LiftWEC

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

Deliverable D2.10

Assessment of Baseline Configurations and Specification of Final Configuration

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EXECUTIVE SUMMARY

This document constitutes Deliverable ‘D2.10 Assessment of Baseline Configurations and Specification of Final Configuration’ 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 details the process used to select the Final LiftWEC Configuration, as well as an outline specification of that configuration. The Final LiftWEC Configuration defines the subject matter for the investigations and assessments that will be conducted during Phase 4 of the project.

The selection of the Final LiftWEC Configuration was the culmination of a two-day all-consortium workshop held in May/June 2022. The aim of this workshop was to evaluate the four Baseline LiftWEC Configurations, leading to the selection of one of these Configurations as the Final LiftWEC Configuration. In preparation for the workshop, each technical work package prepared a short presentation on each of the Baseline Configurations. These presentations were used to disseminate work package opinions throughout the consortium before the LiftWEC Concept Evaluation Tool was used to quantitatively rank the four configurations in terms of their perceived suitability for further investigation and development. While these quantifications were intended to guide the decision, they were not binding in terms of the highest scoring configuration being selected as the Final LiftWEC Configuration.

Results of the quantitative evaluations suggest that the Spar-Buoy configuration holds the greatest potential for further development. While this ranking was not binding, after significant discussion of the options available it was decided that the Spar LiftWEC would indeed be selected as the Final LiftWEC Configuration. This decision was made by consensus and no objections were presented.

This document further details these activities before presenting an outline description of the Final LiftWEC Configuration. Appendices are also presented which provide both the workshop agenda as well as the work-package presentations assessing the four Baseline Configurations.

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1 INTRODUCTION

This document constitutes Deliverable *'D2.10: Assessment of Baseline Configurations and Specification of Final Configuration*' 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. It is the intention of the LiftWEC project to culminate in the proposal of a single device configurations that the consortium considers suitable for further investigation and development as a potentially viable WEC concept.

The LiftWEC project consists of 4 phases. Phase 1 involved a knowledge gathering and development exercise with the aim of producing an initial understanding of the operational principles of lift-based WECs. This knowledge was then used to generate 17 Preliminary LiftWEC Configurations. These preliminary configurations were developed during a 3 day collaborative workshop, the details of which are reported in Deliverable D2.3. Phase 2 of the project saw the completion of targeted work that would enable the consortium to determine the most promising of those Preliminary Configurations. Deliverable 2.8 reported on the analysis of the Preliminary Configurations and subsequent selection of what was deemed to be the most promising of the Preliminary Configurations. Four of the Preliminary Configurations were identified as potentially promising and were selected as the Baseline Configurations. Phase 3 of the project saw detailed investigations of the Baseline Configurations completed by the technical work packages. This work was used to select the Baseline Configuration that was thought to have the greatest potential for further development as the Final LiftWEC Configuration (the subject of this deliverable). Phase 4 of the project will conduct detailed investigations into the operation, performance and potential of the Final LiftWEC Configuration.

1.2 PURPOSE OF DELIVERABLE

The primary purposes of this document are to provide an overview of the consortium assessment of the LiftWEC Baseline Configurations that were presented in Deliverable D2.8, and to provide the specification of the Final LiftWEC Configuration that will be analysed during Phase 4 of the project. In addition, this document details the methods used during selection of the Final LiftWEC Configuration and provides the justification for the choice of the final configuration.

1.3 STRUCTURE OF THE DOCUMENT

This document is divided into four sections, including this introductory section. Section 2 details the process used to select the Final LiftWEC Configuration, including details of the various activities completed at the workshop. Section 3 gives an outline of the Final LiftWEC Configuration. Section 4 discusses the potential for repechage in the selection of the Final LiftWEC Configuration. Finally, the main report is supplemented by five Appendices. Appendix A details the agenda of the Final LiftWEC Configuration Identification Workshop, including the names of those in attendance each day. Appendix B-E provide the work package assessment slides for the four Baseline Configurations.

2 FINAL CONFIGURATION IDENTIFICATION PROCESS

The process for selection of the Final LiftWEC Configuration was centred around a two-day workshop, which was attended by all primary researchers in the project as well as a number of other employees at the partner institutions and a member of the technical advisory board. Each technical work package was asked to prepare supplementary materials for the workshop ahead of time. Specifically, each work package was asked to prepare a single presentation slide for each of the four Baseline Configurations (i.e. four slides in total). The format of these slides was pre-defined by Work Package 02. Each slide provided space for the presentation of the work package analysis as well as space to present what the work package felt were the most important pros and cons of each Baseline Configuration. The decision to limit each work package to a single slide for each configuration was deliberate and was intended to encourage participants to focus on the key findings relevant to the selection of the Final LiftWEC Configuration, thus ensuring the concise and efficient sharing of each work package's most prominent thoughts, opinions, and analyses. At the workshop, each technical work package was given 4 minutes of time to present their opinions on each Baseline Configuration (16 minutes in total). When possible, additional time was allowed where Q&A was both constructive and informative.

The pre-workshop production of this information ensured that all workshop attendees would have a sufficient level of familiarity with each configuration upon entering the workshop, as well as recent critical assessment of the various configurations.

An outline of the workshop agenda is provided in Table 2.1 below. The complete agenda, together with a list of participants for each day has been reproduced in Appendix A. Further details on each session are provided in the sub-sections below.

Table 2.1: Outline agenda for Baseline Configuration Identification workshop

Day 1 Session 1	**Review/Discussion of Tower LiftWEC** **Review/Discussion of TLP LiftWEC**
Day 1 Session 2	**Review/Discussion of Spar LiftWEC** **Review/Discussion of Semi-Sub LiftWEC**
Day 1 Session 3	**Additional time for further discussion/knowledge sharing (optional)**
Day 2 Session 1	**Small group evaluation of Tower LiftWEC**
Day 2 Session 2	**Small group evaluation of TLP LiftWEC**
Day 2 Session 3	**Small group evaluation of Spar LiftWEC**
Day 2 Session 4	**Small group evaluation of Semi-Sub LiftWEC**
Day 2 Session 5	**Evaluation feedback & discussion** **Selection & Refinement of Final LiftWEC Configuration**

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2.1 REVIEW/DISCUSSION OF LIFTWEC BASELINE CONFIGURATIONS

During the Review & Discussion of the Baseline Configurations, each work package gave a short presentation highlighting their opinions on their perceived pros and cons of each Baseline Configuration, including an outline of relevant analyses conducted by the work package in reaching those conclusions. A short time for questions, comments and general discussion followed the presentation of each work package and provided an opportunity for constructive support/critique of points to be made by other members of the consortium. Each Baseline Configuration was considered independently. That is, all presentations and discussions were completed for the Tower LiftWEC, after which the TLP was considered, then the Spar Buoy, and finally the Semi-Sub. This ensured the greatest continuity of flow and cumulative building of information and opinion.

As would be expected, there were a range of opinions of what features of individual configurations were most desirable, depending on the viewpoint of the work package. This highlights the importance and suitability of the co-design approach taken during planning and execution of the LiftWEC project, ensuring development occurs with these various factors having been already considered and thoroughly discussed and evaluated. However, it was also promising to see that where differences of opinion occurred, these were typically considered by supportive, constructive, and courteous discussion between project partners such that in many cases, the cause and effect of these discrepancies was identified, enabling the information being presented to be put in context.

For the purpose of dissemination and knowledge sharing, the slides associated with work package assessment of the various configurations have been reproduced in Appendix B-E.

2.2 SMALL GROUP EVALUATION OF BASELINE LIFTWEC CONFIGURATIONS

Following presentation of work package assessments, each Baseline Configuration was assessed using the Evaluation Tool developed within the LiftWEC project and described in deliverables D2.2, D2.4, D2.5, D2.6 and D2.9. The evaluation tool consists of an Excel Spreadsheet where each configuration is quantitatively evaluated on the numeration of 36 parameters spread across 16 categories. Due to the reduced number of configurations compared to previous workshops, all participants were involved in the evaluation of all remaining LiftWEC configurations.

First, the Tower LiftWEC Baseline Configuration was evaluated collaboratively by all workshop attendees. This provided a refresher on the use of the Evaluation Tool and provided a benchmark case against which the remaining 3 Baseline Configurations could be scored. Subsequently, the workshop participants were divided into 2 smaller groups to conduct the remaining 3 evaluations in parallel. Attendees were assigned to provide the greatest and fairest spread of expertise across both groups. This provided greater opportunity for the input of individual voices and opinions that might otherwise have been missed during the evaluations. Results from the exercise are presented in Figure 2–1.

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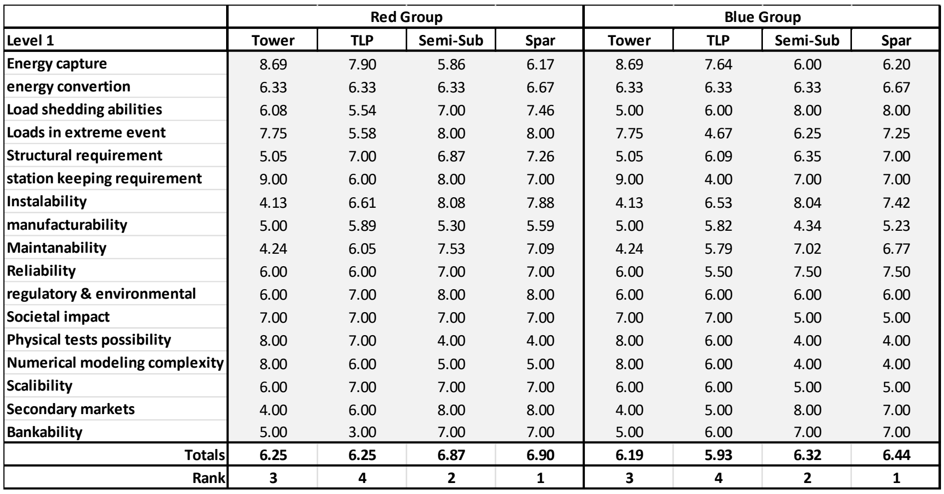

	Red Group				Blue Group			
Level 1	**Tower**	**TLP**	**Semi-Sub**	**Spar**	**Tower**	**TLP**	**Semi-Sub**	**Spar**
Energy capture	8.69	7.90	5.86	6.17	8.69	7.64	6.00	6.20
energy convertion	6.33	6.33	6.33	6.67	6.33	6.33	6.33	6.67
Load shedding abilities	6.08	5.54	7.00	7.46	5.00	6.00	8.00	8.00
Loads in extreme event	7.75	5.58	8.00	8.00	7.75	4.67	6.25	7.25
Structural requirement	5.05	7.00	6.87	7.26	5.05	6.09	6.35	7.00
station keeping requirement	9.00	6.00	8.00	7.00	9.00	4.00	7.00	7.00
Instalability	4.13	6.61	8.08	7.88	4.13	6.53	8.04	7.42
manufacturability	5.00	5.89	5.30	5.59	5.00	5.82	4.34	5.23
Maintanability	4.24	6.05	7.53	7.09	4.24	5.79	7.02	6.77
Reliability	6.00	6.00	7.00	7.00	6.00	5.50	7.50	7.50
regulatory & environmental	6.00	7.00	8.00	8.00	6.00	6.00	6.00	6.00
Societal impact	7.00	7.00	7.00	7.00	7.00	7.00	5.00	5.00
Physical tests possibility	8.00	7.00	4.00	4.00	8.00	6.00	4.00	4.00
Numerical modeling complexity	8.00	6.00	5.00	5.00	8.00	6.00	4.00	4.00
Scalibility	6.00	7.00	7.00	7.00	6.00	6.00	5.00	5.00
Secondary markets	4.00	6.00	8.00	8.00	4.00	5.00	8.00	7.00
Bankability	5.00	3.00	7.00	7.00	5.00	6.00	7.00	7.00
Totals	**6.25**	**6.25**	**6.87**	**6.90**	**6.19**	**5.93**	**6.32**	**6.44**
Rank	**3**	**4**	**2**	**1**	**3**	**4**	**2**	**1**

Figure 2–1: Results from small group evaluations of Baseline Configurations

In previous workshops, the Evaluation tool was found to be especially useful as a tool to encourage structured discussion and to openly identify, challenge and test potential subjective bias. The same finding was made in this workshop, however with a much greater understanding of the technologies now being held by the consortium, it is expected that the quantitative comparisons are probably also now of greater value than they might have been earlier in the project.

Interestingly, the results obtained from both groups result in the exact same ranking of the Baseline Configurations. In both cases, results ranked the four Baseline Configurations in the following order (with the highest ranked configuration listed first):

1. Spar LiftWEC
2. Semi-Sub LiftWEC
3. Tower LiftWEC
4. TLP LiftWEC

2.2.1 Sensitivity Analysis of Baseline Configuration Evaluation Scoring

During the discussions associated with selection of the Final LiftWEC Configuration, INNOSEA, who produced the Evaluation Tool, noted the difficulty in producing such a tool for a technology at such an early stage of development and noted that further refinement of the categories and their weightings might lead to different results[1]. Notwithstanding, in order to further evaluate the sensitivity of the results to amendments in the methods used to quantify the evaluations, INNOSEA conducted a statistical sensitivity analysis on the results, the details of which are included herein.

As outlined in deliverable D2.4, the evaluation tool is split into two phases: a first exercise allowed the team to define the weighting of the different evaluation criterion, and the second phase focuses on the scoring of the selected configuration against each criterion, leading to a global score for each configuration.

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[1] Although during the workshop, further discussion and analysis concluded that even if this were to be the case, there are also still significant qualitative arguments for the selection of the Spar Buoy as the Final LiftWEC Configuration.

The process of generating the weightings and scoring by the consortium yielded several evaluations (nearly one per partner for the weighting of the criterion, and two different set of scores for each configuration), which then allows the evaluation of the variability of each input into the final score of the configurations. The mean and standard deviation of the Level 1 criteria are shown in Table 2-1.

To evaluate the impact of the variability of scores and criterion's weights, a Monte Carlo simulation is conducted using a thousand iterations. For each iteration, the weights of the Level 1 criteria are selected randomly into a normal distribution defined by their mean weight and standard deviation, and the Level 1 scores are selected in a uniform distribution of min and max equals to the scores obtain by the red and blue group (see Figure 2–1). For each iteration, the weights of the criterion are normalised to ensure that their sum is 100%.

The thousand scores obtained for each configuration are presented in box plot format in Figure 2–2. A normal distribution is applied to the scores, and it is presented in Figure 2–3. From these plots, it is visible that the scores of the Tower are less variable, which is due to the fact that this configuration was scored by consensus over a single group. The variability observed is therefore only due to the variability of the weights. Two groups are clearly defined, Tower and TLP on one side, and Semi-Sub and Spar on the other. There is a marked difference between these groups, with very little overlap between the distributions of the scores. This gives credit to the selection of one of the floating options once all the criteria are considered.

Table 2-1: mean weight and standard deviation associated to Level 1 criterion

Criterion	mean weight	standard deviation
Energy capture	8.38%	2.2%
energy conversion	7.21%	2.0%
Load shedding abilities	5.70%	1.8%
Loads in extreme event	8.24%	1.4%
Structural requirement	6.21%	0.9%
station keeping requirement	4.27%	0.7%
Installability	5.83%	0.9%
manufacturability	5.23%	0.9%
Maintainability	6.80%	1.0%
Reliability	8.40%	1.4%
regulatory & environmental	5.40%	2.0%
Societal impact	4.12%	1.4%
Physical tests possibility	4.40%	1.9%
Numerical modelling complexity	4.00%	1.1%
Scalability	5.94%	1.2%
Secondary markets	4.38%	1.3%
Bankability	5.50%	0.5%

Between the 2 different floating solutions, the differences are not so marked. The median values of each are just outside the box of the other, which is normally an indicator of a significant difference between two populations. There is, nonetheless, no suggestion that the choice of the spar should be questioned: the standard deviations of the scores are similar between the two populations, and

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therefore no reason to choose the Semi-sub Configuration over the Spar Configuration based on the results of this sensitivity analysis.

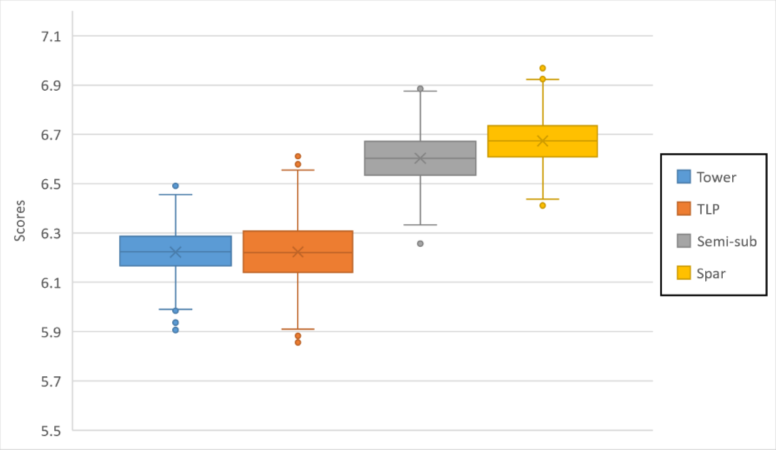

Figure 2–2: results of Monte Carlo simulations for the scores for the 4 Baseline Configurations.

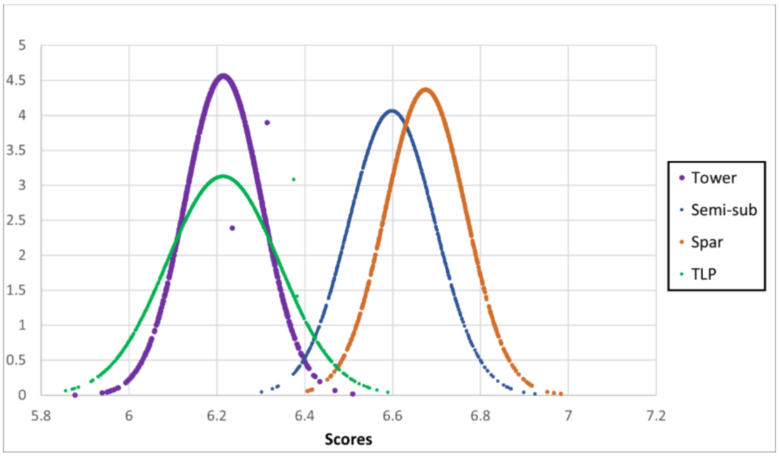

Figure 2–3: results of Monte Carlo simulations for the scores for the 4 configurations presented as normal distributions.

2.3 SELECTION OF FINAL LIFTWEC CONFIGURATION

A round-table discussion and analysis of the results followed completion of the evaluations and presentation of the results to the consortium (the results of the scores being applied were not shown during the exercise). This discussion questioned the points of deviation in the results of the two groups, however in general the scoring was found to be largely similar, albeit with one group typically critiquing negative elements more severely.

After significant deliberation, it was decided that in keeping with the scoring, the Spar Buoy should be selected as the Final LiftWEC Configuration. Partners and other attendees were provided with an opportunity to raise either strong or even minor objections however none were made at the point of decision and so consensus was obtained.

One revision was suggested for incorporation into the Final LiftWEC Configuration. In general, members of the consortium felt that the nominal water depth selected at the start of the project (50m) was too shallow to enable effective use of the single-point catenary mooring system suggested

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for the Spar-Buoy system. As such, the nominal water depth for deployment has now been revised to 100m with a minimum allowable value of 80m assumed.

3 SPECIFICATION OF FINAL LIFTWEC CONFIGURATION

The Final LiftWEC Configuration will form the basis of the majority of works conducted during Phase 4 of the LiftWEC project. As indicated in Section 2.2.1 the Spar LiftWEC was selected as the Final LiftWEC Configuration.

3.1 SPAR LIFTWEC BASIS OF DESIGN OVERVIEW:

The Spar LiftWEC configuration consists of a two-hydrofoil rotor held in place by a twin-tower spar-buoy type float. A 3D CAD rendering of the device is shown in Figure 3–1.

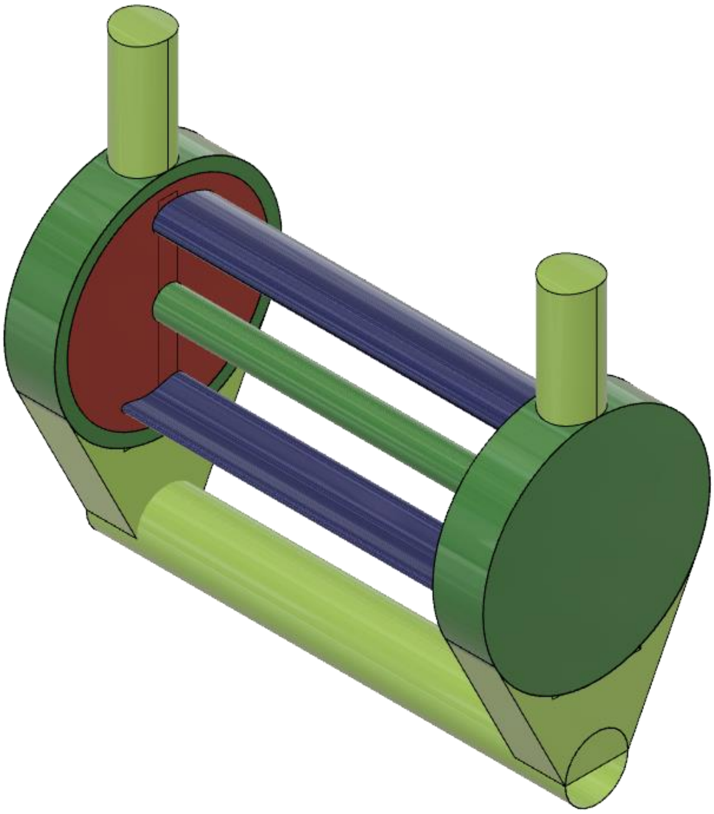

Figure 3–1: 3D Cad Rendering of Spar-Buoy LiftWEC

The structure is held in place by a yoked single-point mooring that sinks to a 3 point catenary line mooring system. The single-point mooring is attached to each tower of the two-tower spar buoy structure via a two-point yoke attachment. The 3 catenary mooring lines are anchored to the seabed using drag anchors. This mooring arrangement allows for free motion of the device in all 6 traditional degrees of freedom, as well as passive yaw of the device to align with the predominant direction of the incident wave-train.

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The 30m span hydrofoils terminate within bearing elements set within the circular endplates. These circular endplates form part of the rotor structure, rotating with the hydrofoils, and are mounted such that they locate within the stator sections of the device (one stator section 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 induced drag, and, (2) to encourage the generation of a lift distribution which is closer to that of a 2-dimensional rotating hydrofoil. Each stator structure houses a direct drive generator which also contains bearing and control mechanisms. Tubular and triangular extrusions extending from the nacelles of the stator section form the spar-buoy elements of the design. A horizontally aligned ballast tube rigidly connects the two sides of the device. The ballast tube is used to reduce pitching of the device due to rotor torque by providing inertial stiffness in the pitch mode of motion. The combined rotor/stator unit is referred to as the power-capture-unit. Submergence control is achieved through ballasting/de-ballasting of the spar-buoy ballast tube and floats. Power-take-off is achieved via two direct drive generators, which are also used to implement phase control. There is no mechanism to control the rotor radius, thus the operational radius of each hydrofoil is fixed. Installation of the anchor and station-keeping system will use non-descript vessels with light-lift cranes and flat-back deck space. Transport of the power-capture-unit for deployment is achieved using tug boats. At the point of deployment, mooring cables are detached from their placeholder buoys and attached to the Nacelles. The ballast tube and floats are then ballasted using sea-water to achieve the desired submergence depth of the rotor and to provide the necessary rotor torque reaction. The design life of the device and all system components is 25 years unless otherwise stated.

3.2 ROTOR SECTION DETAILS

3.2.1 Overview

3.2.1.1 Description of rotor section

The rotor section of the device is shown in *Figure 3–2*. Each hydrofoil (blue) is mounted between two circular endplates (red) and the torque transmitted through a box section (yellow). The hydrofoils are mounted on radial bearings set into the circular end plates. These bearings enable pitch control via actuators (lime green). The entire rotor structure is stiffened by the addition of a cylindrical hollow shaft (green) mounted between the centres of the two endplates on the axis of rotation. The rotor component of the direct drive generators is set behind the endplates and the entire rotor section is located within the bearing structure of the direct drive generators (i.e. the direct drive generators act as the bearing mechanism).

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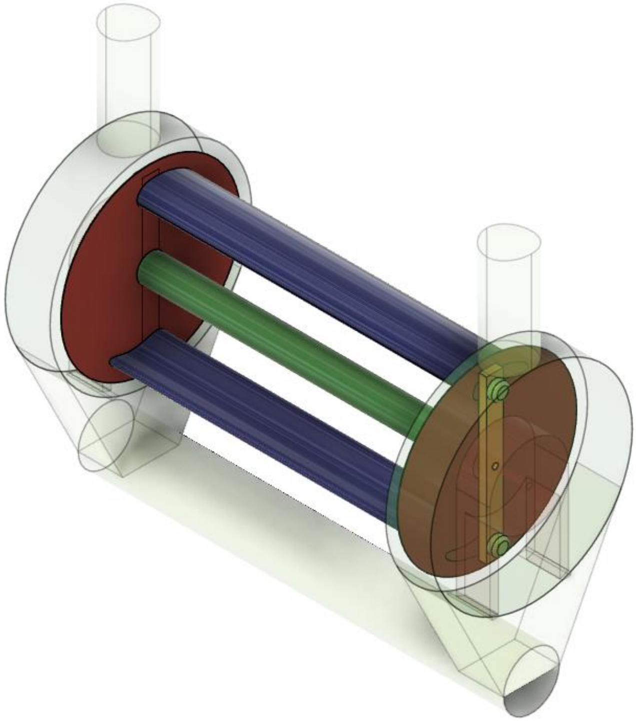

Figure 3–2: Rotor section detail

3.2.2 Hydrofoils

3.2.2.1 Number & layout of hydrofoils

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

3.2.2.2 Mechanical description of hydrofoil elements

Each hydrofoil has the following primary dimensions:

- Span: 30m
- Chord length: 6m
- Fixed operational radius: 6m
- Profile: NACA 0015 (curved along hydrofoil path)

The hydrofoil cross-section is defined with the chord line projected onto the operational radius of the device when the foil is set to 0° pitch angle. Each hydrofoil has a shaft protruding from each end at the centre of action of the hydrofoil cross section. These shafts locate the device within the radial bearing set into the rotor end plates to enable pitch control.

Hydrofoils are of composite construction, similar to wind turbine blades.

3.2.2.3 Linear speed of hydrofoils

Linear speed in 4s waves:	9.4m/s	(expected maximum speed – 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)

3.2.2.4 Design life of hydrofoil elements

15 years. Design life defined by fatigue life.

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3.2.3 Hydrofoil mounting structure

3.2.3.1 Overview of mounting structure

The radius of the rotor endplates is greater than the operational radii of the hydrofoil elements to reduce lift loss due to the finite hydrofoil span, and to restrict the generation of induced drag via tip vortex formation.

3.2.3.2 Mechanical description of mounting structure

The circular endplates are 16 metres in diameter and made of steel plate with scantling as required. A box section connects the hydrofoil ends to the generator rotor to transmit the drive torque. A 2.5 metre diameter circular hollow shaft spans the 30m length between the two end plates.

The endplates are manufactured from welded rolled steel sections and are coated with a marine corrosion resistant paint. The scantlings are structural Tee-beam sections welded to the rear face of the endplates. The centrally located cylindrical shaft spanning the length of the rotor section are constructed as a welded steel pipe.

3.2.4 Pitch actuators

3.2.4.1 Mechanical description of pitch actuators

Double-acting actuators are used for pitch control. Each hydrofoil pitch is controlled by two actuators, one at each end of the hydrofoil. Position feedback from the actuators is used to ensure they operate synchronously to avoid generating unnecessary torsion in the hydrofoils.

3.2.5 Rotor bearing arrangement

3.2.5.1 Attachment to bearing mechanism

The rotor rotates in bearings within the direct drive generators. For more on the direct drive generators see Section 3.3.3.

3.3 STATOR SECTION DETAILS

3.3.1 Overview

3.3.1.1 Description of stator section

The stator section of this configuration is shown in *Figure 3–3* and contains the two Nacelle units.

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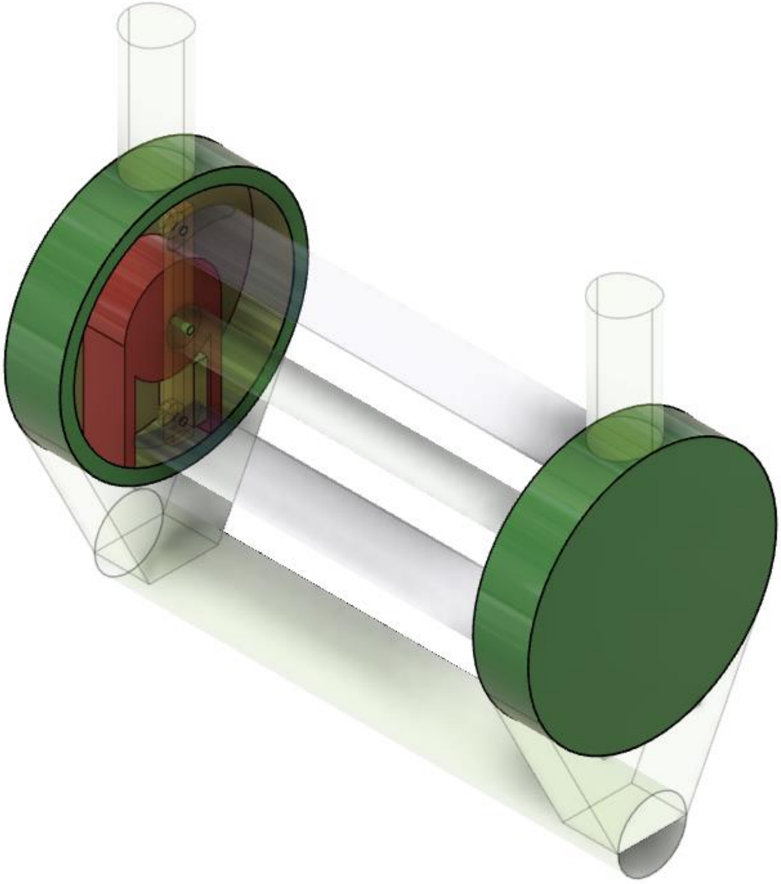

Figure 3–3: Stator section details

The two Nacelles support the device's rotor section and each Nacelle houses a single direct driver generator, ancillary power electronics and braking mechanisms.

3.3.2 Bearing mechanism

3.3.2.1 Description of bearing mechanism

The rotor section rotates on the direct drive generator bearings set within each Nacelle. More detail on the direct drive generators can be found in Section 3.3.3.

3.3.3 Direct drive generator(s)

3.3.3.1 Key function(s)

The direct drive generators provide the mounting and bearing facilities for the rotor of the device as well as the means of power-take-off and phase control.

3.3.3.2 Electrical Specification

The device incorporates two direct drive generators, each with 750 kW rating. It is assumed that generator power performance can be represented by 5% iron losses and 5% copper losses as given in the Equation below.

$$P_{loss} = 0.05\, P_{rating} + 0.05\, P_{capture}$$

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3.3.3.3 Mechanical specification

The generator is assumed to be 3 metres in length with a 7 metre diameter and generate a maximum magnetic shear stress of 10kPa. This results in the generation of 2.3MNm of torque corresponding to a power rating of 1.15MW at 0.5rad/s (5rpm). Additional space is available within the Nacelle if a larger generator is considered to be required to generate this or a larger torque.

3.3.4 Ancillary power electronics

3.3.4.1 Specification of ancillary power electronics

Each individual wave energy converter will have a set of back to back inverters on board converting the generated electricity from AC-DC-AC. In addition, onboard transformers will convert WEC electricity to 33kV for connection to a substation.

3.3.5 Nacelles

3.3.5.1 Overview of Nacelle units

A Nacelle unit sits at each spanwise end of the rotor section. Each Nacelle houses a direct drive generator along with associated ancillary power electronics and braking mechanisms. The Nacelle units provide environmental protection from the marine environment as well as a means of attachment to the semi-submersible. Each Nacelle unit will have two electric bilge pumps to remove water from the Nacelles if required.

3.3.5.2 Mechanical details of Nacelles

Each Nacelle unit consists of an 18 metre diameter cylindrical hollow steel shell (see *Figure 3–3*). Each Nacelle has a length of 4.5m metres. The Nacelle shell consists of steel plate with scantlings as required. In addition, each Nacelle unit has an internal structure for mounting of the generator, ancillary power electronics and braking mechanisms.

3.4 STATION-KEEPING SYSTEM DETAILS

3.4.1 Overview

3.4.1.1 Description of station keeping system

The station-keeping system consists of the spar buoy elements of the design, the single-point sunken mooring and the three catenary mooring cables. The spar-buoy elements of the station keeping system are highlighted in *Figure 3–4*. Note that the system has been designed as presented such that; (1) the pitch stiffness afforded by the spar buoy structure is sufficient to suitably limit pitching of the device due to the operational rotor torque (see Section 3.7), and, (2) the natural periods of the device in heave and pitch are outside the range expected to be excited by incident waves (see Section 3.7).

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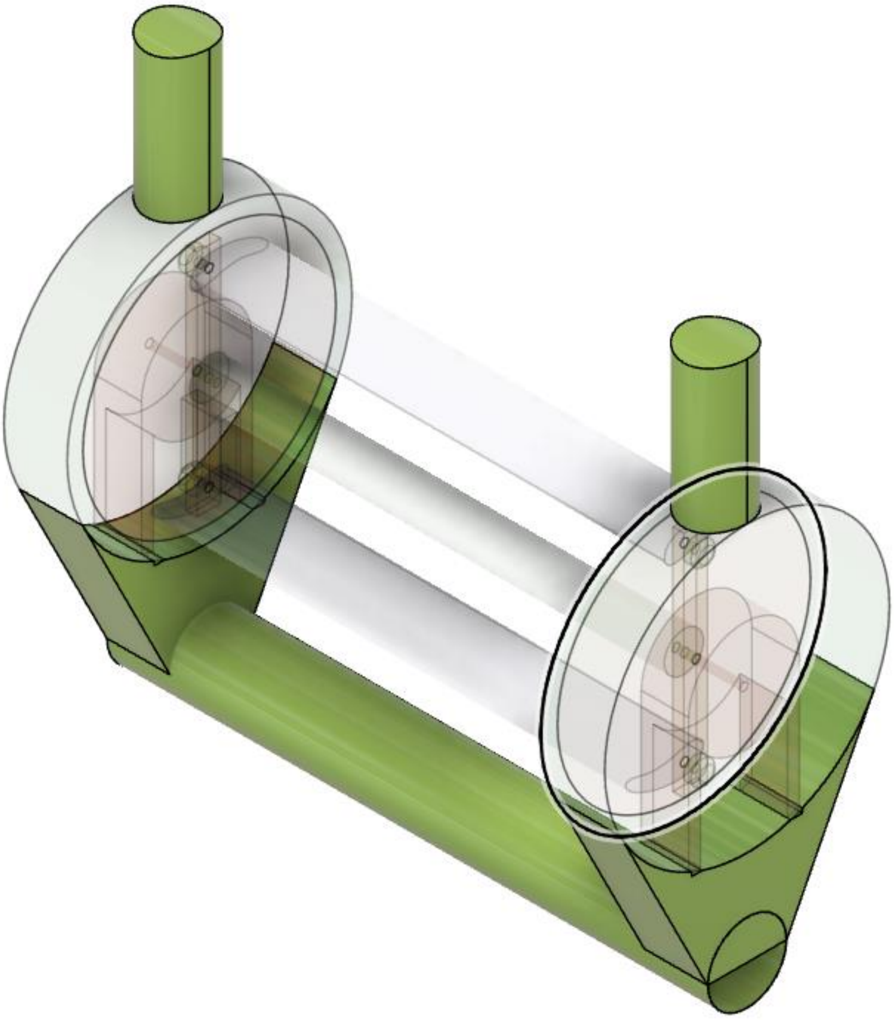

Figure 3–4: Spar LiftWEC element details

3.4.2 Spar LiftWEC Elements

3.4.2.1 Mechanical description of the spar-buoy elements

To facilitate cost reduction and ease design and manufacture, the spar-buoy components of the device have been mechanically integrated into the device Nacelles. That is, the spar-buoy functionality is provided by mechanical elements which extend out from the two nacelle units. These mechanical elements are separated into upper and lower portions that extend from the top and bottom of the nacelles respectively.

The upper portion of the spar-buoy elements consist of two 3m diameter hollow cylindrical sections. One cylinder extends vertically upwards from each Nacelle as shown in *Figure 3–4*. Note however that *Figure 3–4* is provided for illustrative purposes only and the precise dimensions may not match those detailed in the text. Each extrusion extends to a height of 18m vertically upwards from the rotational axis of the device to provide 2m freeboard at maximum submergence.

The lower portion of the spar-buoy elements consists of a trapezium-shaped extension to the bottom of the Nacelle and a ballast tube which spans the width of the device between the two trapezium sections. The ballast tube consists of a 6m diameter welded steel tube that spans the entire 39m of the device. The centre of the horizontal ballast tube is located 16m below the rotational axis of the rotor.

The spar-buoy towers are used to provide additional buoyancy and stiffness in the pitch mode of motion. The spar-buoy ballast tube is used primarily to react the rotor torque generated during operation. The entirety of the spar buoy structure is constructed of welded steel plate with scantling as required.

3.4.2.2 Description of submergence control and installation mechanisms

Baffling within the trapezium-shaped extensions and the ballast tube allow ballasting of each component in sections. Seawater pumps are used to ballast both the ballast tube and the trapezium-shaped extensions both for installation of the device and for submergence control.

3.4.3 Moorings

3.4.3.1 Mechanical description of the single-point catenary mooring

The single point sunken mooring consists of two mooring cables, one attached to each Nacelle of the device. These cables sink to a sunken coupling with net positive buoyancy. The sunken coupling then attaches to the catenary mooring system which sinks to the drag anchor foundation set on the seabed. At present, the expected station-keeping loads are unknown. Specification of the mooring system should be completed when these values are available.

3.5 ANCHOR & FOUNDATION DETAILS

3.5.1 Overview

3.5.1.1 Description of anchor and foundations

The anchoring system consists of six drag anchors, two at the end of each mooring line. Note that the drag anchors are not required to transmit the rotor torque or fundamental reaction forces generated by the device as these are reacted by the buoyancy, weight and inertia of the semi-submersible itself. Rather, the anchor and foundation system is only required for station-keeping purposes and so only needs to react the wave loads acting on the semi-submersible. At present, the expected station-keeping loads are unknown. Specification of the drag anchors should be completed when these values are available.

3.5.2 Drag anchor specification

3.5.2.1 Key function

The purpose of the drag anchors is to keep the Spar LiftWEC on station though the catenary mooring system as described in Section 3.4.3.

3.5.2.2 Mechanical description of the drag anchors

It is envisaged that standard drag anchors are used such as those shown in Figure 3–5. The size of these drag anchors will depend on the expected loads and required resistance to motion.

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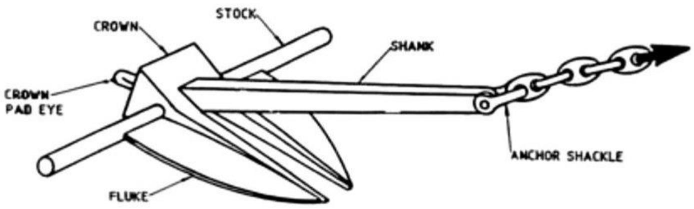

Figure 3–5: Example of a drag anchor that could be used with Spar LiftWEC

3.6 CONTROL STRATEGY DETAILS

3.6.1 Overview

3.6.1.1 Description of device control

Control is broken down into the following categories:

Phase Control: Phase control refers to the device's control of the instantaneous position, velocity and acceleration of the rotor/hydrofoils. This configuration permits the implementation of phase control as detailed in Section 3.6.2.

Pitch Control: Pitch control refers to the device's control over the pitch angle of the hydrofoil elements. This configuration permits the implementation of pitch control as detailed in Section 3.6.3.

Moment of Inertia Control: Moment of Inertia control refers to the device's control of the instantaneous moment of inertia of the rotor elements. This configuration does not permit the implementation of moment of inertia control as noted in Section 3.6.4.

Radius Control: Operational radius control refers to the device's control of the operational radius of the hydrofoil elements. This configuration does not permit the implementation of radius control as noted in Section 3.6.5.

Submergence Control: Submergence control refers to the device's control over the rotor submergence beneath the free water surface. This configuration permits the implementation of submergence control as detailed in Section 3.6.6.

Yaw Control: Yaw control refers to the device's control over the yaw (heading) angle of the rotor section. This configuration does not incorporate yaw control.

3.6.2 Rotor phase control

3.6.2.1 Phase control objectives and strategy

The rotor phase control objective of this configuration is to maximise the power capture, whilst avoiding excessive fatigue loads on the structure.

The rotor control strategy is defined as 'Phase Optimal', meaning that active, instantaneous, real-time control is used to maximise the hydrodynamic performance of the device. This is achieved through identification and implementation of the instantaneous kinematic (position, velocity, acceleration etc.) conditions required to achieve the minimum cost of energy generated. This control strategy effectively seeks to extract the maximum amount of energy for the lowest possible structural task and

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operational expenditure. However, the relationship between a given structural task and the cost of providing that structural reaction may not be linear and so this relationship must be further considered in developing the control strategy.

3.6.2.2 Phase control operational requirements and implementation

Phase control of the rotor will be applied using four-quadrant control of the direct drive generators (see Section 3.3.3).

3.6.2.3 Impact of phase control

Ensuring that the hydrofoils have the optimum phase relationship with the incoming wave is necessary to maximise the power capture. This is equivalent to achieving resonance in a traditional wave energy converter so that the energy is always flowing from the sea into the wave energy converter.

3.6.3 Hydrofoil pitch control

3.6.3.1 Pitch control objectives and strategy

The primary objective of the hydrofoil pitch control of this configuration is to maximise the power capture, whilst avoiding excessive fatigue loads on the structure. In addition, the pitch control system may be used to decouple the device from the incident waves, either to reduce peak loads or to reduce power capture should this be desirable.

Pitch control will typically be implemented as real-time, instantaneous pitch control in a continuous fashion. Pitch control should be used such the ideal instantaneous angle of attack is experienced by a given hydrofoil at all times.

3.6.3.2 Pitch control operational requirements and implementation

Pitch control will be applied via a series of linear actuations. For more details on the Pitch Actuators see Section 3.2.4. The pair of linear actuators on each hydrofoil will operate in tandem to minimise the generation of torsional loads in the hydrofoil. However, the pitch of each hydrofoil is independently controllable, which may be used to maximise the power capture.

3.6.3.3 Impact of pitch control

Pitch control allows the lift force generated by the hydrofoil to be matched to the incident waves. In any sea-state there is an optimum lift force to maximise power capture, and pitch control enables this optimum lift force to be achieved.

3.6.4 Moment of inertia control

No control of the moment of inertia is envisaged in this configuration.

3.6.5 Hydrofoil radius control

No control of the hydrofoil radius is envisaged in this configuration.

3.6.6 Rotor submergence control

3.6.6.1 Submergence control objectives and strategy

The primary objective of the rotor submergence control of this configuration is to maximise the power capture, whilst avoiding excessive fatigue loads on the structure. An additional objective of submergence control is to protect the rotor from wave slamming or wave impact loads during storms by increasing the rotor submergence depth. A final objective of rotor submergence control is to facilitate particular marine operations.

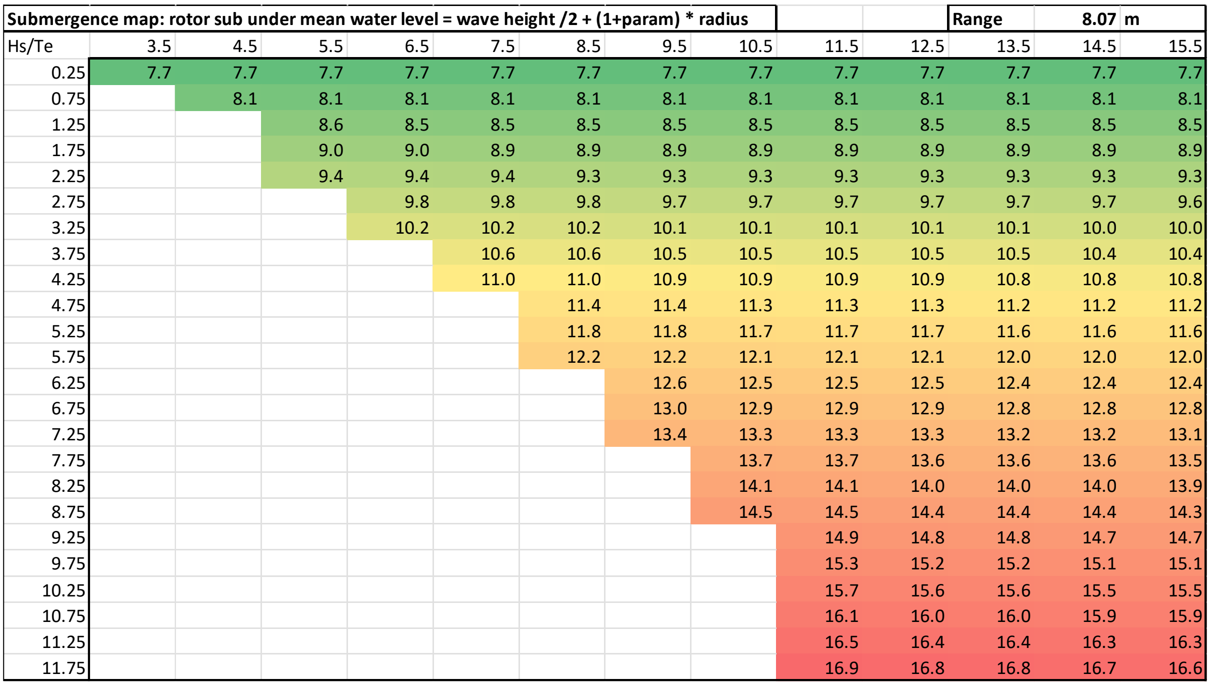
Control of the rotor submergence depth is on a sea-by-sea basis (assuming changes in submergence will take approximately 10-15 minutes to achieve). This is often termed slow-control.

For operational sea states, the objective of the submergence control strategy is to set the turbine as high as possible in the water column to maximize its exposure without risking having a blade piercing the surface.

The highest crest to though wave height H_{CT} as defined from DNV.GL (2017), Clause 3.5.11.5. (JONSWAP sea states with a γ=3.3 and 1h duration are assumed) is estimated. The submergence S_R of the rotor axis from the water surface at rest is defined as:

$$S_R = \frac{H_{CT}}{2} + 1.25 \cdot radius$$

This ensures a blade tip clearance of 1.5m in all cases. The table below present the theoretical submergence for all sea states. The range is estimated counting on sea states between Hs=1.25m to Hs=8.75m, plus an extra 2m to account for the potential tidal range.



Submergence map: rotor sub under mean water level = wave height /2 + (1+param) * radius										**Range**	**8.07**	**m**
Hs/Te	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
0.25	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
0.75		8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
1.25			8.6	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
1.75			9.0	9.0	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9
2.25			9.4	9.4	9.4	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3
2.75				9.8	9.8	9.8	9.7	9.7	9.7	9.7	9.7	9.7	9.6
3.25				10.2	10.2	10.2	10.1	10.1	10.1	10.1	10.1	10.0	10.0
3.75					10.6	10.6	10.5	10.5	10.5	10.5	10.5	10.4	10.4
4.25					11.0	11.0	10.9	10.9	10.9	10.9	10.8	10.8	10.8
4.75						11.4	11.4	11.3	11.3	11.3	11.2	11.2	11.2
5.25						11.8	11.8	11.7	11.7	11.7	11.6	11.6	11.6
5.75						12.2	12.2	12.1	12.1	12.1	12.0	12.0	12.0
6.25							12.6	12.5	12.5	12.5	12.4	12.4	12.4
6.75							13.0	12.9	12.9	12.9	12.8	12.8	12.8
7.25							13.4	13.3	13.3	13.3	13.2	13.2	13.1
7.75								13.7	13.7	13.6	13.6	13.6	13.5
8.25								14.1	14.1	14.0	14.0	14.0	13.9
8.75								14.5	14.5	14.4	14.4	14.4	14.3
9.25									14.9	14.8	14.8	14.7	14.7
9.75									15.3	15.2	15.2	15.1	15.1
10.25									15.7	15.6	15.6	15.5	15.5
10.75									16.1	16.0	16.0	15.9	15.9
11.25									16.5	16.4	16.4	16.3	16.3
11.75									16.9	16.8	16.8	16.7	16.6

More details are provided in LW-WP02-INN-DT02-1x0 Submergence strategy.xlsx

3.6.6.2 Submergence control operational requirements and implementation

Control of the rotor submergence depth is achieved by ballasting/de-ballasting the various elements of the spar-buoy.

3.6.6.3 Impact of submergence control

The power capture is generally higher the closer that the hydrofoil is to the surface and so in typical conditions the hydrofoil is kept as close to the surface as possible without risking breaching the surface. Conversely, in large sea-states submergence control can be used to allow the WEC to continue

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generating power without excessive loads on the structure. Finally, in the most extreme sea-states submergence control can be used to limit the structure loads by minimising the interactions with the incident waves.

3.6.7 Yaw control

3.6.7.1 Yaw control objectives and strategy

No active yaw control will be applied. The device is expected to passively yaw to orientate itself towards the incoming waves by means of the single point mooring arrangement.

3.6.7.2 Impact of yaw control

Allowing the device to orientate itself orthogonal to the mean direction of wave propagation should help to maximise the power capture. Aligning to the mean direction of wave propagation is also expected to reduce the torsional loads on the rotor due to an asymmetrical variation in the lift force along the length of the hydrofoil.

3.7 DEVICE HYDRODYNAMICS

3.7.1 Rotor axis motions

The rotor's axis of rotation is free to move in all 6 degrees of freedom due to; (1) forces generated by the rotor (hydrofoils) during operation, (2) wave action on the semi-submersible, and (3) other environmental forces (tidal, wind, etc.).

An estimate of the expected operational pitching of the rotor axis was assessed using an analysis based on the principles of static equilibrium (reported in internal LiftWEC document LW-WP02-MF-N48). It was estimated that device pitch due to the rotor torque was less than 11°.

Real time motion of the rotor axis in heave and surge should be determined by an appropriate high-fidelity numerical method.

3.7.2 Natural frequency

The natural frequency of the device in heave and pitch was assessed as part of LW-WP02-MF-N48. In that document it was found that the natural frequencies of the structure in heave and pitch were approximately 31 and 30 seconds respectively. These are assumed to be sufficiently beyond the expected range of incident wave frequencies that excitation of these frequencies should not be a significant issue for the device.

3.8 DEVICE LOAD PATHS

3.8.1 Rotor reaction torque

The reaction source of the rotor torque is the pitch stiffness of the spar-buoy.

The torque generated by the rotor, which is resisted by the direct drive generators, is ultimately reacted by the spar-buoy. A suitably rigid structural path is therefore required from the rotor, through the generator to the spar-buoy.

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3.8.2 Fundamental reaction loads

The reaction source of the fundamental loads is a combination of the inherent buoyancy and self-weight of the combined rotor and spar-buoy portions of the device. A suitably rigid structural path is therefore required from the rotor, through the generator to the spar-buoy.

3.9 WAVE FARM DESIGN

3.9.1 Outline wave farm design

3.9.1.1 Device layout

The 100-unit farm (150 MW) should see devices placed in a zig-zag formation to reduce the crest-wise device spacing required owing to the slack-line mooring configuration. Devices will be placed at a crest-wise spacing of 273m, or seven times the total device span (including Nacelles). Spacing in the direction of wave propagation between adjacent devices will be 95m. This level of spacing is suggested as the device must be able to passively yaw according to the prevailing wave direction. If operational procedures permit, this spacing could be reduced from a hydrodynamic perspective without a significant loss of power capture. The layout may also be modified based on the seabed conditions.

3.9.2 Wave Farm Electrical Components

3.9.2.1 Specification of wave farm electrical components

TBC.

3.9.3 Grid connection

3.9.3.1 Specification of subsea cable

TBC.

3.9.3.2 Grid connection substation

TBC.

3.10 SITE DETAILS

3.10.1 Location

3.10.1.1 Geographical location of proposed site

The proposed deployment site is located at 47.84° N, 4.83° W in the Bay of Audierne off the west coast of France close to Quimper (see *Figure 3–6*).

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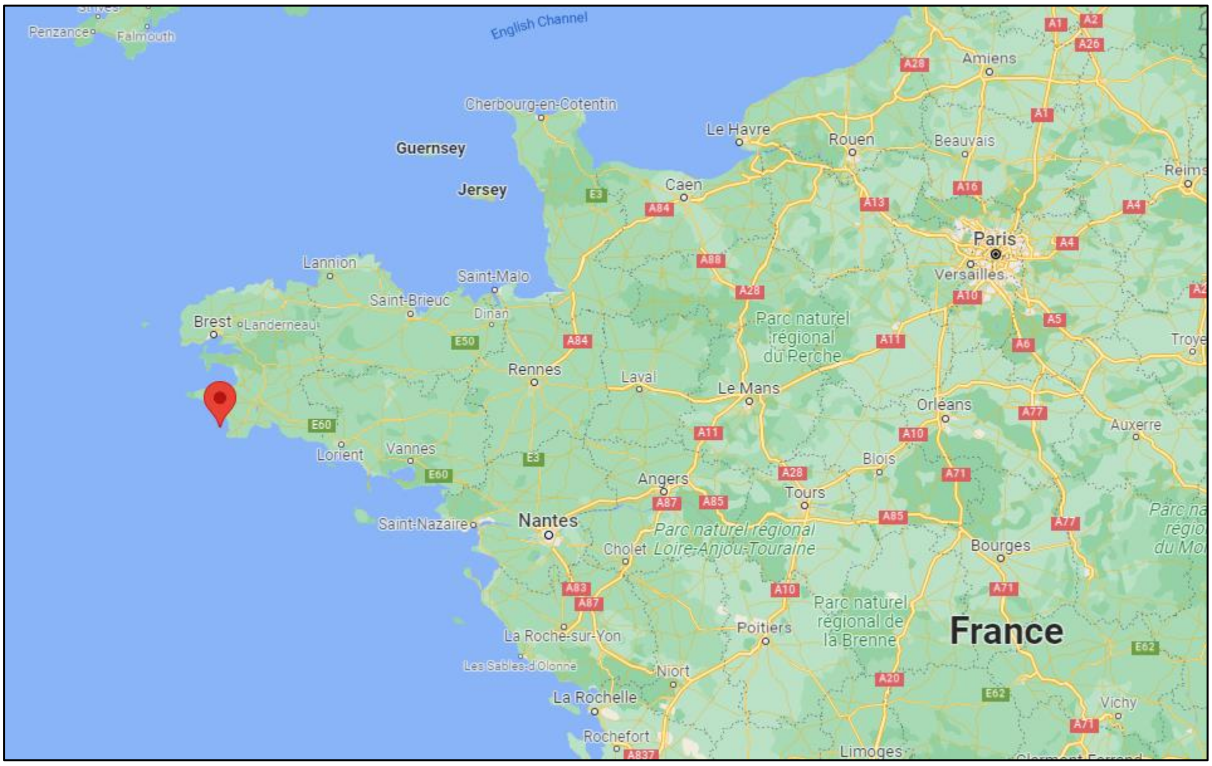

Figure 3–6: Location of proposed wave farm. Image taken from Google Maps.

3.10.1.2 Distance to port

The distance to a port suitable for installation vessels is assumed to be 50 km.

3.10.1.3 Distance to maintenance

The distance to a port suitable for maintenance vessels is assumed to be 20 km.

3.10.2 Spatial planning

3.10.2.1 Site size and shape

For a zig-zag array of 100 devices, the proposed marine site requirement is 10.9km^2 (27.3km x 0.4km).

3.10.3 Ground conditions

3.10.3.1 Geotechnical strata specification

The general geotechnical strata at the site is that the seabed consists of consolidated sand/mud to a depth of at least 30 metres below the seabed. A more detailed description is provided in LiftWEC Deliverable D9.2.

3.10.4 Environmental conditions

3.10.4.1 Water depth

The mean water depth across the site is 80m. It is assumed the water depth does not deviate significantly from this mean across the extent of the site.

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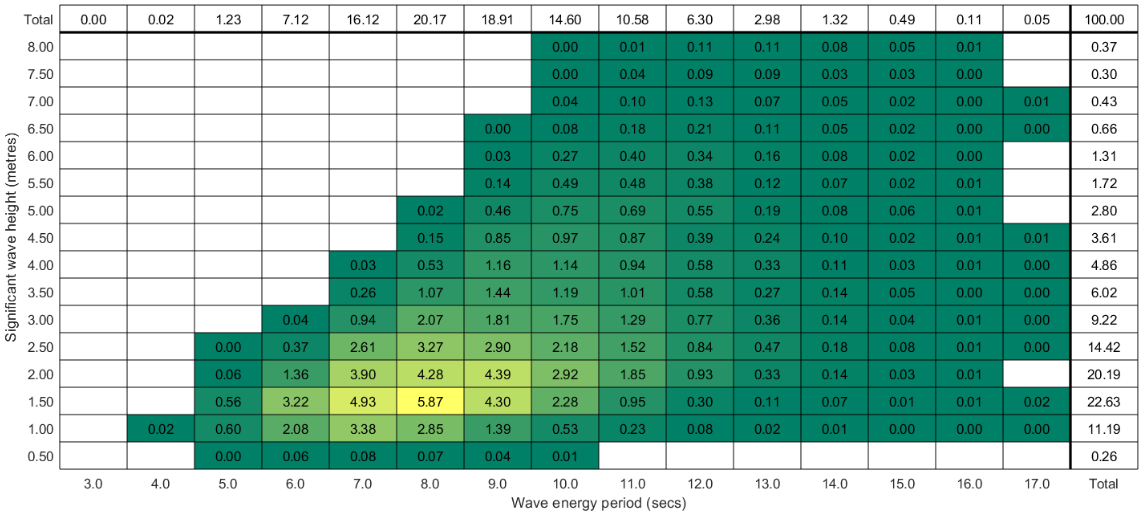
3.10.4.2 Wave climate

The scatter table for the site is provided in *Figure 3–7*.



Significant wave height (metres)																
Total	0.00	0.02	1.23	7.12	16.12	20.17	18.91	14.60	10.58	6.30	2.98	1.32	0.49	0.11	0.05	100.00
8.00								0.00	0.01	0.11	0.11	0.08	0.05	0.01		0.37
7.50								0.00	0.04	0.09	0.09	0.03	0.03	0.00		0.30
7.00								0.04	0.10	0.13	0.07	0.05	0.02	0.00	0.01	0.43
6.50							0.00	0.08	0.18	0.21	0.11	0.05	0.02	0.00	0.00	0.66
6.00							0.03	0.27	0.40	0.34	0.16	0.08	0.02	0.00		1.31
5.50							0.14	0.49	0.48	0.38	0.12	0.07	0.02	0.01		1.72
5.00						0.02	0.46	0.75	0.69	0.55	0.19	0.08	0.06	0.01		2.80
4.50						0.15	0.85	0.97	0.87	0.39	0.24	0.10	0.02	0.01	0.01	3.61
4.00					0.03	0.53	1.16	1.14	0.94	0.58	0.33	0.11	0.03	0.01	0.00	4.86
3.50					0.26	1.07	1.44	1.19	1.01	0.58	0.27	0.14	0.05	0.00	0.00	6.02
3.00				0.04	0.94	2.07	1.81	1.75	1.29	0.77	0.36	0.14	0.04	0.01	0.00	9.22
2.50			0.00	0.37	2.61	3.27	2.90	2.18	1.52	0.84	0.47	0.18	0.08	0.01	0.00	14.42
2.00			0.06	1.36	3.90	4.28	4.39	2.92	1.85	0.93	0.33	0.14	0.03	0.01		20.19
1.50			0.56	3.22	4.93	5.87	4.30	2.28	0.95	0.30	0.11	0.07	0.01	0.01	0.02	22.63
1.00		0.02	0.60	2.08	3.38	2.85	1.39	0.53	0.23	0.08	0.02	0.01	0.00	0.00	0.00	11.19
0.50			0.00	0.06	0.08	0.07	0.04	0.01								0.26
	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	Total

Wave energy period (secs)

Figure 3–7: Wave spectra for the proposed wave farm location

Direction data TBC.

3.10.4.3 Tidal climate

The maximum tidal range for the site is 2.0 metres.

3.10.5 Weather window analysis

Although a detailed weather window analysis

3.10.6 Leasing requirements

The seabed is leased on a fixed term basis for the total expected lifetime of the project (25 years).

3.11 OPERATIONS & MAINTENANCE DETAILS

3.11.1 Installation

3.11.1.1 Preparatory siteworks

The preparatory siteworks will be undertaken by a specialist contractor following a detailed survey of the seabed. The actual siteworks undertaken is anticipated to vary with each location depends on the specific seabed and geotechnical conditions for that location.

3.11.1.2 Anchor and station-keeping system installation activities

Initially, drag anchors will be installed using light-lift anchor handling vessels. The slack-line catenary mooring cables will then be attached to the drag anchors. The same vessel can simultaneously deploy the surface-based place-holder buoy while attaching the top of the mooring line system to this marker buoy for ease of power-capture-unit deployment.

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3.11.1.3 Power-capture-unit and spar-buoy deployment

The power-capture-unit and the integrated spar-buoy are deployed as a single unit. The entire unit is towed to site using two conventional tug units. During towing, the system is de-ballasted and the spar buoy will float horizontally at the free water surface. At the point of deployment, the single point mooring cables are attached to the ballast tube and the ballast tube and trapezium-shaped extensions of the nacelles are ballasted using seawater until the device is vertical. 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 (if required).

3.11.1.4 Power-capture-unit recovery operations

Recovery procedure for the power-capture-unit is as the reverse of the deployment procedure using the same procedures and assets (see Section 3.11.1.3).

3.11.2 Operations & maintenance strategy

3.11.2.1 Device maintenance strategy overview

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 and spars as required according to the deployment/recovery procedures described above.

3.11.2.2 Wave farm maintenance strategy overview

In a station of 100 units, it is envisaged that 2-3 ‘spare’ power-capture-units would be kept at “base” for replacement of units brought in for maintenance, thus alleviating time pressures on O&M activities and reducing concerns over weather window availability.

3.11.3 Description of maintenance operations

3.11.3.1 Power-Capture-Unit maintenance operations

All power-capture-unit (PCU) maintenance activities will be undertaken by returning the power-capture-unit to base. The PCU will be maintained on preferred contractor and best-value tender basis for works required.

3.11.3.2 Single-point mooring and catenary mooring line maintenance operations

No significant maintenance expected. Any damage will likely warrant simple replacement of mooring lines. Inspection via ROV.

3.11.3.3 Drag anchors maintenance operations

No significant maintenance expected. Inspection via ROV.

3.11.3.4 Wave farm electrical maintenance operations

TBC.

3.11.4 Decommissioning

3.11.4.1 Overview of decommissioning activities

Decommissioning of the system refers to the removal of the catenary mooring lines and the micro-pile foundations. Removal of the power-capture-unit is covered by the ‘*Recovery*’ operations outlined in a Section 3.11.1.4.

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The drag anchors will be recovered by a light lift vessel and ROV.

3.12 LEVELIZED COST OF ENERGY

3.12.1 Assumptions

Unless specifically stated, cost estimates have been calculated based on the costs gathered under Deliverable 8.1 (Têtu and Fernandez-Chozas, 2020)[2] and included as default values in the LIftWEC LCOE Calculation Tool (Fernandez-Chozas *et al.*, 2022)[3]. It could be discussed whether these default costs, gathered in 2020, are no longer representative of current (spring 2022) prices. For example, steel prices are currently higher (about 20%) than a year ago. In the present exercise, prices before Covid19 and supply chain issues are considered. This is because we notice that many of the other WECs are showing costs calculated also before 2022, and therefore the relative comparison should be valid. Also, the current volatility of the price of raw materials might not be representative of future long term trends, and therefore caution should be used before using the latest data for R&D project with potential realisation in the medium to long term future.

3.12.2 Single WEC Capital expenditure (CAPEX)

3.12.2.1 Development costs

Development and consenting costs are estimated at **approx. 0.5 MEUR (**is equal to 14% of CAPEX of the Spar LiftWEC configuration). **[4]**

3.12.2.2 WEC Structure and Prime mover. Cost Estimates.

A hydrofoil span of 30 m is considered, there are two hydrofoils per rotor, their profile is NACA 0012 (curved along hydrofoil path), and have a 6 m chord length. The unit volume for each hydrofoil is of 9 m^3 (Arredondo-Galeana *et al*., 2021)[5]. If built of **composite**, and assuming an average density of fibreglass of 2000 kg/m^3, total mass of the two hydrofoils is of **36 tonnes**.

The structure of the prime mover (nacelle and rotor) is a 6 meter diameter rotor, built in steel (assumption of 7850 kg/m^3 density) and has a **total mass of 120 tonnes** (Arredondo-Galeana *et al*., 2021)[4]. This includes a centrally rotating shaft the drives the PTO and two lateral supports at both ends of the shaft.

Hence, the WEC structure and prime mover, has a total approximate mass of **150 tonnes**.

The support structure for the spar buoy is estimated at a **total weight of 85 tonnes of steel, at a cost of 3400 EUR/ton**. This might be a conservative estimate.

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[2] A. Têtu and J. Fernandez-Chozas, "Deliverable D8.1 - Cost Database," The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces, Tech. Rep., 2020. Available at: https://liftwec.com/wp-content/uploads/2020/06/LW-D08-01-1x3-Cost-database.pdf; [Accessed 19th January, 2022].

[3] Fernandez-Chozas J, Nielsen K., Pascal R. "Deliverable 8.3 – The LiftWEC LCOE Calculation Tool". The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces (2022).

[4] Fernandez-Chozas J, Nielsen K., Pascal R. "Deliverable 8.4 – LCOE Estimates of Baseline Configurations". The LiftWEC Project. Development of a new class of wave energy converter based on hydrodynamic lift forces (2022).

[5] A. Arredondo-Galeana, N. Clave, R. Pascal, W. Shi, F. Brennan, and P. Lamont-Kane, "Deliverable D6.2 – Transportation and Maintenance LiftWEC ULS Assessment," LiftWEC – Development of a new class of wave energy converter based on hydrodynamic lift forces, Tech. Rep., 2021.

3.12.2.3 Moorings and Installation Cost Estimates

Single point mooring connection system is assumed. This should make marine operations quicker and faster, and possible in higher sea states.

Total cost of the mooring, including lines, anchors and connectors are estimated to be **300.000 EUR** (WES, 2016)[6], as done for Pelamis P2.

The system will require an additional turret in front of the device, and a tether from each nacelle to the turret. A 10% cost increase (30.000 EUR) compared to the semi-sub mooring cost is foreseen, hence **330.000 EUR in total**.

3.12.2.4 Control Cost Estimates

The spar LiftWEC has two controls (pitch and phase control):

- Pitch control of the hydrofoils enabled by two actuators per hydrofoil, one at each end.
- Phase control implemented by direct drive generators, one in each stator.

Submergence is enabled by ballasting, at an approximate cost of 35.000 EUR. There is no yaw control as such, but the system can weather-vane thanks to the moorings.

Total control is thus estimated at 75.000 EUR for the pitch control and 35.000 EUR for the ballasting, **in total 110.000 EUR**.

3.12.3 Single WEC Operational expenditure (OPEX)

3.12.3.1 Maintenance Strategy overview and OPEX estimates

LiftWEC 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. These will be repaired and then re-deployed with i.e. 50-ton tug vessels.

A simple attach/de-attach procedure is expected for the spar buoy thanks to the single-point connection, which allows for a quick and fast operation, which can also be carried out at higher wave heights (and thus, requires for less waiting for weather windows).

OPEX for spar buoy is estimated at 125 kEUR/year.

3.12.4 Annual Energy Production. Power Matrix.

Current estimates on LiftWEC power performance are based on the results from the 2D, regular waves testing, which has also served to validate the numerical models. The next development step is to carry out 3D testing, which will evaluate the effect on the energy capture of a rotor moving or not; and hence, more certainty on power production estimates. Until those results are available (approx. by end of 2022) it has been decided to use estimates for LiftWEC power production based on the CycWEC device.

The power matrix depicted in Figure 3.12.3 has been extracted from (Siegel, 2019)[7], which corresponds to a 60 m span hydrofoil and 5 m chord length cycloidal wave energy converter. LiftWEC baseline configurations have two, 30 m hydrofoils. Accordingly, the same power matrix as in Siegel

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[66] WES (2016) “Moorings and Connection Systems Cost Metrics”. Prepared by Quoceant Ltd. to Wave Energy Scotland.

[7] Siegel S., 2019. “Numerical benchmarking study of a Cycloidal Wave Energy Converter”. Renewable Energy 134 (2019). 309-405

(2019) divided by two has been chosen for the calculation of the TLP LiftWEC, which shares overall structural similarities to CycWEC device.

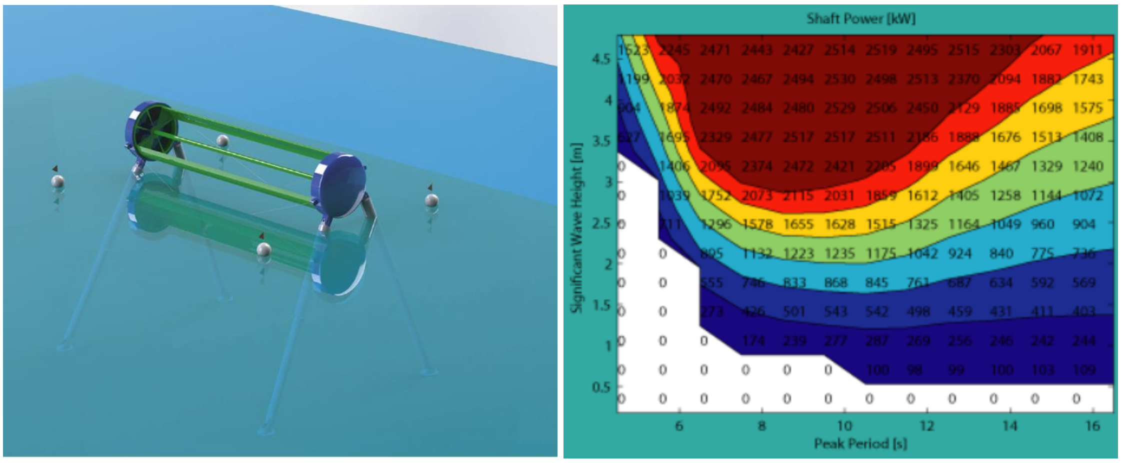

Figure 3.12.3: The Cycloidal Wave Energy Converter (CycWEC) in maintenance position (left) and its power matrix (right). Dimensions: 6-meter radius, 5m chord length, 60m hydrofoils span, 2.5 MW designed power output) (Siegel, 2019).

The down-rated power matrix operating at Ifremer site provides an **annual energy production 2.7 GWh/y** (2722 MWh/y). This value is taken as a reference for the TLP LiftWEC and is also assumed valid for the Spar Buoy.

3.12.5 Uncertainties

There are uncertainties associated both to the input as well as the output values. The economic assessment is subject of several assumptions that will be verified as the development process evolves. It is estimated that at the current stage of development of LiftWEC, results have an uncertainty that varies between [-30% to 80%].

3.12.6 Inputs, CAPEX, OPEX and LCOE Summary Table

	Spar Buoy
Main dimension (width of the WEC) [m]	30 m
Secondary dimension (Rotor diameter) [m]	12 m
Water depth [m]	50 m
Prime mover: Rotor (in steel) [ton]	120
Prime mover: Hydrofoils (fibreglass) [ton]	36
Support structure weight (in steel) [ton]	85
Foundation / mooring [ton]	140
Rated Power (P_r) [MW]	1.5 MW
Annual Energy Production (AEP) MWh/y	2700
Capacity factor	25%
Average annual Capture width ratio	29%

	Spar Buoy
CAPEX [EUR]	
Development costs	500.000
Structural cost: nacelle & rotor	400.000
Hydrofoils	340.000
PTO and housing	750.000
Mooring cost (lines + anchors)	330.000
Support structure	290.000
Control cost	110.000
Installation + Mooring installation cost	275.000
Total CAPEX [MEUR]	**3.6 M€**
Annual OPEX [kEUR/y]	125 k€/y
LCOE (25 years, r=5%) [EUR/MWh]	**140 €/MWh**
CAPEX per MW [MEUR/MW]	**2.9 M€/MW**

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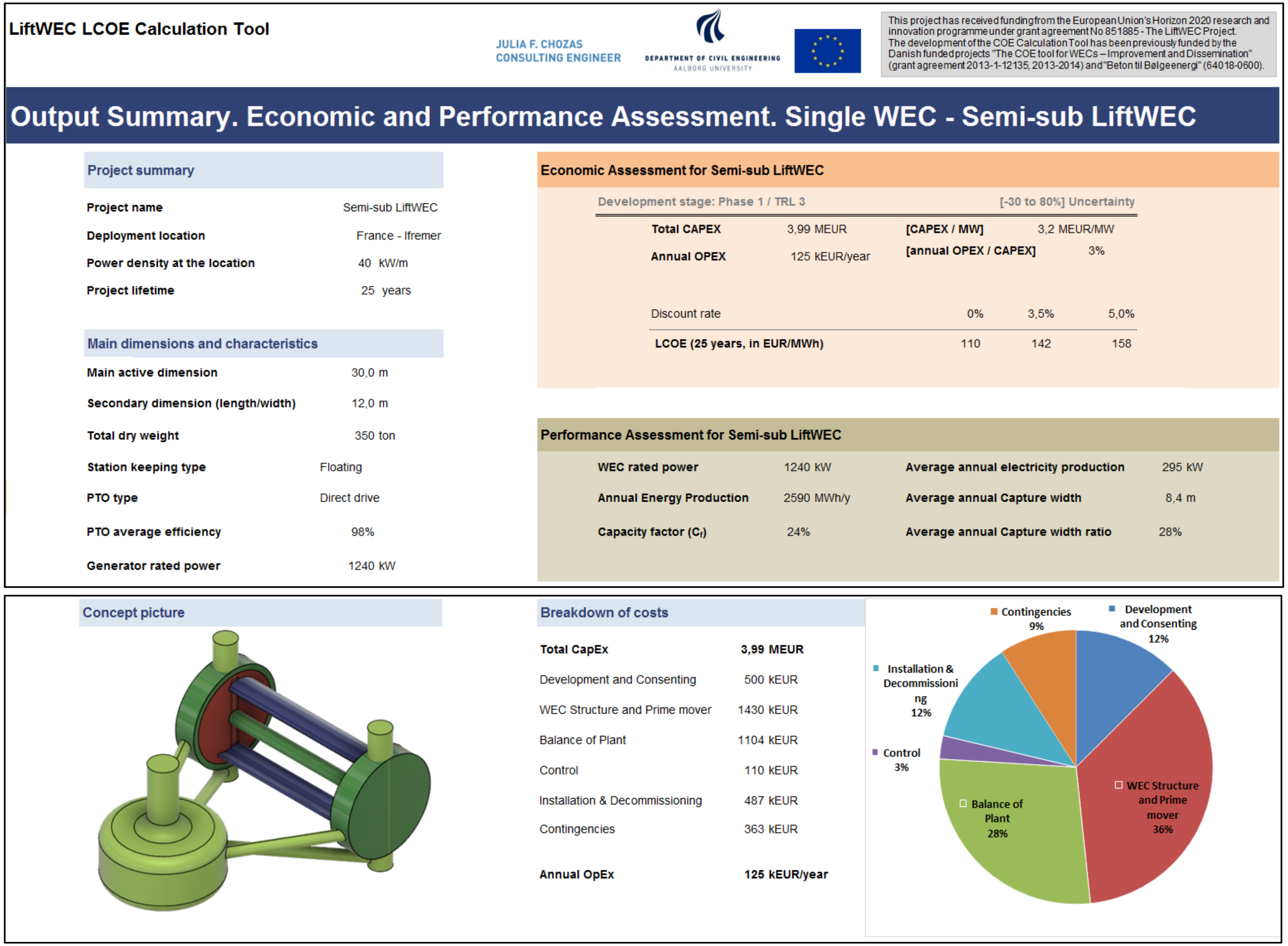
3.12.7 Output Summary Table from LiftWEC LCOE Calculation Tool



LiftWEC LCOE Calculation Tool

JULIA F. CHOZAS CONSULTING ENGINEER

DEPARTMENT OF CIVIL ENGINEERING AALBORG UNIVERSITY

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885 - The LiftWEC Project. The development of the COE Calculation Tool has been previously funded by the Danish funded projects "The COE tool for WECs – Improvement and Dissemination" (grant agreement 2013-1-12135, 2013-2014) and "Beton til Bølgeenergi" (64018-0600).

Output Summary. Economic and Performance Assessment. Single WEC - Semi-sub LiftWEC

Project summary

Project name	Semi-sub LiftWEC
Deployment location	France - Ifremer
Power density at the location	40 kW/m
Project lifetime	25 years

Main dimensions and characteristics

Main active dimension	30,0 m
Secondary dimension (length/width)	12,0 m
Total dry weight	350 ton
Station keeping type	Floating
PTO type	Direct drive
PTO average efficiency	98%
Generator rated power	1240 kW

Economic Assessment for Semi-sub LiftWEC

Development stage: Phase 1 / TRL 3 — [-30 to 80%] Uncertainty

Total CAPEX	3,99 MEUR	**[CAPEX / MW]**	3,2 MEUR/MW
Annual OPEX	125 kEUR/year	**[annual OPEX / CAPEX]**	3%

Discount rate	0%	3,5%	5,0%
LCOE (25 years, in EUR/MWh)	110	142	158

Performance Assessment for Semi-sub LiftWEC

WEC rated power	1240 kW	**Average annual electricity production**	295 kW
Annual Energy Production	2590 MWh/y	**Average annual Capture width**	8,4 m
Capacity factor (C_f)	24%	**Average annual Capture width ratio**	28%

Concept picture

Breakdown of costs

Total CapEx	**3,99 MEUR**
Development and Consenting	500 kEUR
WEC Structure and Prime mover	1430 kEUR
Balance of Plant	1104 kEUR
Control	110 kEUR
Installation & Decommissioning	487 kEUR
Contingencies	363 kEUR
Annual OpEx	**125 kEUR/year**

3.12.8 Wave farm LCOE, 1 GW installed capacity

LCOE estimates a 1 GW wave farm of spar LiftWECs has been derived. As a first assumption, it is interesting to understand when a 1 GW accumulated deployment capacity could be reached.

Assuming that LiftWEC will follow a stage-gate approach, going through the 5 recommended development stages agreed by the wave energy sector; seems reasonable to assume a 10-year development road from TRL1/2 to TRL9. This process is estimated at about 10 years, starting from year 2020 where the LiftWEC Project started. Figure below has been presented within the OES Guidelines[8] as a best practice example for the industry, where CorPower development road to commercialisation is exemplified:

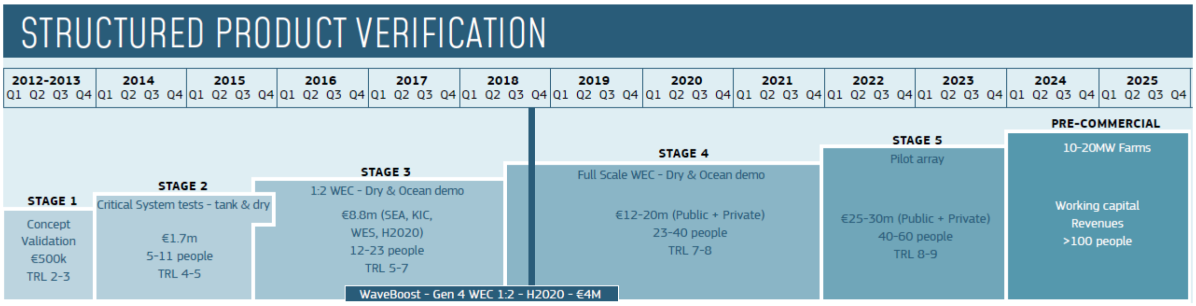
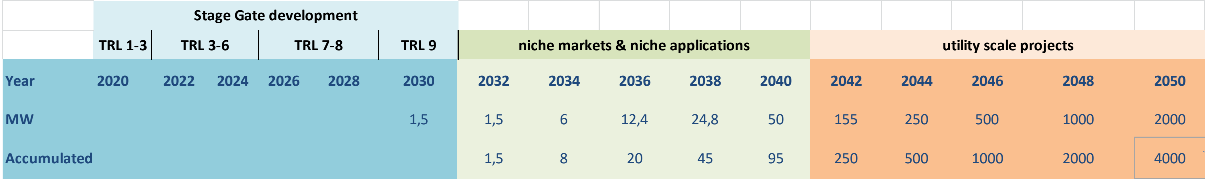


Figure 15. Example timeline for product verification in five stages according to IEA-OES / equimar best practice, (CorPower Ocean) [7].

Assuming LiftWEC rated power is about 1.5 MW, and that commercial prototype could be installed by 2030 and the first pilot array by 2034, a 1 GW accumulated installed capacity could be reached by 2045. By 2050, the deployment capacity could be up to 4 GW, representing a 10% share of the total ocean energy installed capacity targets of the European Union. Note these targets cover both tidal and wave deployments.



	Stage Gate development															
	TRL 1-3	TRL 3-6		TRL 7-8		TRL 9	niche markets & niche applications					utility scale projects				
Year	**2020**	**2022**	**2024**	**2026**	**2028**	**2030**	**2032**	**2034**	**2036**	**2038**	**2040**	**2042**	**2044**	**2046**	**2048**	**2050**
MW						1,5	1,5	6	12,4	24,8	50	155	250	500	1000	2000
Accumulated							1,5	8	20	45	95	250	500	1000	2000	4000

The EU Strategy for Offshore Renewable Energy[9], presented by the end of 2020 towards a climate neutral future, assumed that "… *the Commission estimates that the objective to have an installed capacity of at least 60 GW of offshore wind and* ***at least 1 GW of ocean energy by 2030****, with a view* ***to reach by 2050*** *300 GW and* ***40 GW of installed capacity****, respectively, is realistic and achievable".* Ocean Energy Europe (the voice of the wave and tidal energy sector in Europe) has an ambition beyond EU targets. **Ocean Energy Europe's 2030 vision**[10] projects ocean energy deployments of **3 GW by 2030** and of **100 GW by 2050.**

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[8] 8 Hodges J., Henderson J., Ruedy L., Soede M., Weber J., Ruiz-Minguela P., Jeffrey H., Bannon E., Holland M., Maciver R., Hume D., Villate J-L, Ramsey T., "An International Evaluation and Guidance Framework for Ocean Energy Technology", IEA-OES (2021).

[9] EU Offshore Renewable Energy Strategy for a climate neutral future (Brussels, 19.11.2020)

[10] Ocean Energy Europe 2030 Vision

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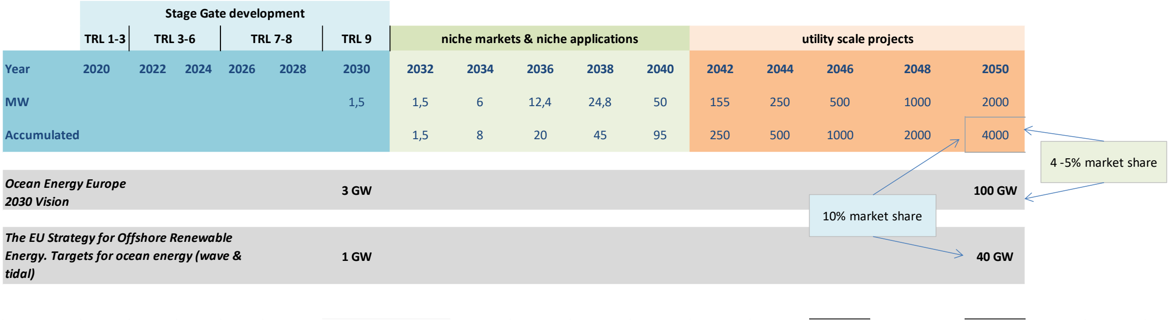


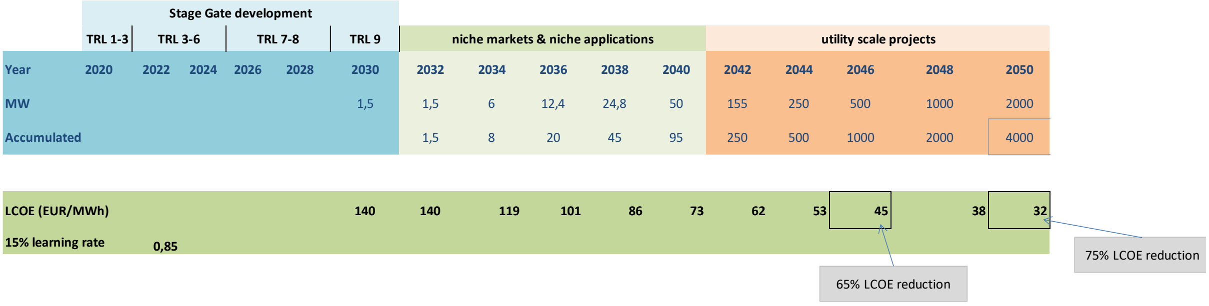
	Stage Gate development																
	TRL 1-3	TRL 3-6		TRL 7-8		TRL 9	niche markets & niche applications					utility scale projects				
Year	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044	2046	2048	2050
MW						1,5	1,5	6	12,4	24,8	50	155	250	500	1000	2000
Accumulated							1,5	8	20	45	95	250	500	1000	2000	4000
Ocean Energy Europe 2030 Vision						3 GW										100 GW
The EU Strategy for Offshore Renewable Energy. Targets for ocean energy (wave & tidal)						1 GW										40 GW

4 -5% market share

10% market share

A learning curve is a widely used method to estimate the development of costs for a given product. Every time the volume of a product is doubled, the cost is reduced by a progress rate (the inverse of a learning rate). Recommendations on which learning rate would be realistic for LiftWEC have been reviewed. The **OES-IEA (2015)**[3] observed an average 17% learning rate for WECs (based on respondents at TRL 6 or above). In 2018 the **EC-JRC**[11] noted learning rates for WECs from 9% to 30%; indicating that studies that are not explicit on the sub-technology would use a learning rate range between 6% and 15%. The EC-JRC then applied a 10% overall learning rate for ocean energy in their reference case, 15% in their optimistic scenario, and 7% in their pessimistic scenario. ***Magagna et al***.[12] indicates that due to the effects of economy of scale, once cumulative capacity is above 300 MW, then the learning rate would move from 10% to 18%. Based on these, a constant learning rate of 15% has been considered a conservative value, also being representative for the industry.

Applying a 15% learning rate to the LCOE (85% progress rate) the estimated LCOE for different accumulated deployments is obtained. The reference LCOE is 140 EUR/MWh. Figure below indicates LCOE estimates for deployed capacities of 1 GW and 4 GW. The **LCOE is of 45 EUR/MWh** and of **30EUR/MWh**, respectively, proving competitive to all forms of renewable electricity generation.



	Stage Gate development																
	TRL 1-3	TRL 3-6		TRL 7-8		TRL 9	niche markets & niche applications					utility scale projects				
Year	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044	2046	2048	2050
MW						1,5	1,5	6	12,4	24,8	50	155	250	500	1000	2000
Accumulated							1,5	8	20	45	95	250	500	1000	2000	4000
LCOE (EUR/MWh)						140	140	119	101	86	73	62	53	45	38	32
15% learning rate		0,85														

75% LCOE reduction

65% LCOE reduction

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[11] EC-JRC (2018) Cost development of low carbon energy technologies: Scenario-based cost trajectories to 2050, 2017 edition. European Commission Joint Research Centre Technical Reports.

[12] *Magagna et al.* (2018) Ocean energy in Europe: assessing support instruments and cost-reduction needs. International Journal of Marine Energy · March 2018

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Based on the reference LCOE of 140 EUR/MWh, an LCOE of 45 EUR/MWh and 30 EUR/MWh correspond to a LCOE reduction of 65% and 75%, respectively. These values are aligned with the OES LCOE assessment[13], indicating that a 50 to 75% LCOE reduction from early deployments to commercial arrays is expected:

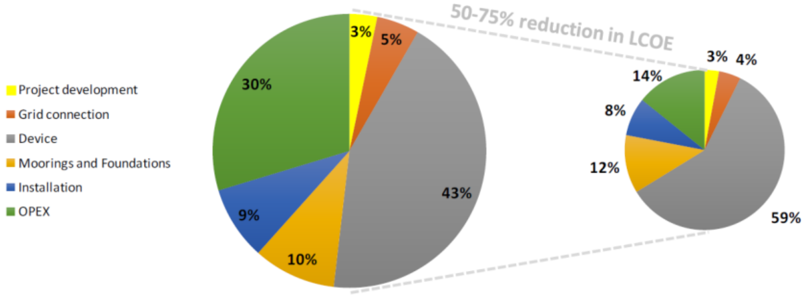

Figure 19: Wave LCOE Percentage Breakdown by Cost Centre Values at Current Stage of Deployment (Left) and the Commerical Target (Right) [Note: the area of the chart represents the LCOE].

3.13 CONFIGURATION VARIANTS

3.13.1 Variant CB04A

3.13.1.1 Variant description

This is the basic variant and is as described above.

3.13.2 Variant CB04B

3.13.2.1 Variant description

This variant is associated with the anchoring system. Micro piles, screw piles and structural steel footing elements are used for anchoring purposes in place of the drag embedment anchors.

3.13.2.2 Variant impact on LCoE

In specific seabed conditions this variant may be expected to reduce the LCoE, especially where the seabed is not suitable for a drag embedment anchor

3.13.3 Variant CB04C

3.13.3.1 Variant description

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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[13] International Levelised cost of energy for ocean energy technologies-2015

3.13.3.2 Variant impact on LCoE

In specific seabed conditions this variant may be expected to reduce the LCoE, especially where the seabed is not suitable for a drag embedment anchor

3.13.4 Variant CB04D

3.13.4.1 Variant description

This variant is associated with the power train design and operation. This variant includes a higher speed generator and gearbox. This may have advantages with a reduction in rotor inertia or increase in secondary conversion efficiency.

3.13.4.2 Variant impact on LCoE

TBC.

4 LIFTWEC CONFIGURATION REPECHAGE

The Final LiftWEC Configuration has been identified based on the knowledge currently available to the consortium, together with an analysis of the reasonably expectable performance of each Baseline configuration. However, this knowledge and analysis is necessarily partial, and it is possible that a different conclusion on the potential performance of each configuration would be different with additional knowledge, analysis, or changes in the available technologies.

An example of where repechage was significant, and it can be argued is still significant, is in the relative performance of horizontal and vertical axis wind turbines. Forty years ago, both horizontal and vertical axis wind turbines were seriously considered, with some considering that vertical axis turbines have a greater potential because their blades would not be influenced by fatigue due to self-weight stress in each rotation of the axis as occurs in horizontal axis turbines. At that time, steel blades were the dominant technological solution, which limited horizontal axis turbines to a maximum rating of about 300 kW, whilst vertical axis turbines did not have this issue and could theoretically have higher ratings and potentially a lower LCoE. However, the production of composite blades largely resolved the issue of blade fatigue due to self-weight and the higher noise generated by vertical axis wind turbines meant that horizontal axis turbines become the dominant solution with which we are familiar. It is interesting to note that repechage of vertical axis wind turbines for offshore installations may now again be worth considering as noise is unlikely to be an issue and the large tower heights means that the resonance of the support tower may now be an issue, which is exasperated by the location of the nacelle on the top of the tower as is the case for horizontal-axis wind turbines.

It is not anticipated that repechage will be applied to the final LiftWEC configuration as part of the current project as it is important to maintain a focus on the elected final LiftWEC configuration to ensure that its is fully investigated. However, the repechage of the other Baseline configurations may be worth considering following this project, especially where advances in technology and understanding may change the relative potential of the configurations.

4.1 REPECHAGE OF THE TOWER LIFTWEC CONFIGURATION

The Tower LiftWEC configuration was not chosen as the final configuration primarily because of the anticipated high costs of installation and O&M, as well as high structural loads, although it had the highest energy capture potential. This configuration would become significantly more attractive if the costs of installing a monopile in 50m water depth significantly reduced. This could occur if there are significant advances in the installation of fixed offshore wind turbines, and the installation techniques and costs of monopiles should be monitored to assess whether this configuration deserves reconsideration. Another reason that this configuration could be reconsidered is if the movement of the LiftWEC rotor axis resulted in a significantly larger reduction in the power capture than currently anticipated.

4.2 REPECHAGE OF THE TLP LIFTWEC CONFIGURATION

The TLP LiftWEC configuration was not chosen as the final configuration primarily because of concerns about the performance and reliability of the tension cables, which requires the development of an entirely novel technology. This configuration would become significantly more attractive if the issues of the performance and reliability of the tension cables were resolved. This could occur as there are other wave energy converters that rely on tension cables from their operation. Any development of the technology for these other wave energy converters may be transferable to this configuration, which would then deserve reconsideration. Another reason that this configuration could be reconsidered is if the movement of the LiftWEC rotor axis resulted in a significantly larger reduction in the power capture than currently anticipated.

4.3 REPECHAGE OF THE SEMI-SUB LIFTWEC CONFIGURATION

The Semi-Sub LiftWEC configuration was not chosen as the final configuration primarily because it appeared to require a larger amount of structure relative to the Spar LiftWEC configuration. This configuration may become more attractive if some issues associated the stability of the Spar LiftWEC configuration become difficult to resolve, whilst the essential performance of a floating LiftWEC remained acceptable

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Appendix A FINAL CONFIGURATION IDENTIFICATION WORKSHOP

A.1 WORKSHOP AGENDA

Dates: Tuesday 31st May 2022, Tuesday 7th June 2022.

Location: Zoom.

Day 1	Dur.	Content	Resp.
Session 1 (120’) 09:00 – 11:00 BST 10:00 – 12:00 CEST	15’ 5’ 50’ 50’	Introduction to Workshop Overview of Baseline Configurations Review/discussion of Tower LiftWEC* Review/discussion of TLP LiftWEC*	MF PLK MF PLK
Break	45’		
Session 2 (120’) 11:45 – 13:45 BST 12:45 – 14:45 CEST	50’ 50’ 20’	Review/discussion of Spar LiftWEC* Review/discussion of Semi-sub LiftWEC* Introduction to small group evaluation	MF PLK MF
Break	45’		
Session 3 14:30 – 16:30 BST 15:30 – 17:30 CEST		Additional time for overrun/further questions/free discussion. Workshop may finish early.	MF

Day 2	Dur.	Content	Resp.
Session 3a (60’) 09:00 – 10:00 BST 10:00 – 11:00 CEST	60’	Small group evaluation of Tower LiftWEC$	MF
Break	15’		
Session 3b (60’) 10:15 – 11:15 BST 11:15 – 12:15 CEST	60’	Small group evaluation of TLP LiftWEC$	PLK
Break	30’		
Session 4a (60’) 11:45 – 12:45 BST 12:45 – 13:45 CEST	60’	Small group evaluation of Spar LiftWEC$	MF
Break	15’		
Session 4b (60’) 13:00 – 14:00 BST 14:00 – 15:00 CEST	60’	Small group evaluation of Semi-sub LiftWEC$	PLK
Break	30’		
Session 5 (120’) 14:30 – 16:30 BST 15:30 – 17:30 CEST	30’ 30’ 60’	Evaluation feedback Selection of Final Configuration Plan for analysis of Final Configuration	RP MF PLK

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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)
Kim Neilson (AAU)	Kim Neilson (AAU)
Lucille Antoine (MU)	Lucille Antoine (MU)
Andrei Ermakov (AE)	Mohammad Sameti (MU)
Claire Baron (INN)	Gerrit Olbert (TUHH)
Allan Thompson (Technical Advisory Board)	Abel Arredondo-Galeana (US)
Gerrit Olbert (TUHH)	Rémy Pascal (INN)
Abel Arredondo-Galeana (US)	Louis Papillon (INN)
Rémy Pascal (INN)	Pedro Vinagre (WavEC)
Louis Papillon (INN)	Julia Chozas (JCC)
Julia Chozas (JCC)	Ashton Reed (QUB - morning)
Carwyn Frost (QUB – morning)	Carwyn Frost (QUB - afternoon)
Jimmy Murphy (UCC – afternoon)	

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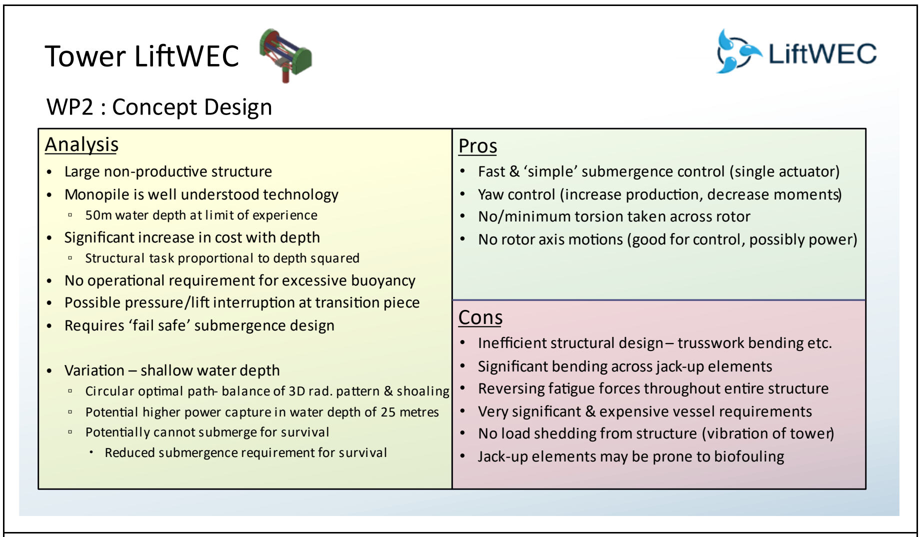
Appendix B WORK PACKAGE ASSESSMENT OF TOWER LIFTWEC



Tower LiftWEC

LiftWEC

WP2 : Concept Design

Analysis

- Large non-productive structure
- Monopile is well understood technology
  - 50m water depth at limit of experience
- Significant increase in cost with depth
  - Structural task proportional to depth squared
- No operational requirement for excessive buoyancy
- Possible pressure/lift interruption at transition piece
- Requires 'fail safe' submergence design

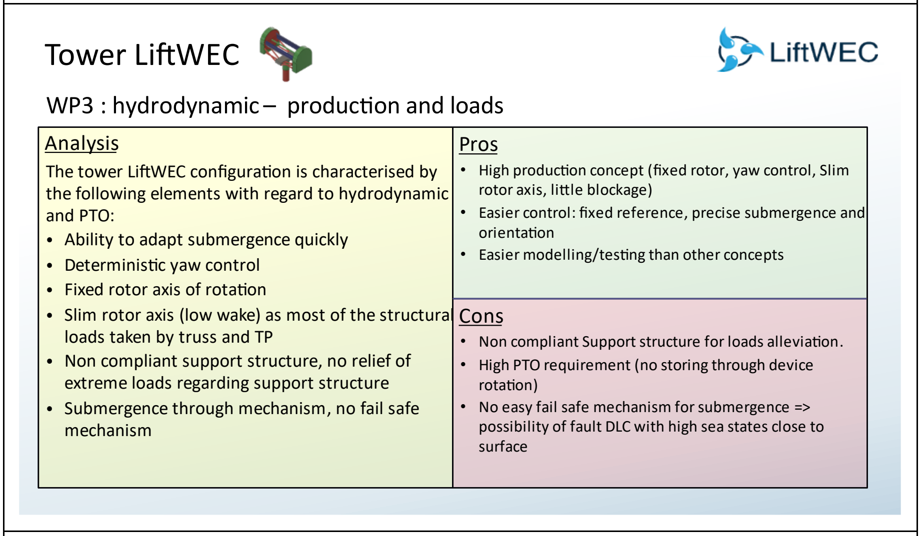
- Variation – shallow water depth
  - Circular optimal path- balance of 3D rad. pattern & shoaling
  - Potential higher power capture in water depth of 25 metres
  - Potentially cannot submerge for survival
    - Reduced submergence requirement for survival

Pros

- Fast & 'simple' submergence control (single actuator)
- Yaw control (increase production, decrease moments)
- No/minimum torsion taken across rotor
- No rotor axis motions (good for control, possibly power)

Cons

- Inefficient structural design – trusswork bending etc.
- Significant bending across jack-up elements
- Reversing fatigue forces throughout entire structure
- Very significant & expensive vessel requirements
- No load shedding from structure (vibration of tower)
- Jack-up elements may be prone to biofouling



Tower LiftWEC

LiftWEC

WP3 : hydrodynamic – production and loads

Analysis

The tower LiftWEC configuration is characterised by the following elements with regard to hydrodynamic and PTO:

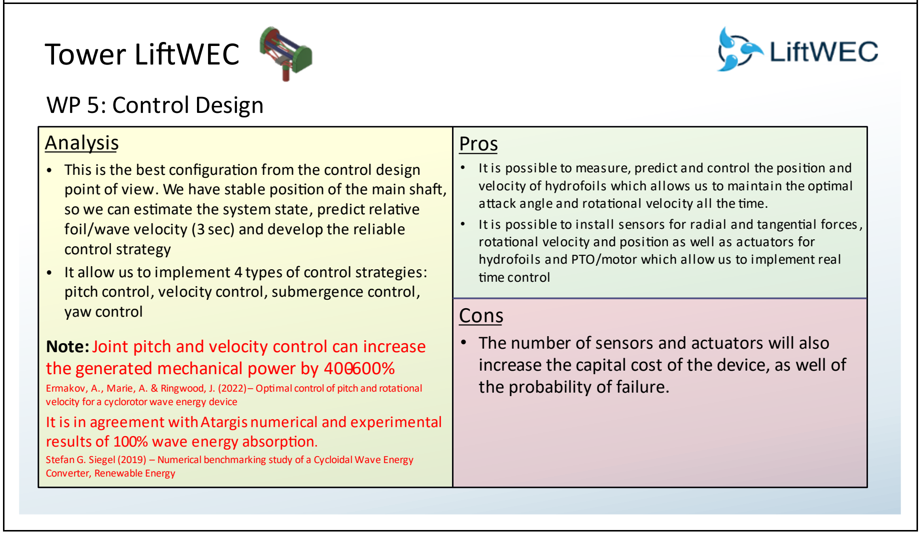
- Ability to adapt submergence quickly
- Deterministic yaw control
- Fixed rotor axis of rotation
- Slim rotor axis (low wake) as most of the structural loads taken by truss and TP
- Non compliant support structure, no relief of extreme loads regarding support structure
- Submergence through mechanism, no fail safe mechanism

Pros

- High production concept (fixed rotor, yaw control, Slim rotor axis, little blockage)
- Easier control: fixed reference, precise submergence and orientation
- Easier modelling/testing than other concepts

Cons

- Non compliant Support structure for loads alleviation.
- High PTO requirement (no storing through device rotation)
- No easy fail safe mechanism for submergence => possibility of fault DLC with high sea states close to surface



Tower LiftWEC

LiftWEC

WP 5: Control Design

Analysis

- This is the best configuration from the control design point of view. We have stable position of the main shaft, so we can estimate the system state, predict relative foil/wave velocity (3 sec) and develop the reliable control strategy
- It allow us to implement 4 types of control strategies: pitch control, velocity control, submergence control, yaw control

Note: Joint pitch and velocity control can increase the generated mechanical power by 400-600%

Ermakov, A., Marie, A. & Ringwood, J. (2022) – Optimal control of pitch and rotational velocity for a cyclorotor wave energy device

It is in agreement with Atargis numerical and experimental results of 100% wave energy absorption.

Stefan G. Siegel (2019) – Numerical benchmarking study of a Cycloidal Wave Energy Converter, Renewable Energy

Pros

- It is possible to measure, predict and control the position and velocity of hydrofoils which allows us to maintain the optimal attack angle and rotational velocity all the time.
- It is possible to install sensors for radial and tangential forces, rotational velocity and position as well as actuators for hydrofoils and PTO/motor which allow us to implement real time control

Cons

- The number of sensors and actuators will also increase the capital cost of the device, as well as the probability of failure.

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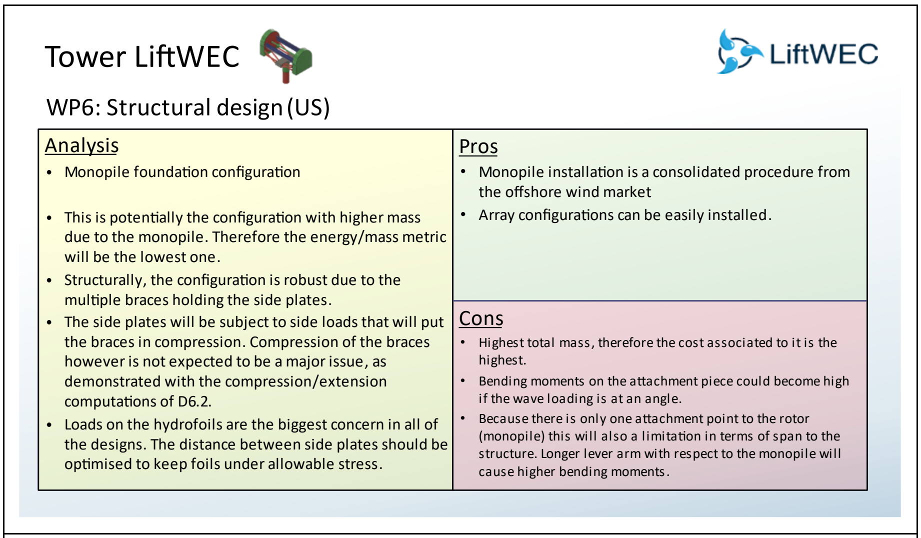


Tower LiftWEC

WP6: Structural design (US)

Analysis

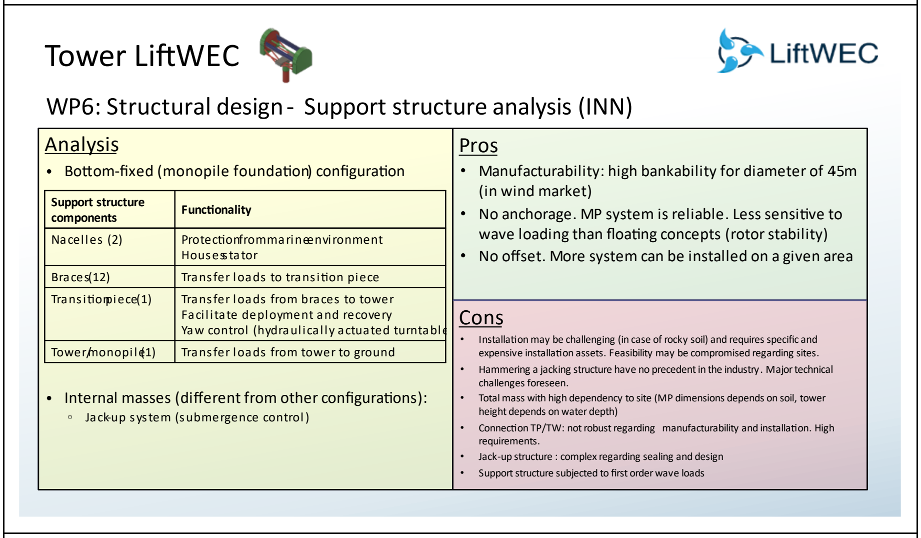
- Monopile foundation configuration
- This is potentially the configuration with higher mass due to the monopile. Therefore the energy/mass metric will be the lowest one.
- Structurally, the configuration is robust due to the multiple braces holding the side plates.
- The side plates will be subject to side loads that will put the braces in compression. Compression of the braces however is not expected to be a major issue, as demonstrated with the compression/extension computations of D6.2.
- Loads on the hydrofoils are the biggest concern in all of the designs. The distance between side plates should be optimised to keep foils under allowable stress.

Pros

- Monopile installation is a consolidated procedure from the offshore wind market
- Array configurations can be easily installed.

Cons

- Highest total mass, therefore the cost associated to it is the highest.
- Bending moments on the attachment piece could become high if the wave loading is at an angle.
- Because there is only one attachment point to the rotor (monopile) this will also a limitation in terms of span to the structure. Longer lever arm with respect to the monopile will cause higher bending moments.



Tower LiftWEC

WP6: Structural design - Support structure analysis (INN)

Analysis

- Bottom-fixed (monopile foundation) configuration

Support structure components	Functionality
Nacelles (2)	Protection from marine environment House stator
Braces (12)	Transfer loads to transition piece
Transition piece (1)	Transfer loads from braces to tower Facilitate deployment and recovery Yaw control (hydraulically actuated turntable
Tower/monopile (1)	Transfer loads from tower to ground

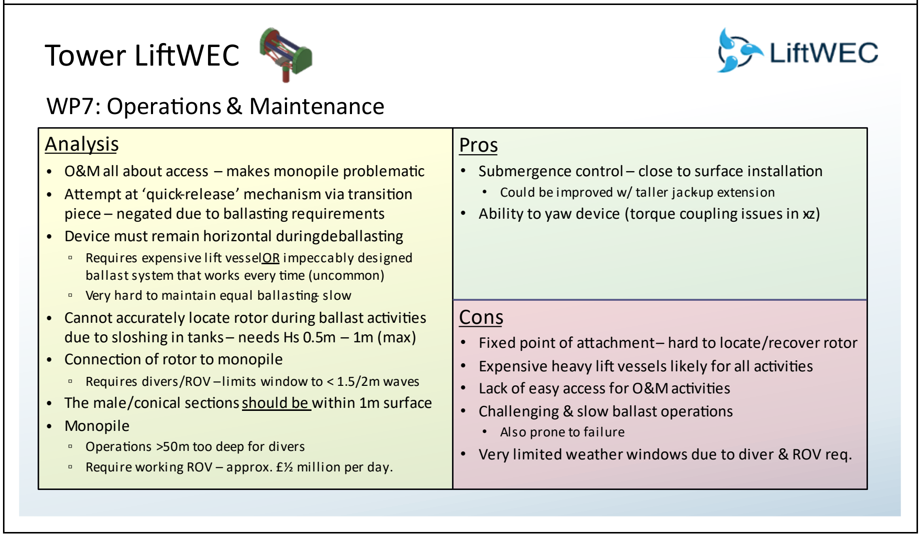
- Internal masses (different from other configurations):
  - Jack-up system (submergence control)

Pros

- Manufacturability: high bankability for diameter of 45m (in wind market)
- No anchorage. MP system is reliable. Less sensitive to wave loading than floating concepts (rotor stability)
- No offset. More system can be installed on a given area

Cons

- Installation may be challenging (in case of rocky soil) and requires specific and expensive installation assets. Feasibility may be compromised regarding sites.
- Hammering a jacking structure have no precedent in the industry. Major technical challenges foreseen.
- Total mass with high dependency to site (MP dimensions depends on soil, tower height depends on water depth)
- Connection TP/TW: not robust regarding manufacturability and installation. High requirements.
- Jack-up structure : complex regarding sealing and design
- Support structure subjected to first order wave loads



Tower LiftWEC

WP7: Operations & Maintenance

Analysis

- O&M all about access – makes monopile problematic
- Attempt at 'quick-release' mechanism via transition piece – negated due to ballasting requirements
- Device must remain horizontal during deballasting
  - Requires expensive lift vessel OR impeccably designed ballast system that works every time (uncommon)
  - Very hard to maintain equal ballasting - slow
- Cannot accurately locate rotor during ballast activities due to sloshing in tanks – needs Hs 0.5m – 1m (max)
- Connection of rotor to monopile
  - Requires divers/ROV – limits window to < 1.5/2m waves
- The male/conical sections should be within 1m surface
- Monopile
  - Operations >50m too deep for divers
  - Require working ROV – approx. £½ million per day.

Pros

- Submergence control – close to surface installation
  - Could be improved w/ taller jackup extension
- Ability to yaw device (torque coupling issues in xz)

Cons

- Fixed point of attachment – hard to locate/recover rotor
- Expensive heavy lift vessels likely for all activities
- Lack of easy access for O&M activities
- Challenging & slow ballast operations
  - Also prone to failure
- Very limited weather windows due to diver & ROV req.

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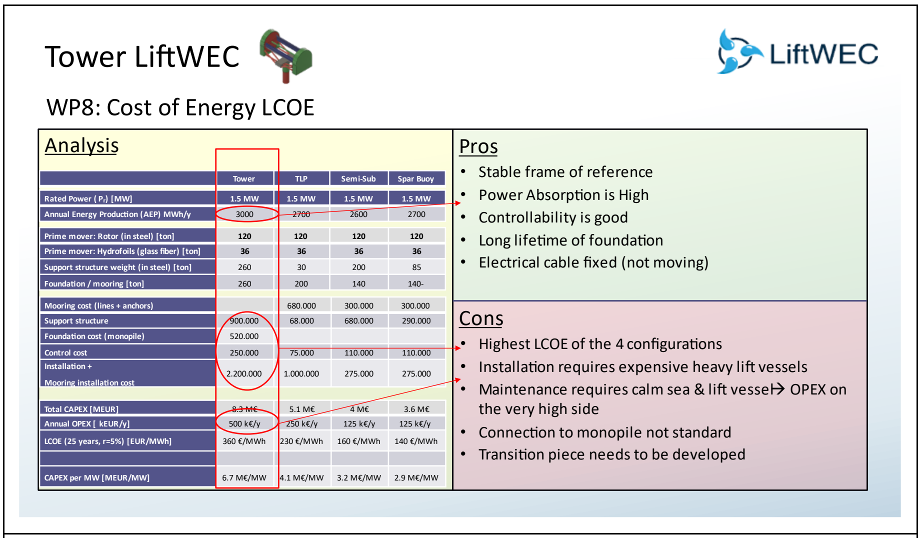


Tower LiftWEC

WP8: Cost of Energy LCOE

Analysis

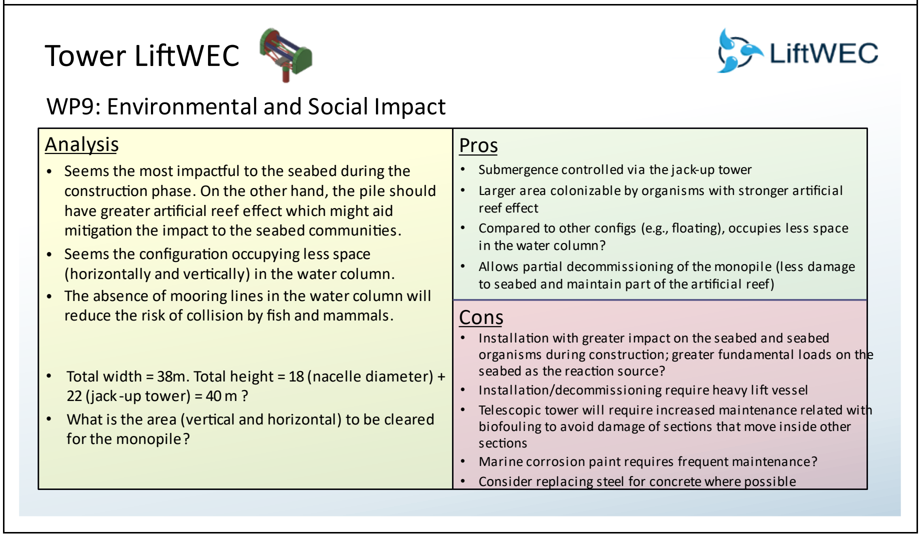
	Tower	TLP	Semi-Sub	Spar Buoy
Rated Power (P_r) [MW]	1.5 MW	1.5 MW	1.5 MW	1.5 MW
Annual Energy Production (AEP) MWh/y	3000	2700	2600	2700
Prime mover: Rotor (in steel) [ton]	**120**	**120**	**120**	**120**
Prime mover: Hydrofoils (glass fiber) [ton]	**36**	**36**	**36**	**36**
Support structure weight (in steel) [ton]	260	30	200	85
Foundation / mooring [ton]	260	200	140	140-
Mooring cost (lines + anchors)		680.000	300.000	300.000
Support structure	900.000	68.000	680.000	290.000
Foundation cost (monopile)	520.000			
Control cost	250.000	75.000	110.000	110.000
Installation + Mooring installation cost	2.200.000	1.000.000	275.000	275.000
Total CAPEX [MEUR]	8.3 M€	5.1 M€	4 M€	3.6 M€
Annual OPEX [kEUR/y]	500 k€/y	250 k€/y	125 k€/y	125 k€/y
LCOE (25 years, r=5%) [EUR/MWh]	360 €/MWh	230 €/MWh	160 €/MWh	140 €/MWh
CAPEX per MW [MEUR/MW]	6.7 M€/MW	4.1 M€/MW	3.2 M€/MW	2.9 M€/MW

Pros

- Stable frame of reference
- Power Absorption is High
- Controllability is good
- Long lifetime of foundation
- Electrical cable fixed (not moving)

Cons

- Highest LCOE of the 4 configurations
- Installation requires expensive heavy lift vessels
- Maintenance requires calm sea & lift vessel→ OPEX on the very high side
- Connection to monopile not standard
- Transition piece needs to be developed



Tower LiftWEC

WP9: Environmental and Social Impact

Analysis

- Seems the most impactful to the seabed during the construction phase. On the other hand, the pile should have greater artificial reef effect which might aid mitigation the impact to the seabed communities.
- Seems the configuration occupying less space (horizontally and vertically) in the water column.
- The absence of mooring lines in the water column will reduce the risk of collision by fish and mammals.

- Total width = 38m. Total height = 18 (nacelle diameter) + 22 (jack-up tower) = 40 m ?
- What is the area (vertical and horizontal) to be cleared for the monopile?

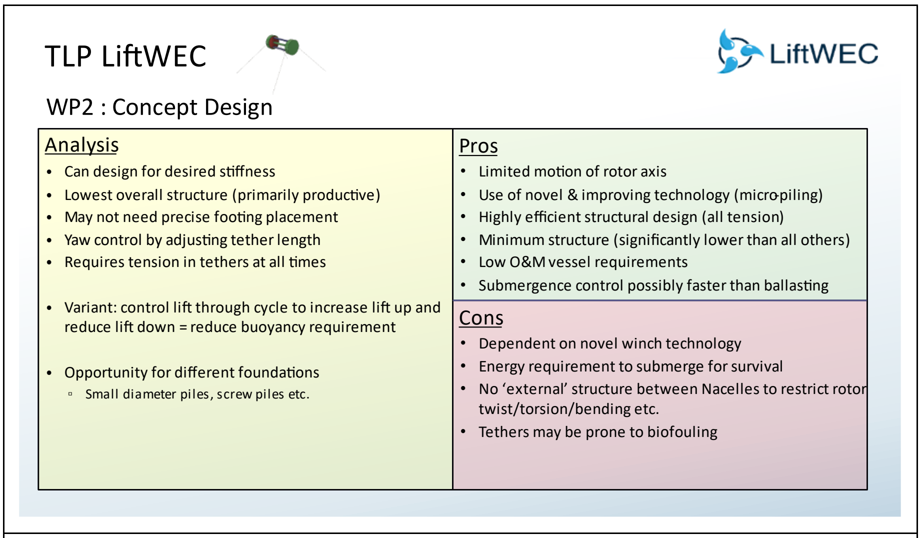
Pros

- Submergence controlled via the jack-up tower
- Larger area colonizable by organisms with stronger artificial reef effect
- Compared to other configs (e.g., floating), occupies less space in the water column?
- Allows partial decommissioning of the monopile (less damage to seabed and maintain part of the artificial reef)

Cons

- Installation with greater impact on the seabed and seabed organisms during construction; greater fundamental loads on the seabed as the reaction source?
- Installation/decommissioning require heavy lift vessel
- Telescopic tower will require increased maintenance related with biofouling to avoid damage of sections that move inside other sections
- Marine corrosion paint requires frequent maintenance?
- Consider replacing steel for concrete where possible

Appendix C WORK PACKAGE ASSESSMENT OF TLP LIFTWEC



TLP LiftWEC

WP2 : Concept Design

Analysis

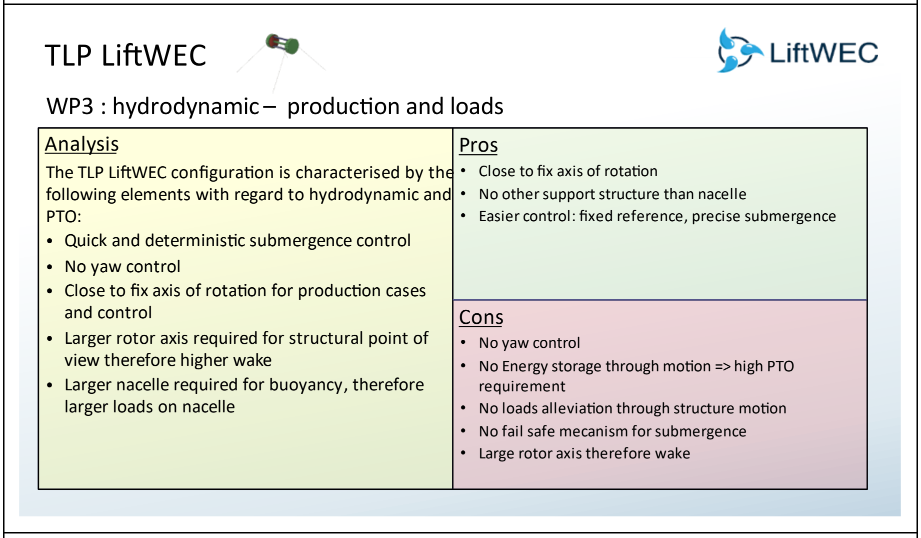
- Can design for desired stiffness
- Lowest overall structure (primarily productive)
- May not need precise footing placement
- Yaw control by adjusting tether length
- Requires tension in tethers at all times
- Variant: control lift through cycle to increase lift up and reduce lift down = reduce buoyancy requirement
- Opportunity for different foundations
  - Small diameter piles, screw piles etc.

Pros

- Limited motion of rotor axis
- Use of novel & improving technology (micropiling)
- Highly efficient structural design (all tension)
- Minimum structure (significantly lower than all others)
- Low O&M vessel requirements
- Submergence control possibly faster than ballasting

Cons

- Dependent on novel winch technology
- Energy requirement to submerge for survival
- No ‘external’ structure between Nacelles to restrict rotor twist/torsion/bending etc.
- Tethers may be prone to biofouling



TLP LiftWEC

WP3 : hydrodynamic – production and loads

Analysis

The TLP LiftWEC configuration is characterised by the following elements with regard to hydrodynamic and PTO:

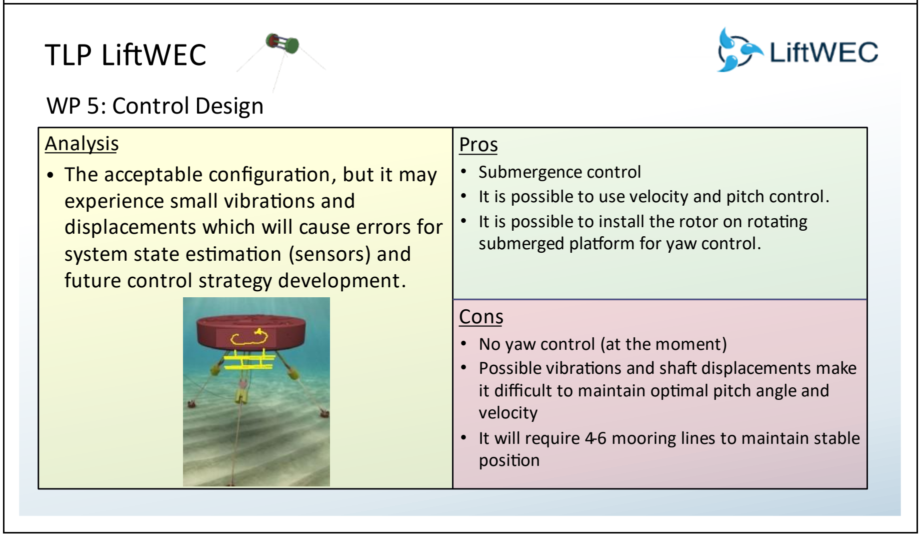
- Quick and deterministic submergence control
- No yaw control
- Close to fix axis of rotation for production cases and control
- Larger rotor axis required for structural point of view therefore higher wake
- Larger nacelle required for buoyancy, therefore larger loads on nacelle

Pros

- Close to fix axis of rotation
- No other support structure than nacelle
- Easier control: fixed reference, precise submergence

Cons

- No yaw control
- No Energy storage through motion => high PTO requirement
- No loads alleviation through structure motion
- No fail safe mecanism for submergence
- Large rotor axis therefore wake



TLP LiftWEC

WP 5: Control Design

Analysis

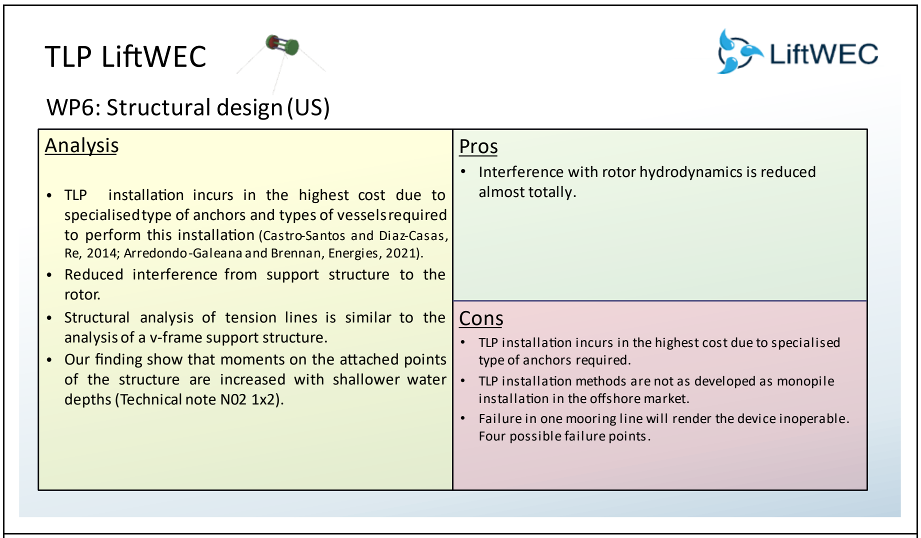
- The acceptable configuration, but it may experience small vibrations and displacements which will cause errors for system state estimation (sensors) and future control strategy development.

Pros

- Submergence control
- It is possible to use velocity and pitch control.
- It is possible to install the rotor on rotating submerged platform for yaw control.

Cons

- No yaw control (at the moment)
- Possible vibrations and shaft displacements make it difficult to maintain optimal pitch angle and velocity
- It will require 4-6 mooring lines to maintain stable position



TLP LiftWEC

WP6: Structural design (US)

Analysis

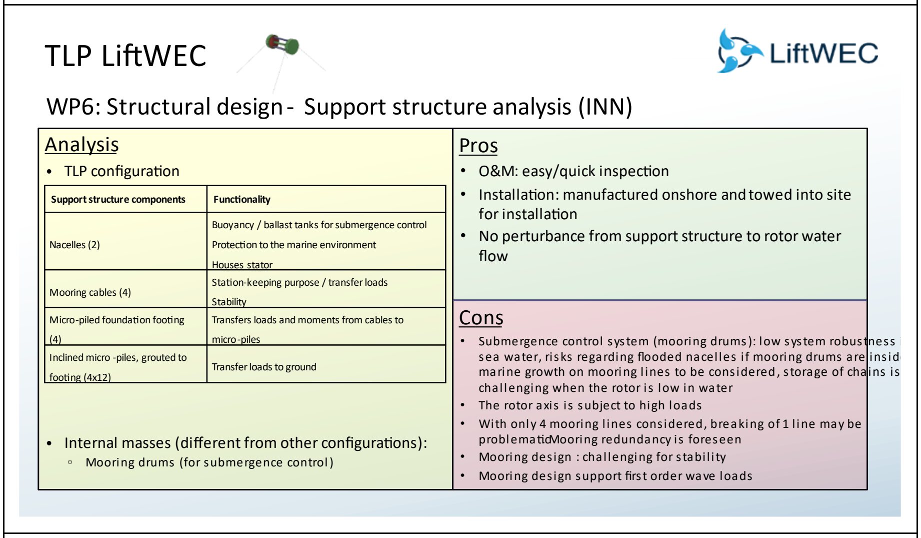
- TLP installation incurs in the highest cost due to specialised type of anchors and types of vessels required to perform this installation (Castro-Santos and Diaz-Casas, Re, 2014; Arredondo-Galeana and Brennan, Energies, 2021).
- Reduced interference from support structure to the rotor.
- Structural analysis of tension lines is similar to the analysis of a v-frame support structure.
- Our finding show that moments on the attached points of the structure are increased with shallower water depths (Technical note N02 1x2).

Pros

- Interference with rotor hydrodynamics is reduced almost totally.

Cons

- TLP installation incurs in the highest cost due to specialised type of anchors required.
- TLP installation methods are not as developed as monopile installation in the offshore market.
- Failure in one mooring line will render the device inoperable. Four possible failure points.



TLP LiftWEC

WP6: Structural design - Support structure analysis (INN)

Analysis

- TLP configuration

Support structure components	Functionality
Nacelles (2)	Buoyancy / ballast tanks for submergence control Protection to the marine environment Houses stator
Mooring cables (4)	Station-keeping purpose / transfer loads Stability
Micro-piled foundation footing (4)	Transfers loads and moments from cables to micro-piles
Inclined micro -piles, grouted to footing (4x12)	Transfer loads to ground

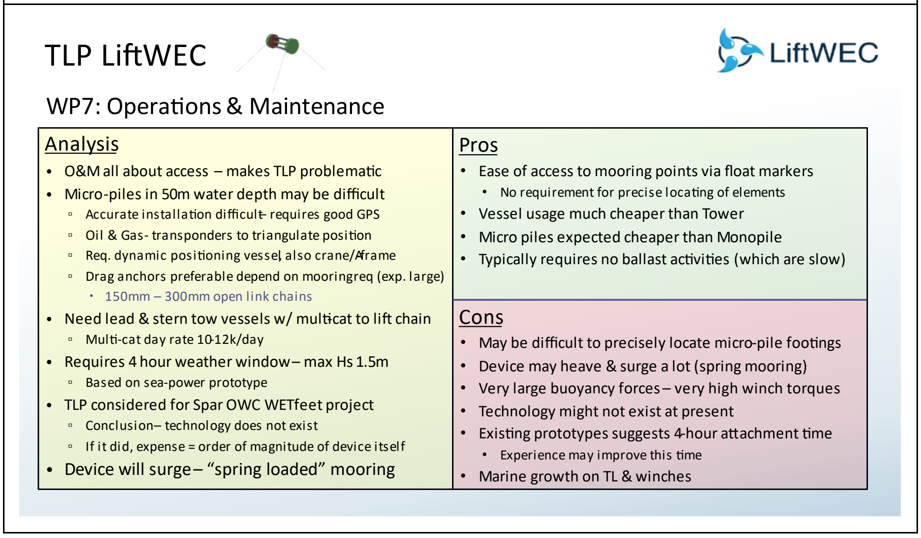
- Internal masses (different from other configurations):
  - Mooring drums (for submergence control)

Pros

- O&M: easy/quick inspection
- Installation: manufactured onshore and towed into site for installation
- No perturbance from support structure to rotor water flow

Cons

- Submergence control system (mooring drums): low system robustness sea water, risks regarding flooded nacelles if mooring drums are insid marine growth on mooring lines to be considered, storage of chains is challenging when the rotor is low in water
- The rotor axis is subject to high loads
- With only 4 mooring lines considered, breaking of 1 line may be problematicMooring redundancy is foreseen
- Mooring design : challenging for stability
- Mooring design support first order wave loads



TLP LiftWEC

WP7: Operations & Maintenance

Analysis

- O&M all about access – makes TLP problematic
- Micro-piles in 50m water depth may be difficult
  - Accurate installation difficult- requires good GPS
  - Oil & Gas- transponders to triangulate position
  - Req. dynamic positioning vessel, also crane/A-frame
  - Drag anchors preferable depend on mooring req (exp. large)
    - 150mm – 300mm open link chains
- Need lead & stern tow vessels w/ multicat to lift chain
  - Multi-cat day rate 10-12k/day
- Requires 4 hour weather window – max Hs 1.5m
  - Based on sea-power prototype
- TLP considered for Spar OWC WETfeet project
  - Conclusion – technology does not exist
  - If it did, expense = order of magnitude of device itself
- Device will surge – "spring loaded" mooring

Pros

- Ease of access to mooring points via float markers
  - No requirement for precise locating of elements
- Vessel usage much cheaper than Tower
- Micro piles expected cheaper than Monopile
- Typically requires no ballast activities (which are slow)

Cons

- May be difficult to precisely locate micro-pile footings
- Device may heave & surge a lot (spring mooring)
- Very large buoyancy forces – very high winch torques
- Technology might not exist at present
- Existing prototypes suggests 4-hour attachment time
  - Experience may improve this time
- Marine growth on TL & winches

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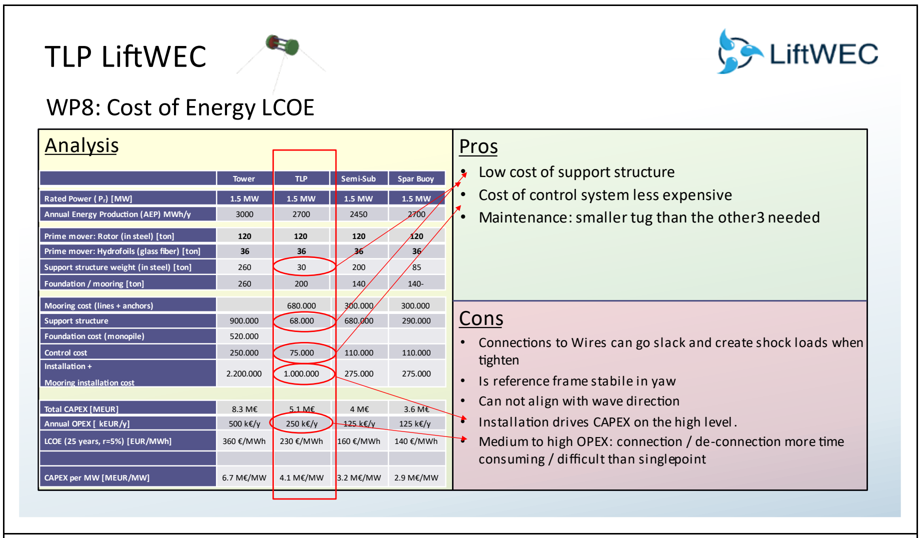

TLP LiftWEC

WP8: Cost of Energy LCOE

Analysis

	Tower	TLP	Semi-Sub	Spar Buoy
Rated Power (P_r) [MW]	1.5 MW	1.5 MW	1.5 MW	1.5 MW
Annual Energy Production (AEP) MWh/y	3000	2700	2450	2700
Prime mover: Rotor (in steel) [ton]	**120**	**120**	**120**	**120**
Prime mover: Hydrofoils (glass fiber) [ton]	**36**	**36**	**36**	**36**
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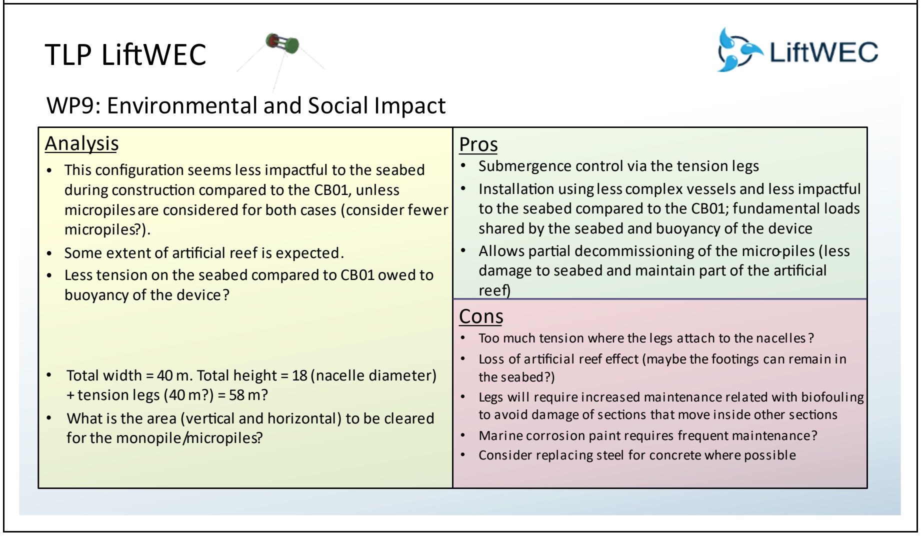
Foundation / mooring [ton]	260	200	140	140-
Mooring cost (lines + anchors)		680.000	300.000	300.000
Support structure	900.000	68.000	680.000	290.000
Foundation cost (monopile)	520.000			
Control cost	250.000	75.000	110.000	110.000
Installation + Mooring installation cost	2.200.000	1.000.000	275.000	275.000
Total CAPEX [MEUR]	8.3 M€	5.1 M€	4 M€	3.6 M€
Annual OPEX [kEUR/y]	500 k€/y	250 k€/y	125 k€/y	125 k€/y
LCOE (25 years, r=5%) [EUR/MWh]	360 €/MWh	230 €/MWh	160 €/MWh	140 €/MWh
CAPEX per MW [MEUR/MW]	6.7 M€/MW	4.1 M€/MW	3.2 M€/MW	2.9 M€/MW

Pros

- Low cost of support structure
- Cost of control system less expensive
- Maintenance: smaller tug than the other3 needed

Cons

- Connections to Wires can go slack and create shock loads when tighten
- Is reference frame stabile in yaw
- Can not align with wave direction
- Installation drives CAPEX on the high level.
- Medium to high OPEX: connection / de-connection more time consuming / difficult than singlepoint



TLP LiftWEC

WP9: Environmental and Social Impact

Analysis

- This configuration seems less impactful to the seabed during construction compared to the CB01, unless micropiles are considered for both cases (consider fewer micropiles?).
- Some extent of artificial reef is expected.
- Less tension on the seabed compared to CB01 owed to buoyancy of the device?

- Total width = 40 m. Total height = 18 (nacelle diameter) + tension legs (40 m?) = 58 m?
- What is the area (vertical and horizontal) to be cleared for the monopile/micropiles?

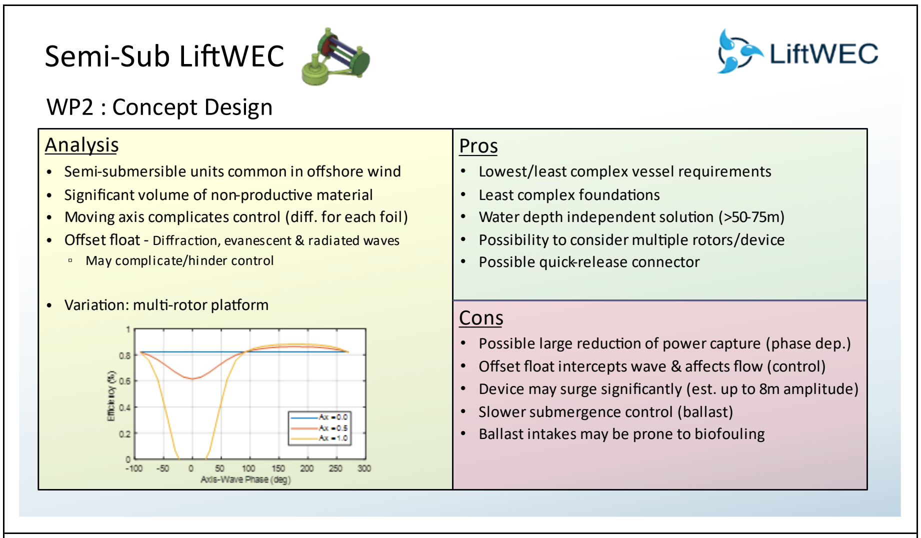
Pros

- Submergence control via the tension legs
- Installation using less complex vessels and less impactful to the seabed compared to the CB01; fundamental loads shared by the seabed and buoyancy of the device
- Allows partial decommissioning of the micro-piles (less damage to seabed and maintain part of the artificial reef)

Cons

- Too much tension where the legs attach to the nacelles?
- Loss of artificial reef effect (maybe the footings can remain in the seabed?)
- Legs will require increased maintenance related with biofouling to avoid damage of sections that move inside other sections
- Marine corrosion paint requires frequent maintenance?
- Consider replacing steel for concrete where possible

Appendix D WORK PACKAGE ASSESSMENT OF SEMI-SUB LIFTWEC



Semi-Sub LiftWEC

WP2 : Concept Design

Analysis

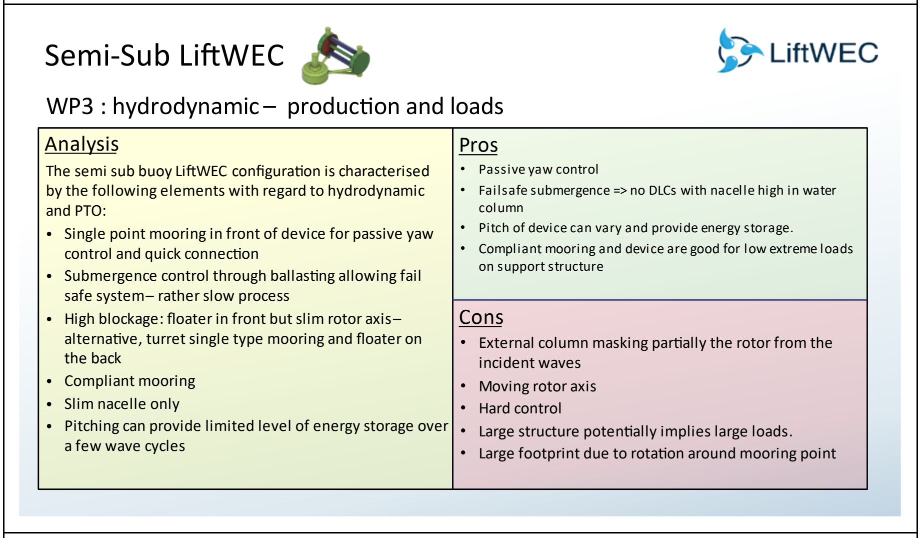
- Semi-submersible units common in offshore wind
- Significant volume of non-productive material
- Moving axis complicates control (diff. for each foil)
- Offset float - Diffraction, evanescent & radiated waves
    - May complicate/hinder control
- Variation: multi-rotor platform

Pros

- Lowest/least complex vessel requirements
- Least complex foundations
- Water depth independent solution (>50-75m)
- Possibility to consider multiple rotors/device
- Possible quick-release connector

Cons

- Possible large reduction of power capture (phase dep.)
- Offset float intercepts wave & affects flow (control)
- Device may surge significantly (est. up to 8m amplitude)
- Slower submergence control (ballast)
- Ballast intakes may be prone to biofouling



Semi-Sub LiftWEC

WP3 : hydrodynamic – production and loads

Analysis

The semi sub buoy LiftWEC configuration is characterised by the following elements with regard to hydrodynamic and PTO:

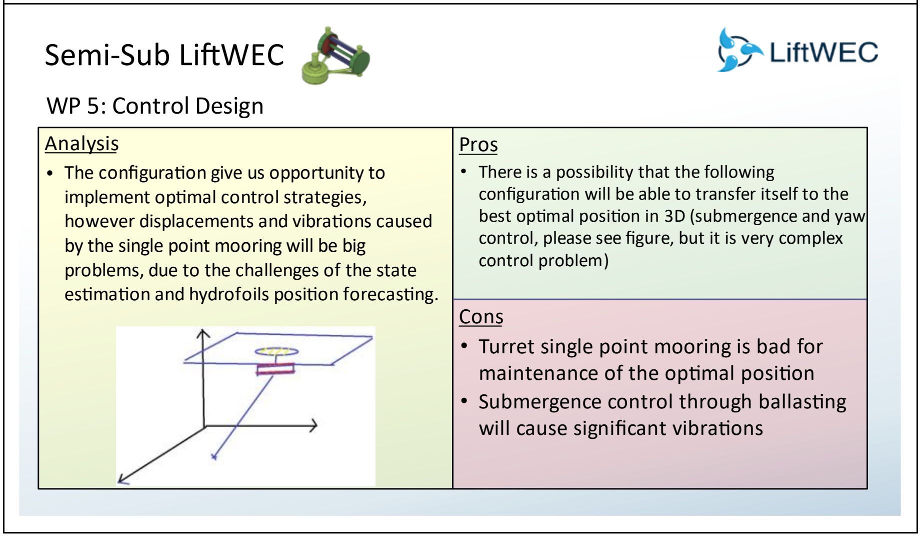
- Single point mooring in front of device for passive yaw control and quick connection
- Submergence control through ballasting allowing fail safe system – rather slow process
- High blockage: floater in front but slim rotor axis – alternative, turret single type mooring and floater on the back
- Compliant mooring
- Slim nacelle only
- Pitching can provide limited level of energy storage over a few wave cycles

Pros

- Passive yaw control
- Failsafe submergence => no DLCs with nacelle high in water column
- Pitch of device can vary and provide energy storage.
- Compliant mooring and device are good for low extreme loads on support structure

Cons

- External column masking partially the rotor from the incident waves
- Moving rotor axis
- Hard control
- Large structure potentially implies large loads.
- Large footprint due to rotation around mooring point



Semi-Sub LiftWEC

WP 5: Control Design

Analysis

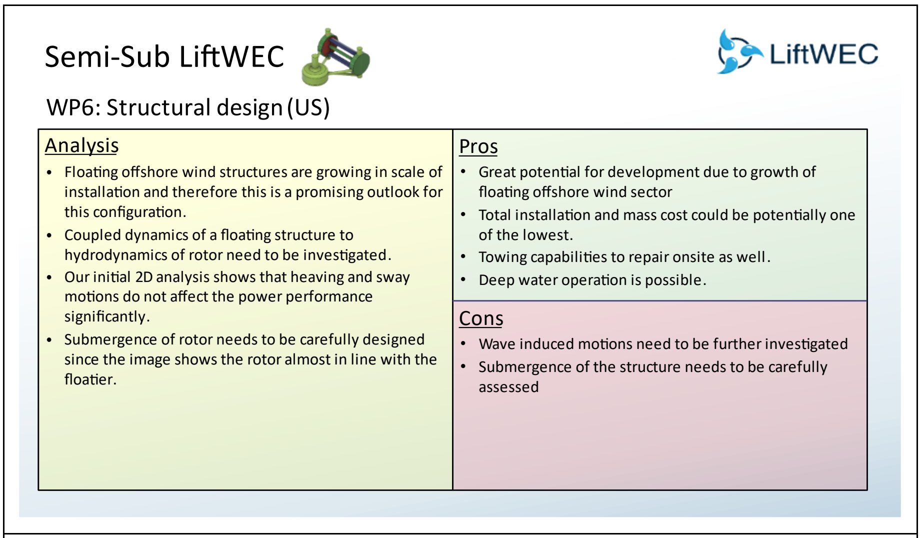
- The configuration give us opportunity to implement optimal control strategies, however displacements and vibrations caused by the single point mooring will be big problems, due to the challenges of the state estimation and hydrofoils position forecasting.

Pros

- There is a possibility that the following configuration will be able to transfer itself to the best optimal position in 3D (submergence and yaw control, please see figure, but it is very complex control problem)

Cons

- Turret single point mooring is bad for maintenance of the optimal position
- Submergence control through ballasting will cause significant vibrations



Semi-Sub LiftWEC

WP6: Structural design (US)

Analysis

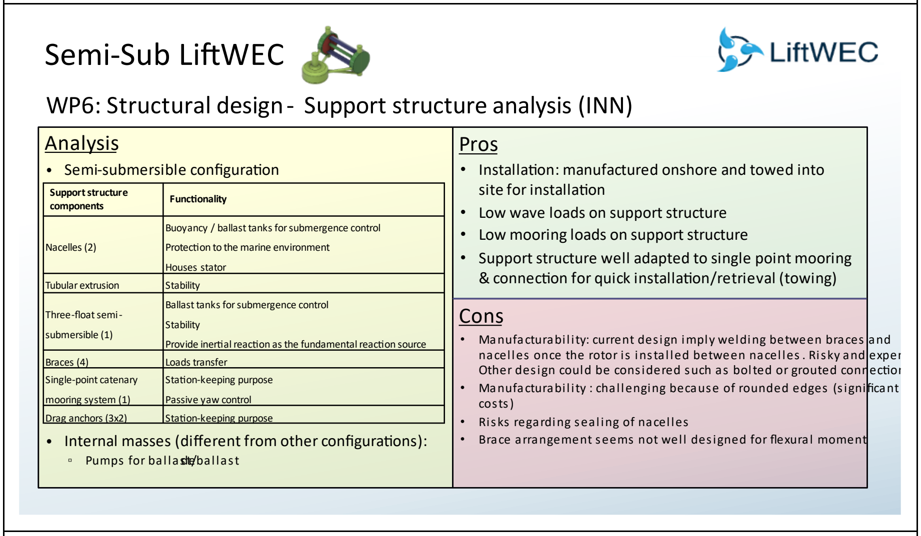
- Floating offshore wind structures are growing in scale of installation and therefore this is a promising outlook for this configuration.
- Coupled dynamics of a floating structure to hydrodynamics of rotor need to be investigated.
- Our initial 2D analysis shows that heaving and sway motions do not affect the power performance significantly.
- Submergence of rotor needs to be carefully designed since the image shows the rotor almost in line with the floatier.

Pros

- Great potential for development due to growth of floating offshore wind sector
- Total installation and mass cost could be potentially one of the lowest.
- Towing capabilities to repair onsite as well.
- Deep water operation is possible.

Cons

- Wave induced motions need to be further investigated
- Submergence of the structure needs to be carefully assessed



Semi-Sub LiftWEC

WP6: Structural design - Support structure analysis (INN)

Analysis

- Semi-submersible configuration

Support structure components	**Functionality**
Nacelles (2)	Buoyancy / ballast tanks for submergence control Protection to the marine environment Houses stator
Tubular extrusion	Stability
Three-float semi-submersible (1)	Ballast tanks for submergence control Stability Provide inertial reaction as the fundamental reaction source
Braces (4)	Loads transfer
Single-point catenary mooring system (1)	Station-keeping purpose Passive yaw control
Drag anchors (3x2)	Station-keeping purpose

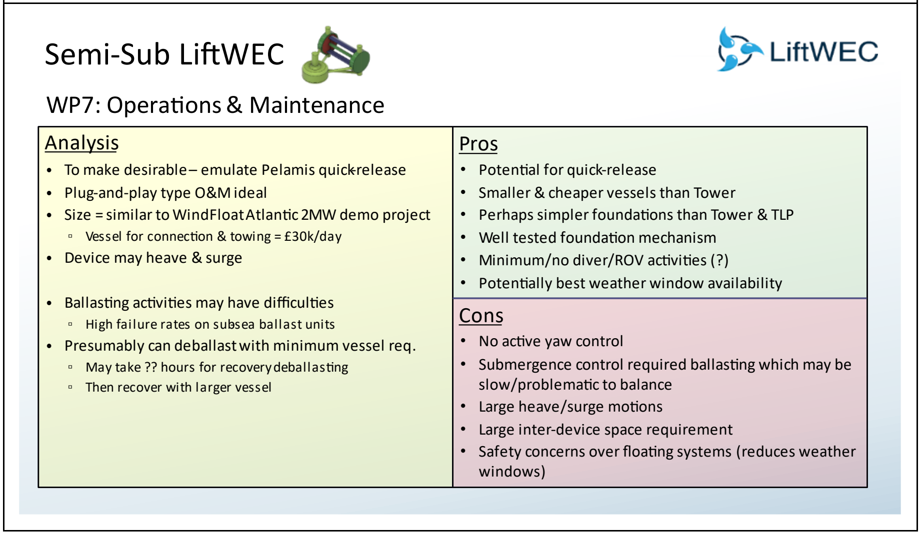
- Internal masses (different from other configurations):
  - Pumps for ballast/deballast

Pros

- Installation: manufactured onshore and towed into site for installation
- Low wave loads on support structure
- Low mooring loads on support structure
- Support structure well adapted to single point mooring & connection for quick installation/retrieval (towing)

Cons

- Manufacturability: current design imply welding between braces and nacelles once the rotor is installed between nacelles. Risky and exper Other design could be considered such as bolted or grouted connectio
- Manufacturability : challenging because of rounded edges (significant costs)
- Risks regarding sealing of nacelles
- Brace arrangement seems not well designed for flexural moment



Semi-Sub LiftWEC

WP7: Operations & Maintenance

Analysis

- To make desirable – emulate Pelamis quick-release
- Plug-and-play type O&M ideal
- Size = similar to WindFloat Atlantic 2MW demo project
  - Vessel for connection & towing = £30k/day
- Device may heave & surge

- Ballasting activities may have difficulties
  - High failure rates on subsea ballast units
- Presumably can deballast with minimum vessel req.
  - May take ?? hours for recovery deballasting
  - Then recover with larger vessel

Pros

- Potential for quick-release
- Smaller & cheaper vessels than Tower
- Perhaps simpler foundations than Tower & TLP
- Well tested foundation mechanism
- Minimum/no diver/ROV activities (?)
- Potentially best weather window availability

Cons

- No active yaw control
- Submergence control required ballasting which may be slow/problematic to balance
- Large heave/surge motions
- Large inter-device space requirement
- Safety concerns over floating systems (reduces weather windows)

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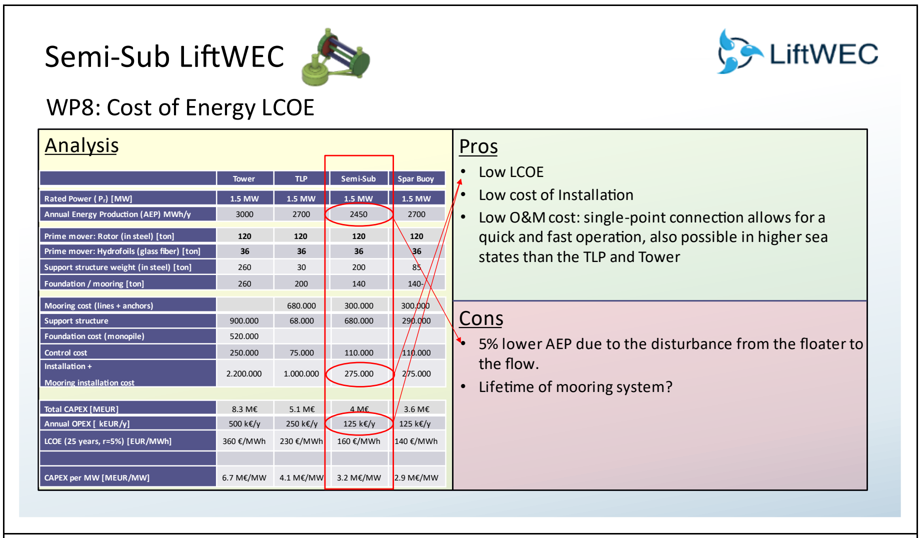


Semi-Sub LiftWEC

WP8: Cost of Energy LCOE

Analysis

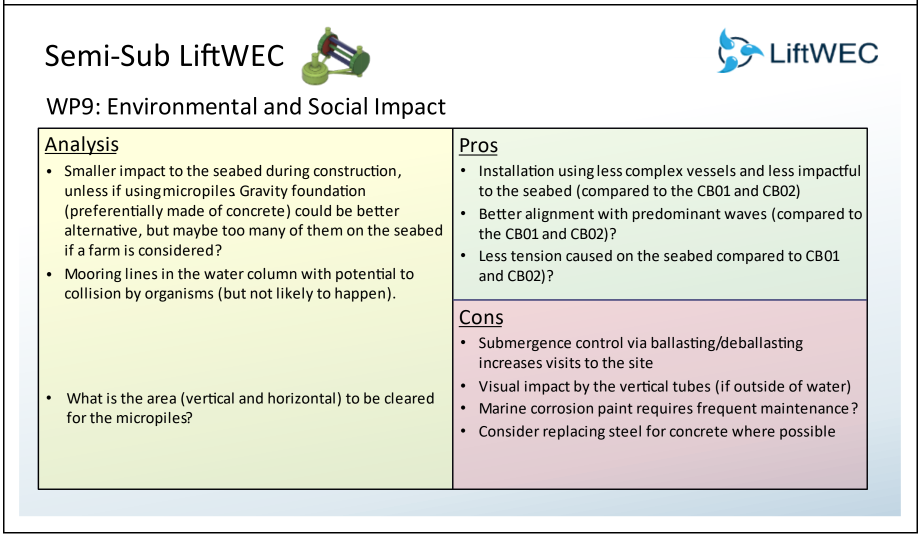
	Tower	TLP	Semi-Sub	Spar Buoy
Rated Power (P_r) [MW]	1.5 MW	1.5 MW	1.5 MW	1.5 MW
Annual Energy Production (AEP) MWh/y	3000	2700	2450	2700
Prime mover: Rotor (in steel) [ton]	**120**	**120**	**120**	**120**
Prime mover: Hydrofoils (glass fiber) [ton]	**36**	**36**	**36**	**36**
Support structure weight (in steel) [ton]	260	30	200	85
Foundation / mooring [ton]	260	200	140	140-
Mooring cost (lines + anchors)		680.000	300.000	300.000
Support structure	900.000	68.000	680.000	290.000
Foundation cost (monopile)	520.000			
Control cost	250.000	75.000	110.000	110.000
Installation + Mooring installation cost	2.200.000	1.000.000	275.000	275.000
Total CAPEX [MEUR]	8.3 M€	5.1 M€	4 M€	3.6 M€
Annual OPEX [kEUR/y]	500 k€/y	250 k€/y	125 k€/y	125 k€/y
LCOE (25 years, r=5%) [EUR/MWh]	360 €/MWh	230 €/MWh	160 €/MWh	140 €/MWh
CAPEX per MW [MEUR/MW]	6.7 M€/MW	4.1 M€/MW	3.2 M€/MW	2.9 M€/MW

Pros

- Low LCOE
- Low cost of Installation
- Low O&M cost: single-point connection allows for a quick and fast operation, also possible in higher sea states than the TLP and Tower

Cons

- 5% lower AEP due to the disturbance from the floater to the flow.
- Lifetime of mooring system?



Semi-Sub LiftWEC

WP9: Environmental and Social Impact

Analysis

- Smaller impact to the seabed during construction, unless if using micropiles Gravity foundation (preferentially made of concrete) could be better alternative, but maybe too many of them on the seabed if a farm is considered?
- Mooring lines in the water column with potential to collision by organisms (but not likely to happen).
- What is the area (vertical and horizontal) to be cleared for the micropiles?

Pros

- Installation using less complex vessels and less impactful to the seabed (compared to the CB01 and CB02)
- Better alignment with predominant waves (compared to the CB01 and CB02)?
- Less tension caused on the seabed compared to CB01 and CB02)?

Cons

- Submergence control via ballasting/deballasting increases visits to the site
- Visual impact by the vertical tubes (if outside of water)
- Marine corrosion paint requires frequent maintenance?
- Consider replacing steel for concrete where possible

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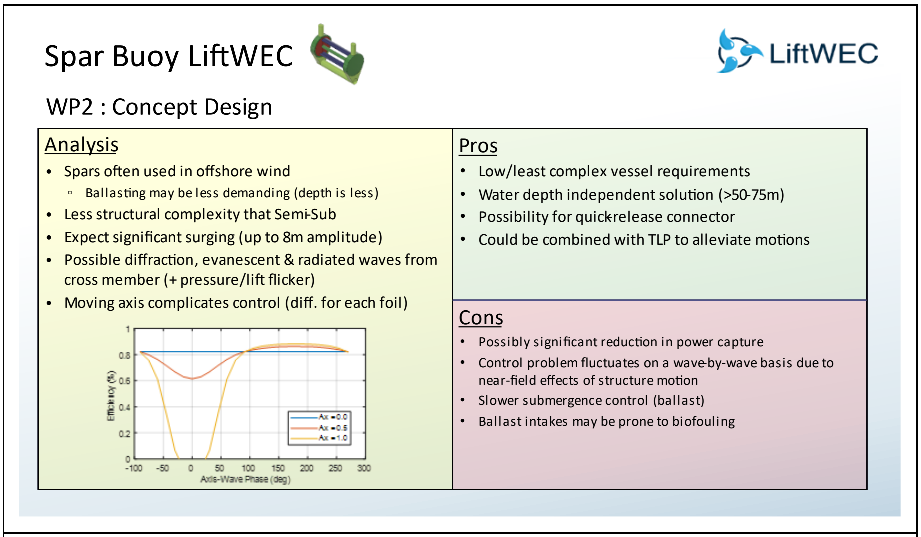
Appendix E WORK PACKAGE ASSESSMENT OF SPAR-BUOY LIFTWEC



Spar Buoy LiftWEC

LiftWEC

WP2 : Concept Design

Analysis

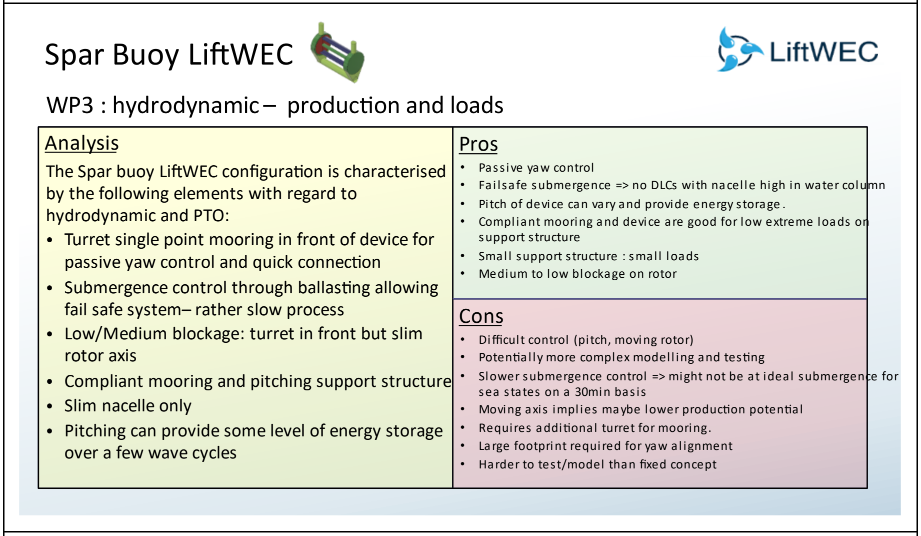
- Spars often used in offshore wind
    - Ballasting may be less demanding (depth is less)
- Less structural complexity that Semi-Sub
- Expect significant surging (up to 8m amplitude)
- Possible diffraction, evanescent & radiated waves from cross member (+ pressure/lift flicker)
- Moving axis complicates control (diff. for each foil)

Pros

- Low/least complex vessel requirements
- Water depth independent solution (>50-75m)
- Possibility for quickrelease connector
- Could be combined with TLP to alleviate motions

Cons

- Possibly significant reduction in power capture
- Control problem fluctuates on a wave-by-wave basis due to near-field effects of structure motion
- Slower submergence control (ballast)
- Ballast intakes may be prone to biofouling



Spar Buoy LiftWEC

LiftWEC

WP3 : hydrodynamic – production and loads

Analysis

The Spar buoy LiftWEC configuration is characterised by the following elements with regard to hydrodynamic and PTO:

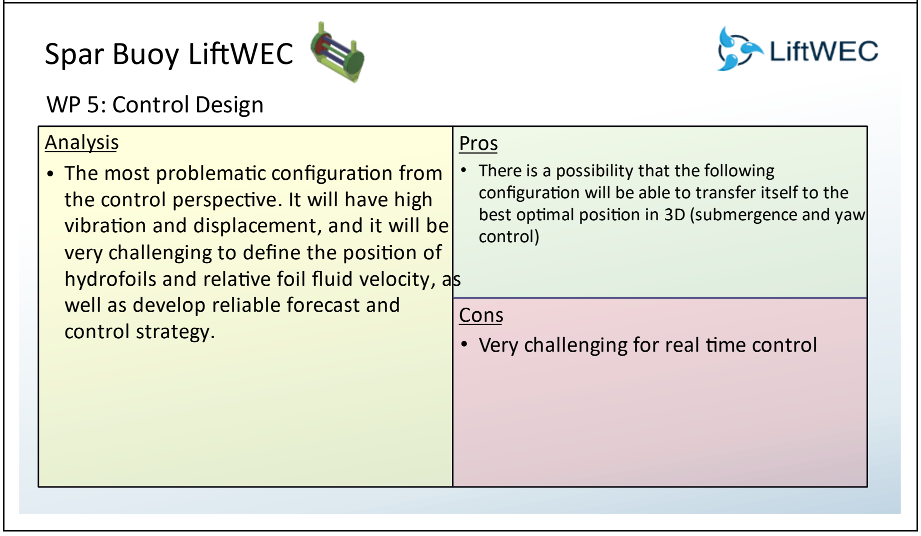
- Turret single point mooring in front of device for passive yaw control and quick connection
- Submergence control through ballasting allowing fail safe system– rather slow process
- Low/Medium blockage: turret in front but slim rotor axis
- Compliant mooring and pitching support structure
- Slim nacelle only
- Pitching can provide some level of energy storage over a few wave cycles

Pros

- Passive yaw control
- Failsafe submergence => no DLCs with nacelle high in water column
- Pitch of device can vary and provide energy storage.
- Compliant mooring and device are good for low extreme loads on support structure
- Small support structure : small loads
- Medium to low blockage on rotor

Cons

- Difficult control (pitch, moving rotor)
- Potentially more complex modelling and testing
- Slower submergence control => might not be at ideal submergence for sea states on a 30min basis
- Moving axis implies maybe lower production potential
- Requires additional turret for mooring.
- Large footprint required for yaw alignment
- Harder to test/model than fixed concept



Spar Buoy LiftWEC

LiftWEC

WP 5: Control Design

Analysis

- The most problematic configuration from the control perspective. It will have high vibration and displacement, and it will be very challenging to define the position of hydrofoils and relative foil fluid velocity, as well as develop reliable forecast and control strategy.

Pros

- There is a possibility that the following configuration will be able to transfer itself to the best optimal position in 3D (submergence and yaw control)

Cons

- Very challenging for real time control

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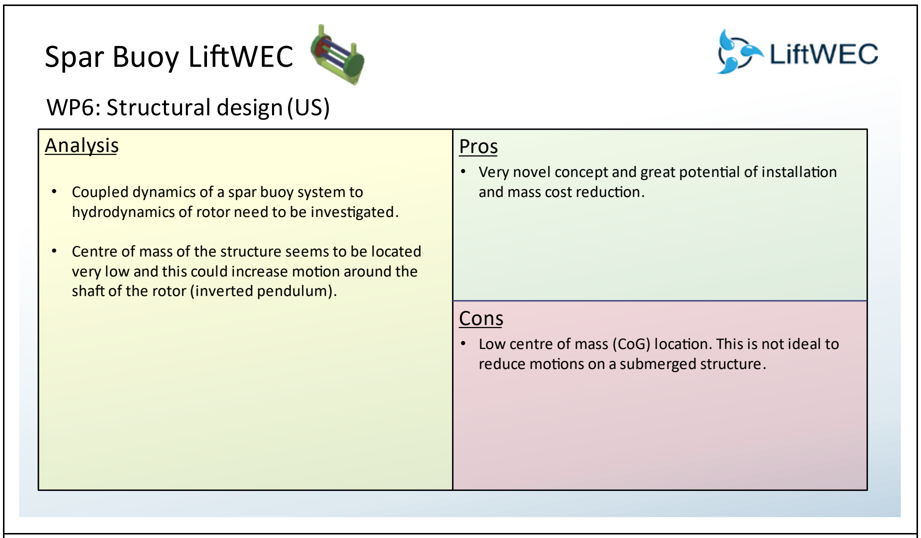


Spar Buoy LiftWEC

WP6: Structural design (US)

Analysis

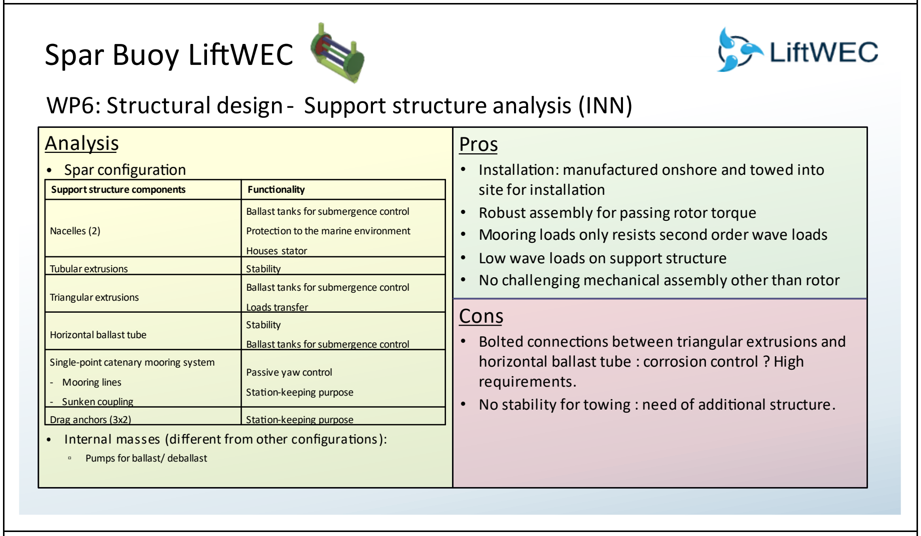
- Coupled dynamics of a spar buoy system to hydrodynamics of rotor need to be investigated.
- Centre of mass of the structure seems to be located very low and this could increase motion around the shaft of the rotor (inverted pendulum).

Pros

- Very novel concept and great potential of installation and mass cost reduction.

Cons

- Low centre of mass (CoG) location. This is not ideal to reduce motions on a submerged structure.



Spar Buoy LiftWEC

WP6: Structural design - Support structure analysis (INN)

Analysis

- Spar configuration

Support structure components	Functionality
Nacelles (2)	Ballast tanks for submergence control Protection to the marine environment Houses stator
Tubular extrusions	Stability
Triangular extrusions	Ballast tanks for submergence control Loads transfer
Horizontal ballast tube	Stability Ballast tanks for submergence control
Single-point catenary mooring system - Mooring lines - Sunken coupling	Passive yaw control Station-keeping purpose
Drag anchors (3x2)	Station-keeping purpose

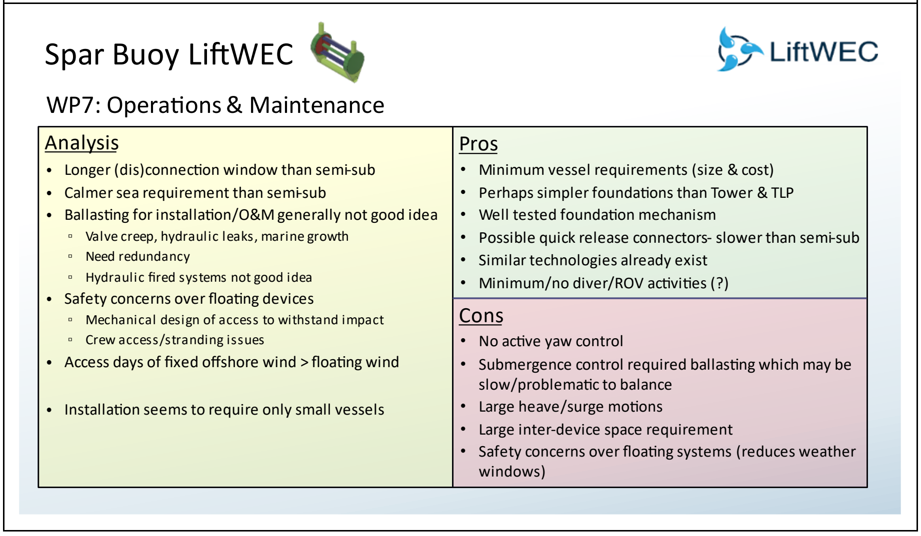
- Internal masses (different from other configurations):
  - Pumps for ballast/ deballast

Pros

- Installation: manufactured onshore and towed into site for installation
- Robust assembly for passing rotor torque
- Mooring loads only resists second order wave loads
- Low wave loads on support structure
- No challenging mechanical assembly other than rotor

Cons

- Bolted connections between triangular extrusions and horizontal ballast tube : corrosion control ? High requirements.
- No stability for towing : need of additional structure.



Spar Buoy LiftWEC

WP7: Operations & Maintenance

Analysis

- Longer (dis)connection window than semi-sub
- Calmer sea requirement than semi-sub
- Ballasting for installation/O&M generally not good idea
  - Valve creep, hydraulic leaks, marine growth
  - Need redundancy
  - Hydraulic fired systems not good idea
- Safety concerns over floating devices
  - Mechanical design of access to withstand impact
  - Crew access/stranding issues
- Access days of fixed offshore wind > floating wind
- Installation seems to require only small vessels

Pros

- Minimum vessel requirements (size & cost)
- Perhaps simpler foundations than Tower & TLP
- Well tested foundation mechanism
- Possible quick release connectors- slower than semi-sub
- Similar technologies already exist
- Minimum/no diver/ROV activities (?)

Cons

- No active yaw control
- Submergence control required ballasting which may be slow/problematic to balance
- Large heave/surge motions
- Large inter-device space requirement
- Safety concerns over floating systems (reduces weather windows)

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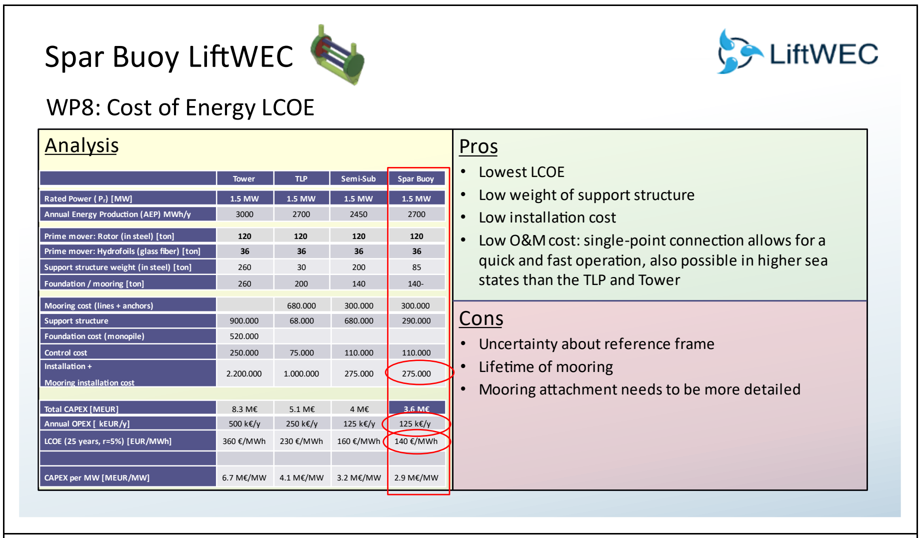

Spar Buoy LiftWEC

WP8: Cost of Energy LCOE

Analysis

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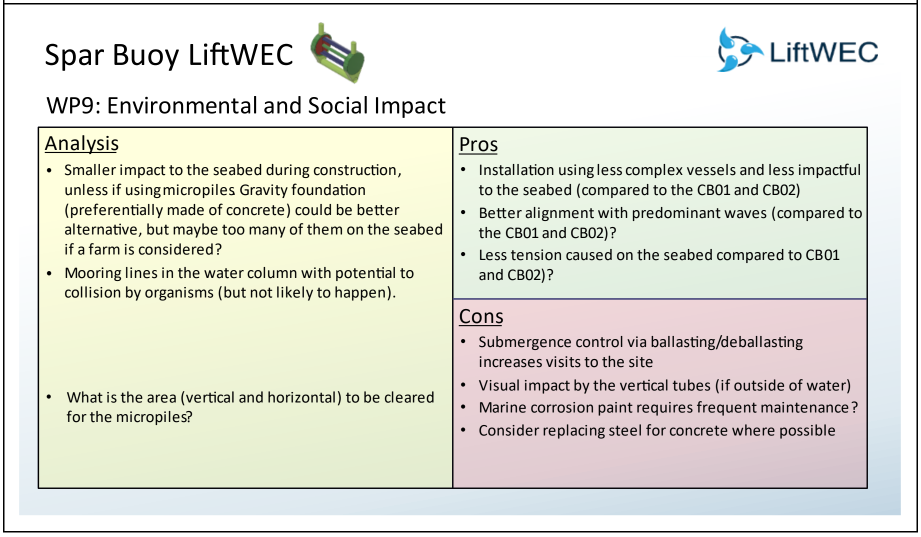
CAPEX per MW [MEUR/MW]	6.7 M€/MW	4.1 M€/MW	3.2 M€/MW	2.9 M€/MW

Pros

- Lowest LCOE
- Low weight of support structure
- Low installation cost
- Low O&M cost: single-point connection allows for a quick and fast operation, also possible in higher sea states than the TLP and Tower

Cons

- Uncertainty about reference frame
- Lifetime of mooring
- Mooring attachment needs to be more detailed



Spar Buoy LiftWEC

WP9: Environmental and Social Impact

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