating principles

The rotor operating condition is defined as 'Phase Optimal', meaning that real time control should be used to maximise the hydrodynamic performance of the device.

H.2.3 Axis of rotation compliance (should this be in stator section?)

The axis of rotation is unfixed as per the freely-floating station-keeping system which is comprised of the combined action of the catenary mooring cables and the semi-submersible structure. It is currently unknown precisely how much compliance might exist in the axis of rotation under wave,

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current or other environmental loading experienced by the structure, however it is expected that motions will be large compared to the cases of Configuration CB01 and Configuration CB02.

H.2.4 Number & layout of hydrofoils

The rotor incorporates two opposing hydrofoils, set 180° apart.

H.2.5 Hydrofoil primary dimensions

Span: 30m. Chord length: 6-7m. Operational radius: 6m.

H.2.6 Hydrofoil cross-section properties

The hydrofoil cross-section has not yet been specified. Where appropriate, assume a NACA 0012 profile.

H.2.7 Hydrofoil materials and manufacturing

Hydrofoils will be of composite construction, similar to wind turbine blades.

H.2.8 Linear speed of hydrofoils

- Linear speed in 4s waves: 9.4m/s* (expected maximum speed – very rare occurrence)
- Linear speed in 10s waves: 3.8m/s* (expected typical mean speed)
- Linear speed in 15s waves: 2.5m/s* (expected minimum speed – rare occurrence)

* These values may increase due to significant compliance/motions of the axis of rotation.

H.2.9 Other hydrofoil design considerations

None.

H.2.10 Description of hydrofoil support/mounting structure

Hydrofoils are rigidly mounted via two solid/perforated endplates. The radius of the end plates should be approximately 1-2m greater than the distance from the axis of rotation to the outermost point of the hydrofoil at the point of greatest radial extension due to pitch. The primary function of these end plates is to stop the flow of water around the ends of the hydrofoil, which would result in the formation of tip vortices and induced drag. Hence, it is important that perforation of the endplates for the purposes of inertial considerations does not significantly increase the formation of tip vortices. A balance of these issues will be required. Where possible, perforation in the end plates should be countered through the use of endplate proximity of the stator structural section, thus still eliminating the potential for the formation of tip vortices.

Pitch control of the hydrofoils is achieved via rotation of a local, circular section of the endplate at the point of hydrofoil attachment. Mounting of these local sections on bearing mechanisms and activation by hydraulic actuators set behind the endplates permits absolute termination of the hydrofoil span ends on the endplate structures without concerns for pressure leakage. If this arrangement is not feasible for structural reasons, it is possible a through-plate rotary bearing with solid shafts extending from the hydrofoil ends could be used instead.

The entire rotor structure is stiffened by the positioning of a 1.5m diameter cylindrical section mounted between the two endplates at the axis of rotation.

H.2.11 Hydrofoil support/mounting structure materials and manufacturing

The rotor endplates and cylindrical strut are of steel construction.

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H.2.12 Additional rotor components

Hydraulic pitch control mechanisms are positioned on the rear face of the endplate sections.

H.2.13 Attachment to generator element

The rotor sections of the radial direct drive generators are attached to the rear face of the rotor endplates.

H.2.14 Attachment to the bearing mechanism

The rotor is permitted rotational motion by means of the bearing mechanism inherent within the radial direct drive generators.

H.2.15 Rotor torque reaction source (aka hydrofoil reaction source)

The torque generated by the rotor, which is resisted by the direct drive generators, is ultimately reacted by an induced torque generated by the hydrostatic and hydrodynamic response of the offset float. A rigid structural path is therefore required from the generator units to the offset float via the generator housing/nacelle and the semi-submersible structure.

H.2.16 Fundamental reaction source

The oscillatory loads generated by the rotor are reacted against the inertia and buoyancy of the semi-submersible structure. A rigid structural path is therefore required from the generator units to the semi-submersible structure via the generator housing/nacelle.

H.2.17 Other rotor design considerations

None.

H.3 Control Design & Operation

H.3.1 Hydrofoil pitch control: function, design & implementation

Pitch control is on a wave-by-wave basis (fast pitch control). Pitch control of each hydrofoil is achieved through linear hydraulic actuators set behind the endplate and attached to the locally rotating point of hydrofoil attachment.

H.3.2 Rotor/Hydrofoil phase control: function, design & implementation

Real time rotor phase control (fast rotor phase control) is achieved through torque control applied via the two direct drive generators.

H.3.3 Moment of inertia control: function, design & implementation

None.

H.3.4 Hydrofoil radius control: function, design & implementation

None.

H.3.5 Rotor submergence control: function, design & implementation

Control of the rotor submergence depth is achieved on a sea-by-sea basis (slow submergence control) via ballasting and de-ballasting of the semi-submersible. This is achieved through seawater pumps located in each float element.

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H.3.6 Yaw control: function, design & implementation

None

H.3.7 Additional control systems

None.

H.3.8 Other control considerations

Control system implementation will require upstream wave measurement.

H.4 Stator/Support Structure Design & Operation

H.4.1 Brief description of stator section

The stator section of this configuration is broken into 2 separate structures, one at each end of the rotor section. Each section includes a single nacelle unit housing a single radial direct driver generator stator, ancillary power electronics and braking mechanisms. Each stator section is rigidly affixed to the semi-submersible at one of the front-facing floats.

H.4.2 Hydrodynamic motion/compliance of stator section

The entire stator section is unfixed as per the freely-floating station-keeping system which is comprised of the combined action of the catenary mooring cables and the semi-submersible structure. It is currently unknown precisely how much compliance might exist in the axis of rotation under wave, current or other environmental loading experienced by the structure, however it is expected that motions will be larger compared to the cases of Configuration CB01 and Configuration C02.

H.4.3 Stator section components & functionality

The radial direct drive generator stator sections provide the mounting and bearing facilities for the rotor of the device. Power take-off and phase (torque) control of the rotor is achieved through the two direct drive generators. The direct drive generators act as the bearing mechanisms which permit free rotation of the rotor section. Braking mechanisms are affixed to the direct drive generator stator.

The direct drive generators are set within the generator housing units/nacelles, which shelter the generators and other ancillary power electronics from the marine environment.

H.4.4 Stator section structural design, materials & manufacturing

The nacelle units each incorporate a generator housing formed of structural steel.

H.4.5 Other stator section details/considerations

None.

H.5 Power Train Design & Operation

H.5.1 Brief description of power train

Hydrodynamic power is captured by the rotor section and converted into unidirectional rotary motion (kinetic energy). This kinetic energy is converted directly into electrical energy by the radial direct drive generators set at either end of the rotor section.

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H.5.2 Hydrodynamic rotor performance

Approx. 30% hydrodynamic efficiency (Capture Width Ratio) at the design point with 2m wave amplitude and 10s wave period, assuming fully fixed rotor.

It is currently unknown how much impact floating motions of the axis of rotation might have on performance.

H.5.3 Power train conversion efficiency

Direct drive generator efficiency assumed at 90%.

H.5.4 Generator type, size & rating

Two radial direct drive generators, each approx. 10-12m diameter, each with 750 kW rating. These could be replaced by a single, 1.5MW generator if preferable due to structural, cost and reliability considerations.

H.5.5 Energy storage mechanisms

None.

H.5.6 Power smoothing mechanisms

None.

H.5.7 Other relevant power train components & functionality

The direct drive generators are additionally used to provide phase control of the rotor.

H.6 Station-Keeping System Design & Operation

H.6.1 Brief description of station-keeping system

The station-keeping facility is provided by the combined action of the 3-float semi-submersible structure and the 3 catenary mooring cables.

H.6.2 Station-keeping system components & functionality

The semi-submersible structure is used to locate the power-capture-unit. The power-capture-unit is rigidly fixed between two of the semi-submersible structure floats. This section acts as the front of the semi-submersible which should be orientated to intercept the mean direction of wave propagation. The 3 floats provide uplift and reactance buoyancy for the device. The structure as a whole also provides inertial reaction as the fundamental reaction source. The third float, which is offset, is used to provide a torque for reaction of the rotor torque generated by the device. The submergence of the system can be varied through ballasting/de-ballasting of the system. These ballasting operations are performed by sea-water pumps set into the semi-submersible floats. These pumps either inject or extract seawater into the floats to change the submergence depth of the structure and thus, the rotor.

All rotor torque and fundamental forces should be reacted by the semi-submersible. Consequently, the 3-point catenary mooring system should be used only to locate the semi-submersible, thus reducing the load which must be reacted at the seabed and in turn reducing anchor sizing requirements. When the device is detached from the catenary mooring cables, the cables are affixed to locating floats for ease of access and recovery as required.

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H.6.3 Station-keeping system sizing, materials & manufacturing

The semi-submersible floats are 5m in diameter and 28m long. The floats are formed from reinforced concrete with steel end-caps. A structural steel framework is used to locate the floats and provide load transfer. The two front floats are set with an internal spacing of 44m. The third float is set in the midspan of this distance with a lateral offset of 23m (centre-to-centre).

The catenary mooring cables are 140m long assuming 40m depth from fair-head to seabed and 80m distance to touchdown.

H.6.4 Other station-keeping system details/considerations

None.

H.7 Anchor/Foundation/Grounding Design & Operation

H.7.1 Brief description of anchor system

The anchor system is based on the use of one or more micropiles for each mooring line.

H.7.2 Anchor system components & functionality

Three micro-piled footings are used to provide a point of rigid attachment for the catenary moorings to the seabed. One footing is provided per catenary.

H.7.3 Anchor system sizing, materials & manufacturing

Steel micro-piles are used to affix a small steel anchoring attachment to the seabed.

H.7.4 Other anchor system details/considerations

None.

H.8 Operations & Maintenance

H.8.1 Brief description of installation procedure & asset requirements

Note that installation refers to the placement and commissioning of the anchor and catenary mooring line elements. Placement of the power-capture-unit (i.e., the combined rotor/stator section) is referred to as '*Deployment*' and is described in a subsequent section.

A micro-piling asset and small lift vessel are used to affix the footing elements to the seabed with guidelines and marker buoys attached.

With the anchor system in place, divers or ROVs are then used to connect the catenary mooring lines to the footings. The free ends of the catenary mooring lines are attached to locating floats for ease of access at the point of power-capture-unit deployment.

H.8.2 Brief description of power-capture-unit deployment procedure & asset requirements

The power-capture-unit (combined rotor/stator section) and semi-submersible is deployed as a single unit. This unit is towed to site using two conventional tug vessels. At the point of deployment, the catenary mooring lines are switched from their locating floats to the semi-submersible. Seawater pumps within the semi-submersible floats are then used to ballast the semi-submersible unit, dropping the power-capture-unit to the desired submergence depth. Deployment should be achievable within a 2 hour window (measured from arrival at deployment location) using 2 tug units.

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H.8.3 Brief description of power-capture-unit recovery procedure & asset requirements

Recovery procedure for the power-capture-unit is as the reverse of the deployment procedure using the same procedures and assets.

H.8.4 Brief description of decommissioning procedure & asset requirements

Decommissioning of the system refers to the removal of the anchor and catenary mooring line elements. Removal of the power-capture-unit is encompassed by the '*Recovery*' operations outlined in a previous section.

Removal of the catenary mooring line cables will be achieved using either diver or ROV intervention. Anchor system recovery will depend on the configuration as follows:

Recovery of the micro-piled footing elements will be via ROV/diver extraction and light-lift vessel use. Recovery of the micro-piled footing elements may also require grout-breaking activities. Micro-pile elements will be left in situ due to the seabed damage that would be required for their removal.

H.8.5 Outline of maintenance strategy

Device maintenance will be primarily on a return-to-base strategy for all but the simplest procedures. Tug boats will be used to recover individual power-capture-units as required according to the deployment/recovery procedures described above.

H.8.6 Relevant farm-scale considerations

Deployment of a 100-unit farm would see placement of devices at approximately a 5x device span centre-to-centre spacing. This allows for a 30m separation distance between adjacent device anchors. For example, assuming a total device span of 42m (30m hydrofoil span + 6m nacelle length) would see a centre-to-centre device placement length of 210m.

H.9 Configuration Variants

H.9.1 Variant CB03A

This is the basic variant and is as described above.

H.9.2 Variant CB03B

This variant is associated with the anchoring system. Three steel drag anchors are used to provide a point of rigid attachment for the catenary moorings to the seabed. One drag anchor is provided per catenary. If redundancy is suggested, two drag anchors should be provided per catenary. A light lift vessel is used to drop drag anchors in location. Recovery of drag anchors will be through the use of a light lift vessel.

H.9.3 Variant CB03C

This variant is associated with the anchoring system. Three gravity foundations are used to provide a point of rigid attachment for the catenary moorings to the seabed. One gravity foundation is provided per catenary. A light-medium lift vessel is used to set the gravity foundations in location. Recovery of gravity foundations will be through the use of a light-medium lift vessel.

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H.9.4 Variant CB03D

This variant is associated with the power train. If the mass of the radial direct drive generator stator induces inertial issues that inference with performance/control, a smaller generator and gearbox arrangement could be used instead.

H.9.5 Variant CB03E

This variant is associated with the station-keeping system. The Configuration variant CB03E replaces the three point mooring attachment with a single point mooring connection. In this configuration, three catenary mooring cables still fall to the seabed, however come together at a mid-depth connection point. A single mooring cable then extends from the connection point to the third (offset) float of the semi-submersible. This permits passive yaw-vaning of the device without significant additional seabed disruption. This also reduces the length of catenary mooring cables required (120m), however may increase compliance/motion of the device or lead to unfavourable orientation of the rotor which cannot easily be rectified.

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Appendix I CB04 LiftWEC Spar Basis of Design

I.1 Outline Description

The LiftWEC Spar configuration consists of a two-hydrofoil rotor held in place by a twin-tower spar-buoy float. The two towers of the spar buoy are rigidly attached by a cross bar towards the bottom of the structure. The structure is held in place by a single point mooring sinking to a 3 catenary mooring cabled anchor system. The single point mooring is attached to each tower of the two-tower spar buoy structure. The 3 catenary moorings may be anchored to the seabed either through micro-piled footings (CB04A), drag anchors (CB04B) or gravity foundations (CB04C). The mooring arrangement allows for reasonable motion of the device, including the axis of rotation, in all 6 traditional degrees of freedom. The 30m span hydrofoils terminate upon a set of circular endplates which locate within a pair of stator housing units (one at each end of the rotor section). The endplate radii are larger than the operational radii of the hydrofoils. The primary functions of these endplates are; (1) to eliminate the formation of tip vortices, thus reducing the induced drag and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. The stator structure houses the bearing, generator, and pitch control mechanisms. The combined rotor/stator unit is referred to as the power-capture-unit. The power-capture-unit is suspended between the two towers of the spar-buoy structure. Submergence control is achieved through ballasting/de-ballasting of the spar-buoy floats. Power take off is achieved via two direct drive generators, which can also be used to implement phase control. There is no mechanism to permit radius control of the device. Installation of the anchor and station-keeping system will depend on the anchor system selected. Transport of the spar-buoy structure, including the power-capture-unit, for deployment is achieved using tug units and ballasting/de-ballasting activities which reorientate the spar buoy onto a horizontal plane to permit ease of towing. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the towers of the spar-buoy unit. The spar-buoy is then ballasted using sea-water to achieve the desired submergence depth of the rotor.

I.2 Rotor Design & Operation

I.2.1 Brief description of rotor section

The rotor section of the device consists of two curved hydrofoil elements, capped by circular endplates and orbiting a rigid cylindrical strut. The rotor component of the radial direct drive generators is set behind the endplates and the entire rotor section is located within the bearing structure of the radial direct drive generator (i.e. the radial direct drive generator also acts as the bearing mechanism).

I.2.2 Rotor/hydrofoil operating principles

The rotor operating condition is defined as 'Phase Optimal', meaning that real time control should be used to maximise the hydrodynamic performance of the device.

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I.2.3 Axis of rotation compliance (should this be in stator section?)

The axis of rotation is unfixed as per the freely-floating station-keeping system which is comprised of the combined action of the catenary mooring cables and the spar-buoy structure. It is currently unknown precisely how much compliance might exist in the axis of rotation under wave, current or other environmental loading experienced by the structure, however it is expected that motions will be large compared to the cases of Configuration CB01 and Configuration CB02.

I.2.4 Number & layout of hydrofoils

The rotor incorporates two opposing hydrofoils, set 180° apart.

I.2.5 Hydrofoil primary dimensions

Span: 30m. Chord length: 6-7m. Operational radius: 6m.

I.2.6 Hydrofoil cross-section properties

The hydrofoil cross-section has not yet been specified. Where appropriate, assume a NACA 0012 profile.

I.2.7 Hydrofoil materials and manufacturing

Hydrofoils will be of composite construction, similar to wind turbine blades.

I.2.8 Linear speed of hydrofoils

- Linear speed in 4s waves: 9.4m/s* (expected maximum speed – very rare occurrence)
- Linear speed in 10s waves: 3.8m/s* (expected typical mean speed)
- Linear speed in 15s waves: 2.5m/s* (expected minimum speed – rare occurrence)

* These values may increase due to significant compliance/motions of the axis of rotation.

I.2.9 Other hydrofoil design considerations

None.

I.2.10 Description of hydrofoil support/mounting structure

Hydrofoils are rigidly mounted via two solid/perforated endplates. The radius of the end plates should be approximately 1-2m greater than the distance from the axis of rotation to the outermost point of the hydrofoil at the point of greatest radial extension due to pitch. The primary function of these end plates is to stop the flow of water around the ends of the hydrofoil, which would result in the formation of tip vortices and induced drag. Hence, it is important that perforation of the endplates for the purposes of inertial considerations does not significantly increase the formation of tip vortices. A balance of these issues will be required. Where possible, perforation in the end plates should be countered through the use of endplate proximity of the stator structural section, thus still eliminating the potential for the formation of tip vortices.

Pitch control of the hydrofoils is achieved via rotation of a local, circular section of the endplate at the point of hydrofoil attachment. Mounting of these local sections on bearing mechanisms and activation by hydraulic actuators set behind the endplates permits absolute termination of the hydrofoil span ends on the endplate structures without concerns for pressure leakage. If this arrangement is not feasible for structural reasons, it is possible a through-plate rotary bearing with solid shafts extending from the hydrofoil ends could be used instead.

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The entire rotor structure is stiffened by the positioning of a 1.5m diameter cylindrical section mounted between the two endplates at the axis of rotation.

I.2.11 Hydrofoil support/mounting structure materials and manufacturing

The rotor endplates and cylindrical strut are of steel construction.

I.2.12 Additional rotor components

Hydraulic pitch control mechanisms are positioned on the rear face of the endplate sections.

I.2.13 Attachment to generator element

The rotor sections of the radial direct drive generators are attached to the rear face of the rotor endplates.

I.2.14 Attachment to the bearing mechanism

The rotor is permitted rotational motion by means of the bearing mechanism inherent within the radial direct drive generators.

I.2.15 Rotor torque reaction source (aka hydrofoil reaction source)

The torque generated by the rotor, which is resisted by the direct drive generators, is ultimately reacted by an induced torque generated by the hydrostatic and hydrodynamic response of the spar-buoy. A rigid structural path is therefore required from the generator units to the spar-buoy structure via the generator housing/nacelle.

I.2.16 Fundamental reaction source

The oscillatory loads generated by the rotor are reacted against the inertia and buoyancy of the semi-submersible structure. A rigid structural path is therefore required from the generator units to the spar-buoy structure via the generator housing/nacelle.

I.2.17 Other rotor design considerations

None.

I.3 Control Design & Operation

I.3.1 Hydrofoil pitch control: function, design & implementation

Pitch control is on a wave-by-wave basis (fast pitch control). Pitch control of each hydrofoil is achieved through linear hydraulic actuators set behind the endplate and attached to the locally rotating point of hydrofoil attachment.

I.3.2 Rotor/Hydrofoil phase control: function, design & implementation

Real time rotor phase control (fast rotor phase control) is achieved through torque control applied via the two direct drive generators.

I.3.3 Moment of inertia control: function, design & implementation

None.

I.3.4 Hydrofoil radius control: function, design & implementation

None.

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I.3.5 Rotor submergence control: function, design & implementation
Control of the rotor submergence depth is achieved on a sea-by-sea basis (slow submergence control) via ballasting and de-ballasting of the spar-buoy tower floats. This is achieved through seawater pumps located in each tower element.

I.3.6 Yaw control: function, design & implementation
Passive vaning.

I.3.7 Additional control systems
None.

I.3.8 Other control considerations
Control system implementation will require upstream wave measurement.

I.4 Stator/Support Structure Design & Operation

I.4.1 Brief description of stator section
The stator section of this configuration is broken into 2 separate structures, one at each end of the rotor section. Each section includes a single nacelle unit housing a single radial direct driver generator stator, ancillary power electronics and braking mechanisms. Each stator section is rigidly affixed to the spar-buoy structure at one of the two tower elements.

I.4.2 Hydrodynamic motion/compliance of stator section
The entire stator section is unfixed as per the freely-floating station-keeping system which is comprised of the combined action of the catenary mooring cables and the spar-buoy structure. It is currently unknown precisely how much compliance might exist in the axis of rotation under wave, current or other environmental loading experienced by the structure, however it is expected that motions will be large compared to the cases of Configuration CB01 and Configuration CB02.

I.4.3 Stator section components & functionality
The radial direct drive generator stator sections provide the mounting and bearing facilities for the rotor of the device. Power take-off and phase (torque) control of the rotor is achieved through the two direct drive generators. The direct drive generators act as the bearing mechanisms which permit free rotation of the rotor section. Braking mechanisms are affixed to the direct drive generator stator.

The direct drive generators are set within the generator housing units/nacelles, which shelter the generators and other ancillary power electronics from the marine environment.

I.4.4 Stator section structural design, materials & manufacturing
The nacelle units each incorporate a generator housing formed of structural steel.

I.4.5 Other stator section details/considerations
None.

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I.5 Power Train Design & Operation

I.5.1 Brief description of power train

Hydrodynamic power is captured by the rotor section and converted into unidirectional rotary motion (kinetic energy). This kinetic energy is converted directly into electrical energy by the radial direct drive generators set at either end of the rotor section.

I.5.2 Hydrodynamic rotor performance

Approx. 30% hydrodynamic efficiency (Capture Width Ratio) at the design point with 2m wave amplitude and 10s wave period, assuming fully fixed rotor.

It is currently unknown how much impact floating motions of the axis of rotation might have on performance.

I.5.3 Power train conversion efficiency

Direct drive generator efficiency assumed at 90%.

I.5.4 Generator type, size & rating

Two radial direct drive generators, each approx. 10-12m diameter, each with 750 kW rating. These could be replaced by a single, 1.5MW generator if preferable due to structural, cost and reliability considerations.

I.5.5 Energy storage mechanisms

None.

I.5.6 Power smoothing mechanisms

None.

I.5.7 Other relevant power train components & functionality

The direct drive generators are additionally used to provide phase control of the rotor.

I.6 Station-Keeping System Design & Operation

I.6.1 Brief description of station-keeping system

The station-keeping facility is provided by the combined action of the two-tower spar-buoy structure and the mooring system. The mooring system comprises of 3 catenary mooring cables which rise from the seabed to a single, mid-water connection point. From this connection point, two cables rise up to attach to the two towers of the spar-buoy structure.

I.6.2 Station-keeping system components & functionality

The spar-buoy structure is used to locate the power-capture-unit. The power-capture-unit is rigidly fixed between the two towers of the spar-buoy structure. The spar-buoy tower elements are floats and provide uplift and reactance buoyancy for the device. The cross-bar section of the spar-buoy structure is a ballasted mass, which provides an inertial reaction source for the rotor both in terms of the rotor reaction and fundamental reaction requirements. The submergence of the system can be varied through ballasting/de-ballasting of the tower elements. These ballasting operations are performed by sea-water pumps set into the spar-buoy towers. These pumps either inject or extract seawater into the floats to change the submergence depth of the structure and thus, the rotor.

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All rotor torque and fundamental forces should be reacted by the spar-buoy. Consequently, the single-point mooring system should be used only to locate the semi-submersible, thus reducing the load which must be reacted at the seabed and in turn reducing anchor sizing requirements. When the device is detached from the catenary mooring cables, the cables are affixed to locating floats for ease of access and recovery as required.

I.6.3 Station-keeping system sizing, materials & manufacturing

The spar-buoy tower floats are 5m in diameter and 28m long. The floats are formed from reinforced concrete with steel end-caps. The cross-bar set between the tower sections is also 5m diameter and formed from reinforced concrete. Structural steelwork is used to provide additional strength to the structure at critical points of stress concentration.

The catenary mooring cables are 40m long assuming 15m depth from fair-head to seabed and 30m distance to touchdown.

I.6.4 Other station-keeping system details/considerations

None.

I.7 Anchor/Foundation/Grounding Design & Operation

I.7.1 Brief description of anchor system

The anchor system is based on the use of one or more micropiles for each mooring line.

I.7.2 Anchor system components & functionality

Three micro-piled footings are used to provide a point of rigid attachment for the catenary moorings to the seabed. One footing is provided per catenary.

I.7.3 Anchor system sizing, materials & manufacturing

Steel micro-piles are used to affix a small steel anchoring attachment to the seabed.

I.7.4 Other anchor system details/considerations

None.

I.8 Operations & Maintenance

I.8.1 Brief description of installation procedure & asset requirements

Note that installation refers to the placement and commissioning of the anchor and catenary mooring line elements. Placement of the power-capture-unit (i.e., the combined rotor/stator section) is referred to as '*Deployment*' and is described in a subsequent section.

A micro-piling asset and small lift vessel are used to affix the footing elements to the seabed with guidelines and marker buoys attached.

With the anchor system in place, divers or ROVs are then used to connect the catenary mooring lines to the footings and the mid-water connection point installed. The free ends of the two mooring lines intended for spar-buoy connection are attached to locating floats for ease of access at the point of power-capture-unit deployment.

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I.8.2 Brief description of power-capture-unit deployment procedure & asset requirements

The power-capture-unit (combined rotor/stator section) and spar-buoy structure is deployed as a single unit. This unit is towed to site using two conventional tug vessels. During towing the spar-buoy structure should be ballasted to remain aligned with the horizontal plane. At the point of deployment, the catenary mooring lines are switched from their locating floats to the spar-buoy. Seawater pumps within the spar-buoy floats are then used to ballast the spar-buoy unit, dropping the power-capture-unit to the desired submergence depth. Deployment should be achievable within a 2 hour window (measured from arrival at deployment location) using 2 tug units. Winches may be required to induce sufficient tension in the mooring lines that run from the mid-water connection point to the spar buoy.

I.8.3 Brief description of power-capture-unit recovery procedure & asset requirements

Recovery procedure for the power-capture-unit is as the reverse of the deployment procedure using the same procedures and assets.

I.8.4 Brief description of decommissioning procedure & asset requirements

Decommissioning of the system refers to the removal of the anchor and catenary mooring line elements. Removal of the power-capture-unit is encompassed by the '*Recovery*' operations outlined in a previous section.

Removal of the catenary mooring line cables and mid-water connection point will be achieved using either diver or ROV intervention. Recovery of the micro-piled footing elements will be via ROV/diver extraction and light-lift vessel use. Recovery of the micro-piled footing elements may also require grout-breaking activities. Micro-pile elements will be left in situ due to the seabed damage that would be required for their removal.

I.8.5 Outline of maintenance strategy

Device maintenance will be primarily on a return-to-base strategy for all but the simplest procedures. Tug boats will be used to recover individual power-capture-units as required according to the deployment/recovery procedures described above.

I.8.6 Relevant farm-scale considerations

Deployment of a 100-unit farm would see placement of devices at approximately a 5x device span centre-to-centre spacing. For example, assuming a total device span of 42m (30m hydrofoil span + 6m nacelle length) would see a centre-to-centre device placement length of 210m. This spacing should provide ample room for vaning of the spar-buoy structure.

I.9 Configuration Variants

I.9.1 Variant CB04A

This is the basic variant and is as described above.

I.9.2 Variant CB04B

This variant is associated with the anchoring system. Three steel drag anchors are used to provide a point of rigid attachment for the catenary moorings to the seabed. One drag anchor is provided per catenary. If redundancy is suggested, two drag anchors should be provided per catenary. A light lift

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vessel is used to drop drag anchors in location. Recovery of drag anchors will be through the use of a light lift vessel.

I.9.3 Variant CB04C

This variant is associated with the anchoring system. Three gravity foundations are used to provide a point of rigid attachment for the catenary moorings to the seabed. One gravity foundation is provided per catenary. A light-medium lift vessel is used to set the gravity foundations in location. Recovery of gravity foundations will be through the use of a light-medium lift vessel.

I.9.4 Variant CB04D

This variant is associated with the power chain. If the mass of the radial direct drive generator stator induces inertial issues that inference with performance/control, a smaller generator and gearbox arrangement could be used instead.

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