LiftWEC

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

Deliverable D7.1

Operational Design Considerations

Deliverable Lead	University College Cork
Delivery Date	31st May 2020
Dissemination Level	Public
Status	Final
Version	2.0

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Document Information

Project Acronym	LiftWEC
Project Title	Development of a new class of wave energy converter based on hydrodynamic lift forces
Grant Agreement Number	851885
Work Package	WP7
Related Task(s)	T7.1
Deliverable Number	D7.1
Deliverable Name	Operational Design Considerations
Due Date	31th May 2020
Date Delivered	5th June 2020
Primary Author(s)	Brian Flannery (UCC)
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Document Number	LW-D7-01

Version Control

Revision	Date	Description	Prepared By	Checked By
0.1	30/05/2020	Draft for	BF	JM
1.0	31/05/2020	Draft distributed for consortium review	BF	MF
2.0	05/06/2020	Submission to EU	BF	MF

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EXECUTIVE SUMMARY

This report summarises best practice guidelines and design considerations, for offshore operations. The information herein was by and large sourced from telephone interviews of a number of developers, with experience in areas such as offshore wind, wave, tidal and oil & gas. Initially, challenges encountered specific to the experiences of those surveyed are described in questions and answers format. Broader design tips applicable to a majority of devices are also included in the survey answers.

Topics of interest more specific to the LiftWEC device are described in the later sections of the report. Discussing various possible methods of supplying a reaction force, beit from buoyancy restoring moments, the use of large submerged weight, a fixed seabed mounting or whether the reaction forces can be supplied by the moorings. The use of divers and/or ROVs for maintenance is discussed. The preference for the use of conventional vessels such as tugs is mentioned as well as a section on vessel cost and availability. As the device is likely to be heavily control dependent, a discussion on redundancy in design as well as fault tolerant design is given. The importance of a well designed dynamic cable is also mentioned. Various iterations of the CycWEC device are listed as well as the current proposed iteration. The justification for focusing on this device is the similarity in device operating principals, with the CycWEC being one of the better described devices in the current literature. Finally, the key learnings and recommendations are summarised in a discussion section.

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1 INTRODUCTION

This document constitutes Deliverable *D7.1 Operational Design Considerations* 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.

The project focuses on the development of a novel type of Wave Energy Converter (WEC), called the 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.

The purpose of the deliverable is a set of key design considerations for the LIFTWEC concept, which will feed into the concept development and evaluation work package. This will ensure that the major operational factors, which are likely to, adversely affect the viability of the concept can be considered early in the design process and be accounted for in preliminary device configurations. It will contain a review of all operational phases of a marine renewable energy technology lifecycle and detail the results of an examination of other related sectors (offshore wind, Oil &Gas, Aquaculture). Transferable knowledge and methodologies from these other sectors, which have been demonstrated to be safe, efficient and cost effective, will be described.

In order to gain familiarity with design considerations as well the lessons in offshore energy from other sectors: It was decided to conduct telephone interviewees with those with experience in wind, wave tidal and oil and gas. During those phone calls interviewees were asked to speak about the offshore experiences specific to their own devices, then about considerations and valuable lessons for the industry as a whole and finally if possible, to give feedback/recommendations on the LiftWEC device specifically. In order to protect the anonymity of sources, the document is edited in such a way as to combine statements together with the desired effect of reducing the likelihood of the source being recognised. This methodology naturally comes at the expense of more complete references. Wherever possible references are given if the information is in the public domain. The staccato like nature of the questions and answers section might prove irritable to the reader, in which case apologies for this editorial approach. Specific attention has also been placed on the CycWEC literature, with said device having direct overlap with the proposed LftWEC device.

2 QUESTIONNAIRE

The following section contains questions (in bold text) relating to installation, operations and maintenance and decommissioning. Answers from the various interviewees follow, each question. If different survey members were commenting on the same topic (learning from quarter scale tests for example): answers are combined into a paragraph. This was the approach agreed beforehand with the interviewees, with the purpose of maintaining a degree of anonymity. Stand alone statements are written with a line break.

2.1 INSTALLATION

2.1.1 What were the main challenges of the installation?

Timing was critical for all installations, and the need to know the last known point to bail out. Acquiring the right vessels, in a timely manner; for example, if you rely on a vessel to steam a long distance to site then you must make a decision a long way in advance and so you may risk having vessels on site when weather windows change, thus incurring cost.

Planning: be sure that all the involved parties are informed (check twice)

Engineering: identify clearly the most risky/novel activities in the plan and focus on the contingency plans

Preparation activities: perform tests/training before

Execution: small delays can lead to a big delay (critical path) (Khalid et al., 2020)

Putting people and marine equipment onto tidal site was by far the biggest challenge. Even experienced offshore personnel fail to understand how energetic these sites can be. In many cases we've had very experienced people coming from oil and gas, or with many years offshore experience who begin with a view that 'how hard can it be'. Every single time that person has been astonished in terms of the complexity of the installation considering the site conditions.

Used Oil and gas rigging crew for tidal device, they commented that it was more challenging due to narrow windows (can't do 80% of task, must be carried out to full completion).

Must be careful when emptying ballast tanks as system can capsize or plunge several meters in an uncontrolled manner if trapped air escapes.

Were there any operations which you previously worried about that turned to be OK, likewise were there any operations that you assumed would be relatively easier which turned out to be problematic?

One operation to pull a seabed cable to the surface was more complicated than expected as the connection point had moved along the seabed since the last survey (note this had only been weeks prior).

Each installation carried risks that were on international incident scale. (i.e. vessel loss, personnel accident or death). As such I was apprehensive about all major operations in advance, and approached each with caution. The operation would not commence until a meticulous preparation checklist was followed which would result in the GO decision for the operation (This checklist captured all technical checks of equipment, weather checks, insurance, permits etc.)

In special cases where we did not know have all the answers, (i.e. first time operations), we would undertake marine trials which would be a dry run of the operation in an alternative site.

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Have to weld everything to vessel before deployment. Need a coded welder as well as inspector. Weld inspector payed 8 days special rate for 10 mins work. Rest of time could be spent onboard vessel gym resulting in an excellent physique!

Tidal currents cause significant drag issues, affecting both vessels and ROVs.

What were the major lessons learned and what would you do differently the next time?

Many lessons: The most important is to ensure you have the correct planning, equipment, people and procedures to do the job safely.

Each operation we had detailed debriefs, and lessons learned workshops with key personnel. These meetings are where all the improvements are agreed – truly invaluable. I have a log of hundreds of these lessons and how they relate to an improvement in equipment, personnel or procedure.

Design problems out as you continue through the design process. At the same time you need to recognise a cut off point (in terms of constantly adding features to the design), i.e. stop adding features after a certain TRL level.

Device has to be scalable. On the issue of learning from quarter scale deployments: Scaled down tests are supposed to de-risk full scaled tests. However, problems that you can eliminate are often not dealt with. What resalable info can you extract from quarter scale tests? Due to Froude power scaling ratios, a quarter scale device will have 128 times les power, meaning the quarter scale PTO has little or no resemblance to the intended full scale PTO.

Generally, prototype devices are overengineered (as opposed to building redundancy)-and oversized, (you just want to get some data). How many prototypes went as far as to be relevant for full scale O&M? With Hindsight maybe avoid overengineering some parts but overall would repeat mostly the same steps. If mass production: would fully understand the conditions and thus minimise overengineering., adopting a critical design approach. Size of farm is also a factor. If you have a large MW farm of big devices then you may end building your own vessel. Might need to have motion compensated cranes etc.

Some developers prefer the philosophy of lots of small devices, as if one goes down it’s not as much as problem in terms of loss of revenue. Larger number also has economy of scale. Smaller device is way cheaper to install. Vessel cost goes down, weight is everything.

A major stage gate to get through (drive/boardroom) pressure forced work to be completed before ideal time. This proved to be costly and ideally should be avoided. If device is to be deployed in May, aim for February, as due to nature of delays inherit in process. If you aim for May it could be next February before you get it done!

Stay away from Tidal sites!

What are the major obstacles to installation and how could these obstacles be overcome in future? (if applicable, please include improvements in industry/ licensing/ governance etc.)

It would be useful to have a more central communication for licensing agencies, as the relevant contacts can vary substantially and so it is possible to end up falling foul of a body, depending on who you talk to. For example, it is not clear who should prescribe the aids to navigation even within the Maritime and Coastguard Agency (UK organisation).

Stakeholder engagement – this needs to be controlled from the outset to ensure fisheries or other stakeholders are in support of the project.

US laws (Jones act) preventing use of a foreign vessel (offshore wind farms)

No foreshore license!!

Incompetent Governance and Marine Industry.

No money anywhere!

Better alignment between leasing and licensing. i.e. the MW ratings are not in sync. There are different types of lease depending on capacity. Need license to use the sea, takes in environmental concerns. Electrical license connection have e.g. 3MW or 5MW thresholds. For a demo array adopt 5MW as a threshold.

Depending on deployment location, a limited supply chain can adversely affect operations. Need to be near a major supply vessel hub.

2.1.2 Vessel availability/ Vessel expense

Could you comment on vessel availability/ vessel expense?

Using local vessels where possible significantly reduces cost, since you reduce risk of making a “go” decision for a vessel that needs to steam to site, only for the weather window to close, or not being able to take advantage of an unexpected weather window to conduct operations. The limitations of this strategy include the limitations of local available vessels, e.g. crane capacity, but can be designed out if identified at an early stage.

Installation strategy uses tug boats plus large fishing vessels, eliminating the need for special jack up vessels. Work floats have small cranes (EMEC workboat superCAT has hydraulic crane up to 5 Tonne) so try to keep weight of component below threshold.

Vessels are the main cost driver for offshore operations.

Installation should be central to device design to ensure the device can be installed using conventional vessels that are readily available, (this will lower the cost).

Installation should also consider the use of standardised equipment where possible to reduce costs. (by increasing market availability)

A lot of uncertainty hiring vessels from different country to that of the deployment. Vessel owners control the scenario. If considering building your own vessel: it can be difficult to compete with Dutch companies (for example) who are subsidised with low rate government loans.

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2.1.3 Installation cost

Overall Installation cost? (did the cost conform to estimates)

This is project specific but, in most cases, can be accurately costed with suitable contingency, (for either weather or technical stand down).

£50,000 per dynamic cabling connection designed for extreme pressure. Go for a spliced connection. Wet mate connectors are a problem.

The more important consideration here is the LCOE for the project is within a market acceptable range. A low cost installation technique is essential. Rough guideline for vessel day rates:

- Crew transfer = €1,200
- Multicat = €2,000.
- 50 Tonne Tug = €8,000/ day
- 70Tonne Tug = €12,000 / day
- Small Construction Vessel (OCV 250) = £30,000 / day
- Large Construction Vessel (OCV 400 like the Viking Neptune) = £80,000 / day

2.2 OPERATION & MAINTENANCE

2.2.1 O&M Strategy

What was your O&M strategy for your device(s)?

Majority of operations can be conducted at site, for example blade or turbine replacement. Small vessels can be used for inspections and simple modifications, thus reducing cost of O&M. (referring to a wave energy converter)

Strategy was removal once every 5 years, but the turbine designers found this difficult to achieve. Removals were closer to every year (tidal).

Array of 50 devices: O&M strategy (have 52 devices). Every 5 years lift out device 1, replace with spare device A. Repair device 1. Replace device 2 with refurbished device 1 etc.

Carry out maintenance April to September: build weather risk into analysis. Unexpected O&M need to get out at first available weather window. Even if can get access, may be be limited as to what you can do.

Inspection once a month, with major inspection every 6 months. All systems above waterline, lead to easier inspections. Check for chaffing and rubbing on connectors, shackles and cables. Large device so can get on board in H_s up to 2m for failure maintenance.

Electronics and power conversion components are all solid state, (i.e. nothing mechanical, all electronics) having known lifetimes. e.g. 500 KW rated component can go for 2years before repair. Lifetime is proportional to power and heat. Siemens cabinets can handle certain known acceleration limits. If a bearing failure then you will need to tow back to shore. Power cable can be quickly released of with benefit of power cable being on device, with surface access. Towing is much cheaper than lifting/loading onto a vessel.

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The Pelamis P-750 device could be removed and towed back to shore in three hours.

2.2.2 O&M Challenges

What were the main challenges of the O&M?

Scheduling activities for R&D projects, since inspections and scheduling is constantly under investigation.

Retrieval of the device is an equally sized challenge to installation.

Marine debris was an additional risk.

Vessel held up at sea for 18 hours in a force 9 severe storm (had a large vessel).

Responding to emergency O&M shutdown. Incident in November but had to wait till neap tide, resulting in restricted accessibility.

Never leave anything underneath the water! Biofouling can have significant O&M issues. Biofouling on cables adds weight as well as drag (can double or quadruple the amount of drag). This increase the load as well as the load fatigue cycle. Every five years 100-200 m of rope needs to be replaced.

Were there any operations which you previously worried about that turned to be OK, likewise were there any operations that you assumed would be relatively easier which turned out to be problematic?

Chartered a large vessel from oil and gas with ROV capable of 5m/s. Deployed ROV at site but dynamic positioning wasn’t able to maintain station (due to string tidal currents).

Inspecting blades from a RIB and lifting/lowering the turbines from the water were both simpler and became very fast and efficient with only a few trials.

Blade replacement at site for floating systems is quite difficult even with minimal swell, as platform and vessel moving independently, so takes longer than otherwise expected from activities on fixed objects e.g. piled devices.

Skill of captain(s) is huge, sometimes using multiple captains simultaneously.

It is common for mooring lines to break every few months.

Tidal sites will have a well defined operating environment that will allow for a factor of safety to be applied. Do not have the 100yr wave design headaches associated with wave energy devices.

What were the major lessons learned and what would you do differently the next time?

Even minimal swell can impede operations for two independently moving platforms.

Important to have humans there for physical senses: “if something is going wrong I can feel it in my boots”. Sense of vibration/smell the smoke etc.

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The importance of doing vessel dry runs/feasibility studies. Spending x amount to do a trial could offset risk by as much as 10x.

Weakest piece will break and need replacement.

Simplicity is key. Keep number of valves and switches to a minimum. PTO is also vitally important: you need to deliver power as close to the primary source as possible (hinge point for example). Further distance to power point means an increase in complexity. Redundancy is key (if this fails what happens).

LCOE could only be achieved if you can do some inspections etc with ROVs.

Think in array terms, can you detach one device from the farm.

If maintenance is offshore, then remove as a pod. I.e. if a valve is damaged remove the entire pod(module) on which valve sits to save time and cost by having the ability to "plug and play". Radio unlatching of shackles is best (used extensively in oil & gas).

If possible use fixed pitch blades, and no gearbox. Variable pitched blades and gearboxes increase the complexity and thus the likelihood of problems.

Used a generator which has a flooded-water gap (IP patented). Water tight nacelles can have problems.

Biofouling is a big issue. With Seabed mounted devices, biofouling is less. and tidal sites will have a large flow rate meaning a large rate of flushing.

Have a mechanical fuse/braking system similar to a heavy goods vehicle(needs to power and energise to move).

Minimise the number of moving parts.

What are the major obstacles to O&M and how could these obstacles be overcome in future? (if applicable, please include improvements in industry/ licensing/ governance etc.)

No way you could hot swap (old one out new one in) without best vessels in world.

Need 20-30% spare turbines at a huge cost per unit?

Cable is biggest constraint-can be destroyed/ you don't want it to get wound up or crushed.

Much smaller ROV window than originally envisioned.

Redundancy in TCC (control unit-brain)- need one, have three sets in there

Electrohydraulic system was too complex, ballast system was also too complicated. Too many electrical components in the system.

The costs of mooring maintenance is generally too optimistic. Difficulty in maintaining moorings; cost of chain inspection schedule. Motion means rust and corrosion (the combination of submergence and emergence leads to oxidisation). Mist check mooring positions regularly.

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Offshore wind can potentially land helicopter for maintenance if no heave and swell, this is not the case for wave energy converters.

Testing all subsystems in benign site is essential. The three phase electrical supply for example: power up at 11,000 V. It does not matter whether components are bespoke or off the shelf. What matters is that they can survive in the working environments they are put in. The only way to ensure this is to test all components in as realistic conditions as possible for as long as possible. Test your components beforehand! Run every part for general testing as well as fatigue. Devices have been/are failing on tiny stuff at sea.

Draw up a de-risking strategy. Consider what is the strategy for testing components at the different TRL levels. No tools for O&M, lots of work on hydrodynamics and working principal but O&M tools are lacking. The traditional design approach is to obsess over hydrodynamics and control optimisation and afterwards to worry about O&M. There is a strong case to be made that the narrative should be flipped, i.e. design an optimal O&M strategy first and then design the device. At the very least both functional basic design and O&M concerns should be tackled in tandem, an approach known as co-design.

OPEX is everything!

2.2.3 Vessel availability/ Vessel expense

Could you comment on vessel availability/ vessel expense?

Smaller and more readily available vessels were targeted for use as much as possible.

If you need a more expensive vessel then you better have a good device.

Bigger the vessel the more you can work but the expense goes way up.

Always plan for earlier than you need, as if needed in May could end up 6 months later before finally get use of vessel: plan for February.

Had double crew, from oil and gas who worked 12 hours on 12 hours off. Tides move 40 mins each day. Have only 6 hours of working opportunity. Can be unlucky in that the tide can occur when crew shift ends.

Mobilisation costs and standby costs are considerable.

Oil and gas based so had own internal fleet to rely upon.

Overall O&M cost? (did the cost conform to estimates)

If Oil prices are high, vessels entail a crippling expense, as all the oil companies are working. If on the other hand oil prices are low and the vessels are not being used price can drop to a quarter of the original price.

Only have the vessel for some time, and cannot extend that time without incurring a very expensive penalty. Pay penalty fee, continue to pay high vessel costs and crucially must compensate next client (who had booked the vessel)

Pay per crew member. Pay fuel depending on weather conditions. Dynamic position can occur an extra £80,000 in extra fuel costs

2.3 DECOMMISSIONING

2.3.1 Decommissioning Strategy

What was/is your decommissioning strategy for your device(s)?

Recover from seabed.

Return to port for disassembly alongside.

Ensure full inspection takes place by ‘turbine team’ to ensure lessons are captured for future designs.

Recycle materials such as steel, copper etc.

Reverse of installation.

The vast majority of those surveyed considered decommissioning as a simple reverse installation procedure .

What were/will be the main challenges of the decommissioning?

Decommissioning activities so far very simple as purely reverse of install, and so improved with repetition.

Were there any operations which you previously worried about that turned to be OK, likewise were there any operations that you assumed would be relatively easier which turned out to be problematic?

Since very similar to install then lessons learnt from install and O&M made decommissioning easier.

Could you comment on vessel availability/ vessel expense?

As per install. For previous decommissioning activities local/less experienced vessels were required, since the lessons learnt were transferable by marine operations manager rather than vessel operators.

Overall Decommissioning cost? (did the cost conform to estimates)

Usually lower than expected as scrap yards will buy the material from you.

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Costs were generally around device retrieval and cranes for disassembly

Overarching comments?

Never refused press! Looking for publicity, as need increased general interest and to get more investors onboard, however wave energy in general has overpromised and underdelivered.

Quality of personnel is crucial and affects outcome. If the design team has many employees with little to no offshore experience, then the learning curve is steep and mistakes are costly.

Majority of devices are both too complex and too heavy. Being overdesigned for survivability means huge structural weight which will always adversely affect LCOE. Devices are often deployed before they are ready (fully designed) due to stage gate pressures. There is a disparity in how the numerical models and basin tests predict performance and the actual at sea performance. Predicted KWh ratings are not achievable and capacity factors are suspect. Honesty is essential.

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3 LIFTWEC DEVICE

The following section pertains to areas of direct design interest to the proposed LiftWEC device.

An issue for the LIFTWEC device is station keeping. How is the generated Torque to be resisted (by fixed structure or by mooring). Survivability is naturally a key issue and since the LiftWEC device utilises lift forces for operation, it may be possible to enter a configuration which is largely transparent to the waves, thus avoiding the most severe of excess forces associated with storms. Nevertheless, an early investigation into lowering the device in the water column for survival mode has been undertaken from an offshore operations perspective. A strong feature from a design principal point of view can become a weak feature from an operations point of view. If the device is always completely submerged (no access for small to medium O&M jobs) then the overall maintenance of the device becomes a problem.

3.1 MOORING

Atargis wave corporation ("Atargis Energy Corporation - Cycloidal Wave Energy Conversion," 2020) investigated the possibility of free floating wave energy converters as shown below.

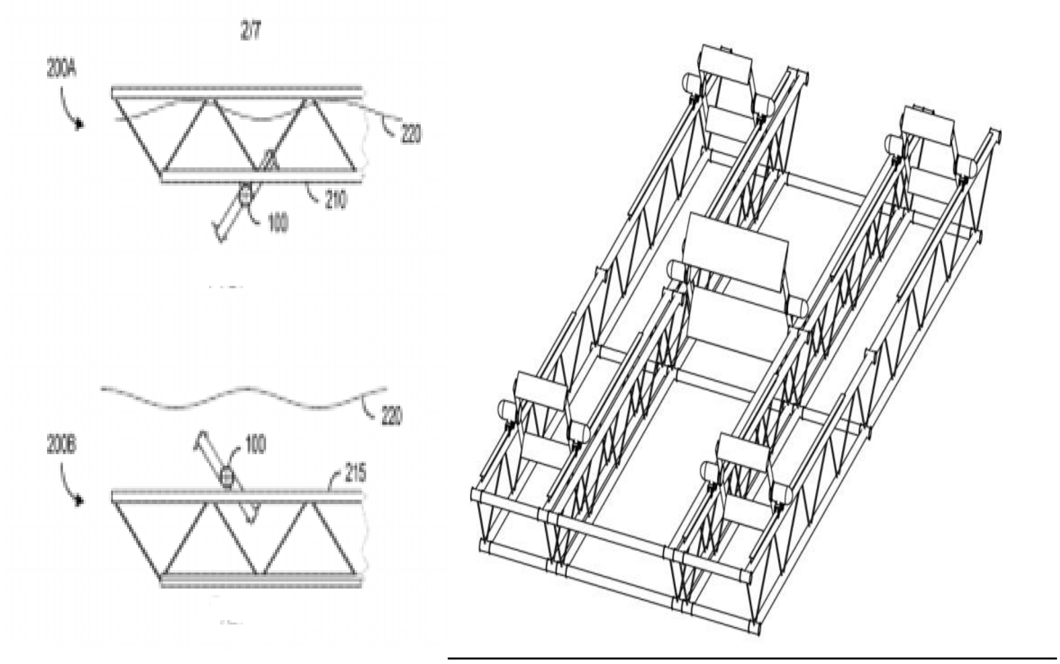

Figure 3-1: Different Floating configurations for the CycWEC device. 3A surface piercing, 3B submerged, 3C multidevice platform. [source Fig 2A,2B (Patent No. WO 2014/026019 A2, 2012) 2C (Siegel, 2010)]

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As any free floating structure like the example shown in Figure 3-1 will consist of several CycWECs connected by a common mounting frame, the cost of this frame needs to be compared to the cost of an ocean floor attachment. Additionally, the floating structure will have its own hydrodynamic characteristics, yet be intrinsically coupled with that of the energy harvesting foils. The floating structure would therefore have to be designed with the difficult tasks, of providing maximal structural support with minimal interference form an energy capture perspective. The required spacing of WECs causes a free floating mounting frame to be at least one wave length in length. Therefore, if the water depth at the deployment location is significantly less than one wave length, ocean floor attachment becomes more cost efficient than free floating implementation due to the smaller size and thus cost of the structure. On the other hand, the technology development required and thus risk incurred for a free floating implementation is significantly higher for a free floating implementation. For these reasons, Atargis Energy shifted its near term focus on development of an ocean floor attached CycWEC installation since it will reduce the time to market as well as the capital required for the development (Siegel, 2010).

The oil and gas industry insists on redundancy in mooring design whereas offshore wind does not. Consequently in floating wind you have bigger lines with a factor of safety design in. Oil and gas have lower sized lines but more of them. I.E instead of one mooring line at each corner, have two. In order to have stability it would be preferable to have at least four connection points apart from each other.

How the moorings are attached to device is vitally important. If hands have to go on device it can be very dangerous. You are still liable for injury (despite the crew volunteering for the job/risk). If the installation/O&M plan is to disconnect a shackle, this involves, beating pins out and using large ratchets. Heavy tooling while in 1-2m swell even with experienced crew is risky. Use as many remote control release mechanisms as possible (used a lot in oil and gas). Sea catch (*Sea Catch Product Catalog*, 2020) or IMENCO shackle can be used in Hs 4-5m (“ROV Operated Shackles - Imenco AS,” 2020). Moorings and cables also pose a significant entanglement risk, particularly for a rotating device like LiftWEC. This problem was encountered by the Openhydro tidal device (“Tangled lines keep Cape Sharp Tidal turbine at bay - Offshore Energy,” 2014)

The use of moorings for submergence as a survivability tactic, has the potential to be extremely beneficial but is undoubtably extremely difficult. If 25m below the surface, the device would see a significant reduction in loads. In order to use compliant moorings, the device needs to have same tension in the lowered survival mode as the normally operation mode. One potential solution would be elastomeric mooring but it is expensive and has ~ 5 Tonne load limit. Examples of elastomeric moorings systems are those of Dupont (“DuPont Thermoplastic Elastomer Helps Keep Marine Devices Afloat,” 2014) and Seaflex (“SEAFLEX - The Mooring System,” 2020). Subsea winches are used in oil and gas. As the cables are operating in harsh subsea environment in terms of corrosion and fouling, they need lubricating oil as well as a protective coating. This has strong environmental issues and is difficult to get permission to use them. Their maintenance becomes a problem also a golden rule of offshore engineering is generally “don’t leave anything below the water”.

The Wetfeet project (Lynch & Philippe, 2020) goes into considerable detail on the various aspects of submergence. There are numerous problems to deal with including:

Submerge the device as deep as possible to lower excitation forces whilst avoiding risks of collision with the seabed. The system should be activated remotely and equipment used should be designed for underwater conditions (pressure, water ingress etc), as well as having redundancy in all

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components carrying out such an important task. Submergence system should adapt to mooring system (including ballasts): accommodating both operational and survival positions. Additionally there will be restrictions to the dynamic cable in both operational modes. The entire process should be fast enough when compared to the anticipation time estimated by weather forecast. The process must be reversible. It has to integrate both submergence and emergence process equipment.

Wetfeet (Lynch & Philippe, 2020) conclude that the repeatability of the process is compromised because of the changing environment (excitation loads, bio-fouling, corrosion, etc.) High tensions have been highlighted in the mooring lines, which induce large capacity equipment requirements not available on the market. No known subsea winch system with a capacity higher than 50 Tonnes seem to exist, although this may be due to current limited demand for larger winches rather than a more fundamental limitation. This equipment also presents some significant challenges of maintenance to be available for service life and are expected to be costly. Subsea additional winches may also be needed to manage some mooring lines during submergence operations to avoid their collision. One single risk has been quantified as high, after mitigation. It is related with the cost of the mooring system. The mooring system is expected to represent a significant cost of the whole system. Furthermore whether the winches where situated beneath the water or inside the device itself, the cost was still prohibitive.

An alternative concept to winches is to use ballast for submergence and compressed air for emergence. Ballasting is relatively easy although still has risks, for example if any trapped air escapes suddenly the device can plummet rapidly. Thus, this method while deemed preferable is not without its problems. Additional devices are required such as pumping system, compressed air tank, remote control system, sophisticated mooring and dynamic cable design etc. These devices will be underwater in survival conditions, therefore sealing issues are critical and have to be studied. Installation ballasting operations often use weighted chain (more stable, more controlled/easier) but the operation needs to be closely monitored by an entire installation team. The repeatability of this extremely delicate process being carried out remotely would be a concern.

The Laminaria device (“Laminaria,” 2020) uses active moorings to lower itself in the water column. In Luminaria’s case the moorings are actually a key part of the PTO and not an ancillary system like the one proposed in Wetfeet. Swedish, Seabased WEC (“SEABASED,” 2020) uses a heaving float with tether and generator system. The device experiences a tidal range, meaning the line could go slack. This is avoided by winching the cable in. Other examples of wave energy devices employing submersion in the design are NEMOS (“NEMOS,” 2020) and Arrecife (“Arrecife Systems,” 2020)

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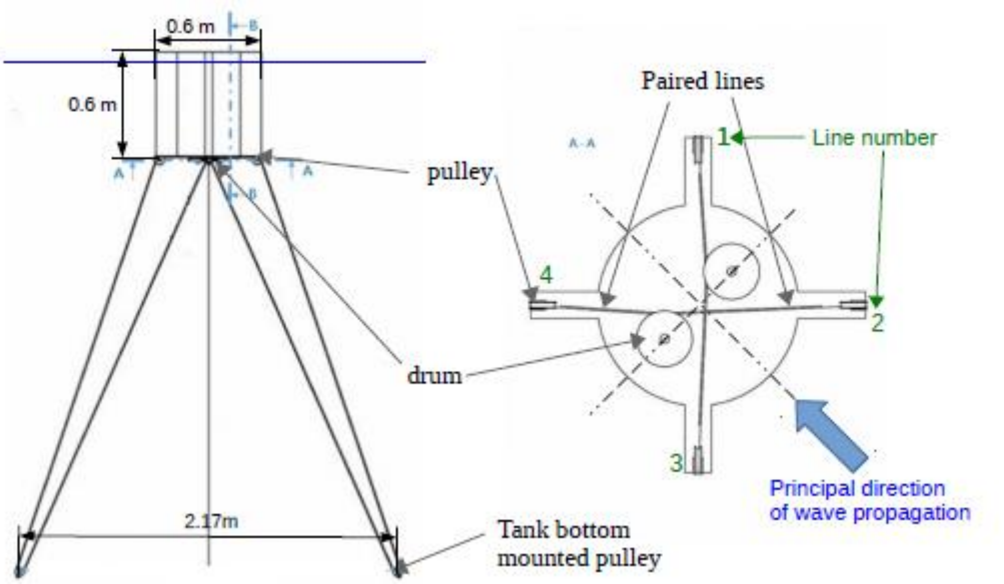

Figure 3-2: Schematic view of the 1:16 scale Laminaria WEC. Mooring line numbers with respect to the main wave direction of propagation are indicated. {source (Pascal, Adrien Combourieu, Nauwelaerts, & Foschini, 2017)

3.2 BUOYANCY TYPE

The generated torque could be resisted by a free floating structure whose buoyancy or hydrostatic stiffness provided a restoring moment. The structure would also need to be slacked moored, but one could envision a design such as that in *Figure 3-1*A. It would be preferable to avoid the hydrofoils emerging from the water resulting in green water and surface slamming effects that would compromise the structure. Additionally, for survivability, the surface structure would need to be either large and robust like a semi-sub platform or so slender as to be almost transparent to the waves.

3.3 MONOPILE

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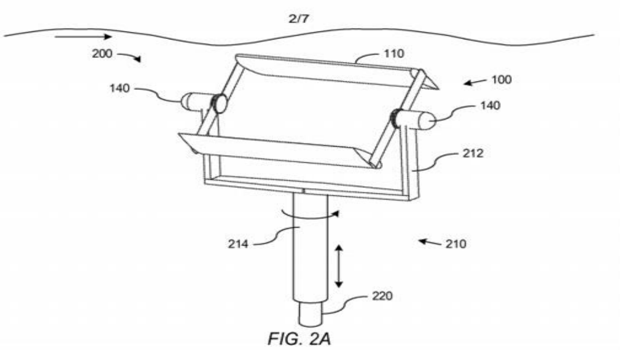

FIG. 2A

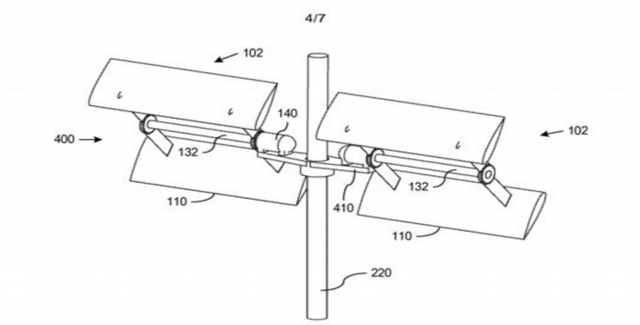

FIG. 4A

Figure 3-3:Fixed configurations of CycWEC device. {source (Patent No. WO 2014/026027 A2, 2014)

Whether a monopile is suitable as a foundation structure and therefore capable of providing a resisting torque to that generated by the device depend on;

Water depth: monopiles are a standard in fixed offshore wind however the maximum depth is usually quoted as 50m. It may be possible to go deeper than this but the cost is likely to increase rapidly.

Water depth would naturally have an influence on the wave regime likely to be encountered, for example moving to a shallow water depth (where it would be easier to install a monopile) might shift the waves from a circular deep water orbit into an elliptical orbit seen in intermediate depths. This will not make operation of the device unfeasible but it would certainly add complexity to the hydrodynamics and control of the device. If a shallow water depth were to be combined with a relative large tidal range, then the working space for the device to both operate normally and emergency space to occupy in storm survival mode is reduced. This could force the radius of the device to be reduced. A more complete analysis would have to considered but it could be the case, that given such a combination the monopile would be oversized in comparison to the device. i.e. the ratio of non power producing structure to power producing structure would be too high.

Seabed surface: if the seabed surface is too rocky or contains too many boulders then a monopile is not suitable for installation

A benefit of a monopile foundation would be the ability to yaw the device so as to face the incoming wave field

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3.4 GRAVITY BASE

If the torque generated by the device is to be resisted by a gravity type structure (in a similar manner to a spar), then the main issue is the weight of the device. Weight is often considered the main penalty factor in offshore operations. Naturally, it has a negative effect on initial CAPEX cost of manufacture but also the vessel costs become very large If the heavy structure has to be lifted. Specialised vessel such as jack-ups are expected to be prohibitable expensive. Furthermore, if you go too large, say for example requiring a lifting capacity of 500 Tonnes: you are narrowing down the poll of vessels from which to choose from. It could be the case that the only vessel available is a 750 Tonne capacity. You may have no other choice than to use this vessel and you will pay for the extra capacity (the 250 Tonne differential) whether you needed it or not. It may be possible to utilise innovative design solutions such as the drop keel floating wind device (Ross & Dai, 2019)used by Floating Energy Systems shown below.

Figure 3-4: Drop Keel floating wind platform [source (Ross & Dai, 2019)*]*

This hybrid type device has the advantages of a semi-submersible in terms of assembly and launch at a quayside location while possessing the spar advantage of a low centre of gravity in operation. If it were possible to utilise conventional towing vessels, then OPEX would be reduced. However, how much weight is required for stability and the effect of this weight on CAPEX would need further investigation.

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3.4.1 Control

The flow field needs to be understood and there is a preference for 2D flow i.e. the incoming waves orthogonal to the device. The device is likely to be heavily control dependant in order to produce power. The no control or limited control power production need to be known. The control will need a lot of sensors and monitors. It is not a trivial task to tune the sensors. Redundancy in both the central control unit (the brain of the system) and the sensors of the system is essential. If a measured variable which is crucial to control (rotor velocity for example) is being misread or faulty then the control system likely will not work. If it is the case that the device has no dumb/unintelligent failsafe mode, then it is essential that the control system remains functional at all times. The sensors should be modular in nature, such that if the primary sensor fails, it can be removed from the chain without interrupting the secondary sensor.

3.4.2 Dynamic Cable

If the device were to be supported by a floating structure, then there are additional concerns for the electrical power cable (often termed dynamic cable in such instances). Naturally if the structural support is supplied by a fixed monopile, then the design of the electrical cable is significantly reduced.

The intersection of the dynamic cable to the main device is a concern. Logically the ideal location would be on a static element of the device, either on the stator directly or through an intermediate part fixed to the stator. The inertia and motion response of the cable would also have to be considered with regards to its influence on the device itself. It could be the case that a single cable on one side of the device would introduce undesirable imbalance to the device operations. It might therefore be worth investigating a two cable, symmetrical approach whereby a cable is located on either side of the device at the same location. This would then balance the device and also add additional redundancy to the system. Since the device is by nature heavily control dependant, it could be the case that a second cable would be of benefit if any problems occurred with the primary cable. Both cables could perhaps join as a single cable lower down the water column forming a “Y” shape. If it were not possible to locate the dynamic cable on a non rotating part of the device then a form of slip ring connector would have to investigated, considering the fatigue and failure modes of such a connection.

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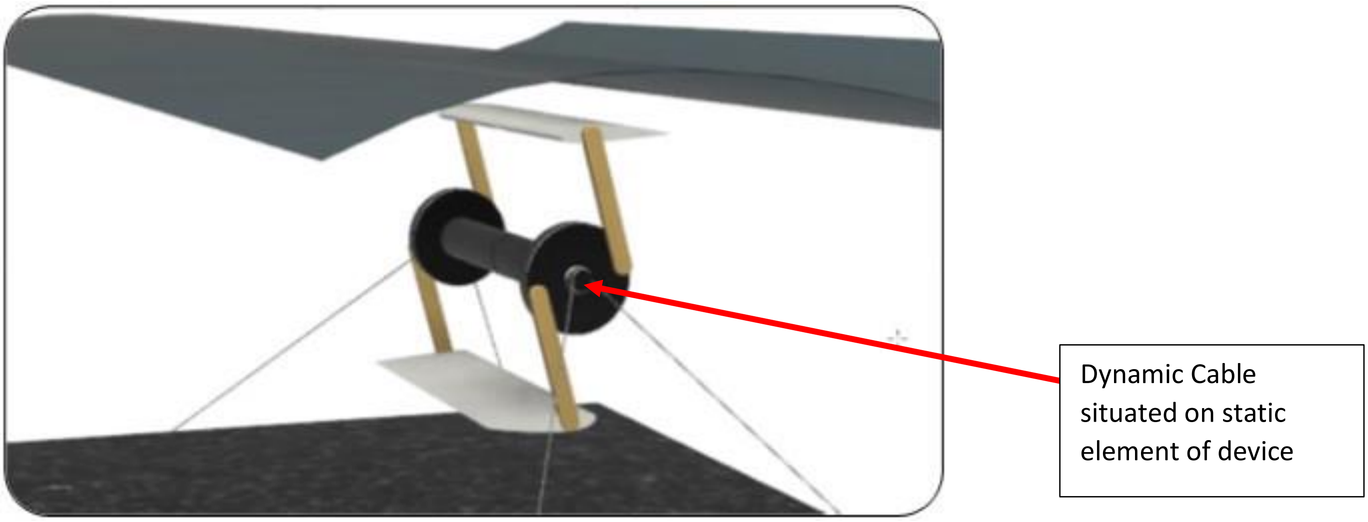

Figure 3-5: Early Draft LiftWEC device

Risers/cables are subjected to different loads than device. They can experience dynamic loads such as wave slamming. It is necessary to decouple cable motions from that of floater. What is the maximum excursion of cable? it will have limits in the x-y plane as well as the z plane. The cable is protected from overbending by a bend-stiffener. Bending stiffener angles on the device should be studied. 45° angle should be affordable, 60° angle is extreme (Lynch & Philippe, 2020). The cost and technical challenges of the riser system increase significantly with water depth.

Design of a riser system for deep-water is a complex iterative multi-discipline process, with many variables. Depending on field layouts, vessel interfaces, fluid properties, and environmental conditions, a riser system is engineered for each particular application supported by prerequisite analysis, material, and testing pre-qualification. An extensive inspection and replacement program is standard for drilling risers and should be considered for the LiftWEC configurations.

Flexible risers are designed in 12 different configurations as shown in Figure 3-6. Eleven of these are used today. The most common configurations are the "lazy wave" and "lazy S" (“DEEPWATER E&P: Dynamic risers key component for deepwater drilling, floating production | Offshore,” 2020)

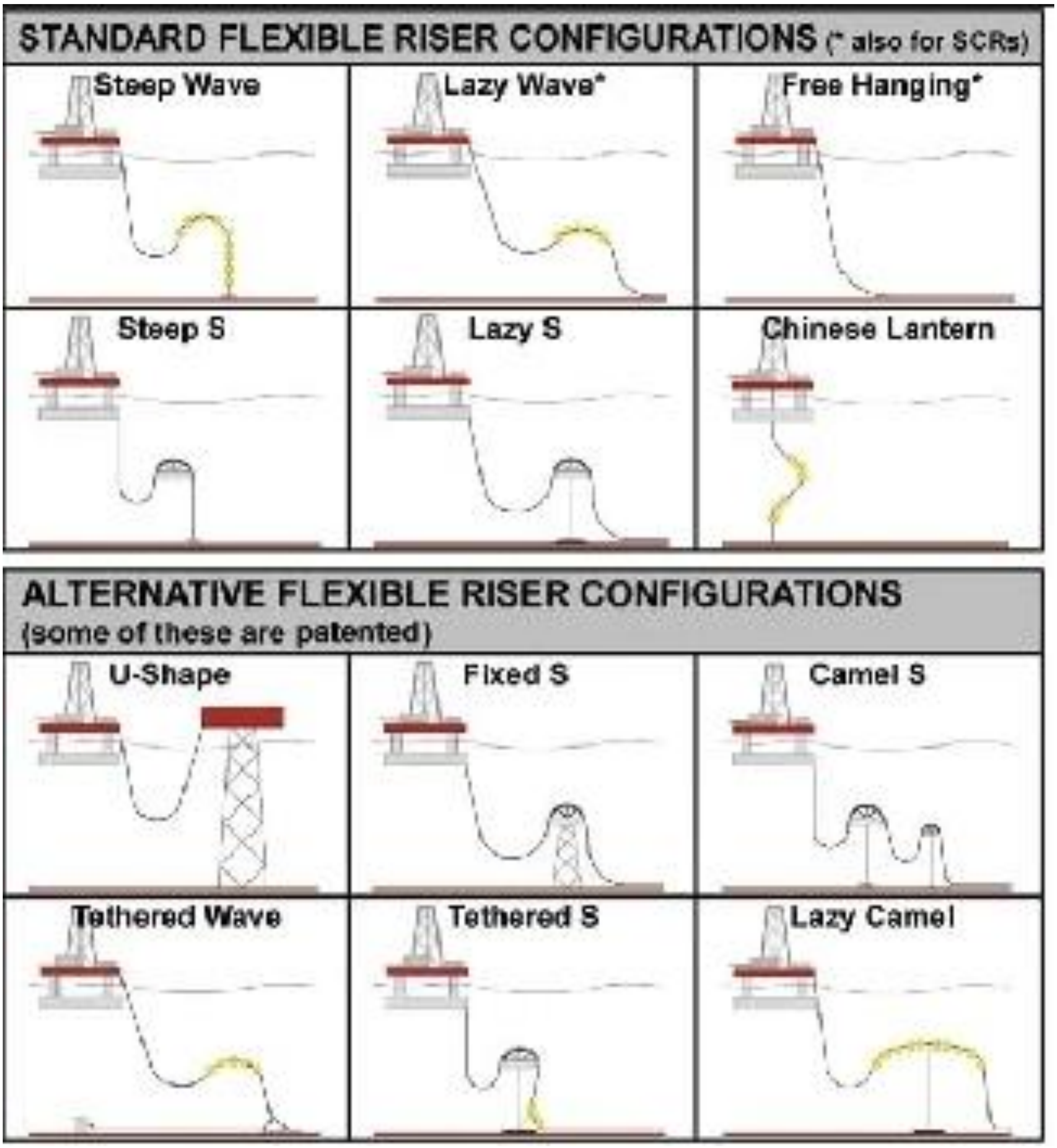

Figure 3-6: Standard flexible riser configurations for floating offshore structures [source ("DEEPWATER E&P: Dynamic risers key component for deepwater drilling, floating production | Offshore," 2020)*]*

In pipelines, the flexible pipe structure itself is standardized with minor differences from manufacturer to manufacturer. The buoyancy is either discrete elements of syntactic material or a buoyancy tank (mid-water arch) of steel or elements of syntactic material. It is suggested to plan to have dynamic cable near a mooring connection point for stability. Currently, a lot of work is being done on joint disconnection/reconnection of mooring and dynamic cable, Wave Energy Scotland for example ("Offshore and subsea specialists plunge into wave power sector," 2020). It is important to plan for automatic cable disconnection systems that do not damage the floater (can act as a whip if it is loose).

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It is possible that bespoke equipment may be needed for cable laying ("Alpha Marine | Services," 2020) although the Oyster WEC used a multicat to run cable. As well as significant motion, cables are also subjected to significant marine growth. In summary the dynamic cable connection represents a significant design problem for the LiftWEC device.

3.4.3 Vessels

It is generally recommended to plan to use conventional vessels as this increases availability and operations costs decrease. Paying for larger vessels which can operate in higher sea states will increase working windows but at a cost. Furthermore, if such vessels are needed for winter maintenance for example, then the likelihood of weather windows needs to be known and the variance accounted for. It is typically considered prohibitively expensive to hire these vessels ("floating hotels" as a characterised by one member) while unable to work due to weather restrictions. If large lifting vessels are required, then the cost will increase and the availability decrease. Weight should be regarded as the penalty for both OPEX and CAPEX. The availability problem is worsened with super structures such as semisubmersible vessels as there are only three in the world. In general, vessels can be chartered from the vessel owner directly or through the use of a broker (typically 1-6 months out). Examples of the different types of charter contracts are given in Figure 3-7 while the difference between summer and winter markets is given in Figure 3-9.

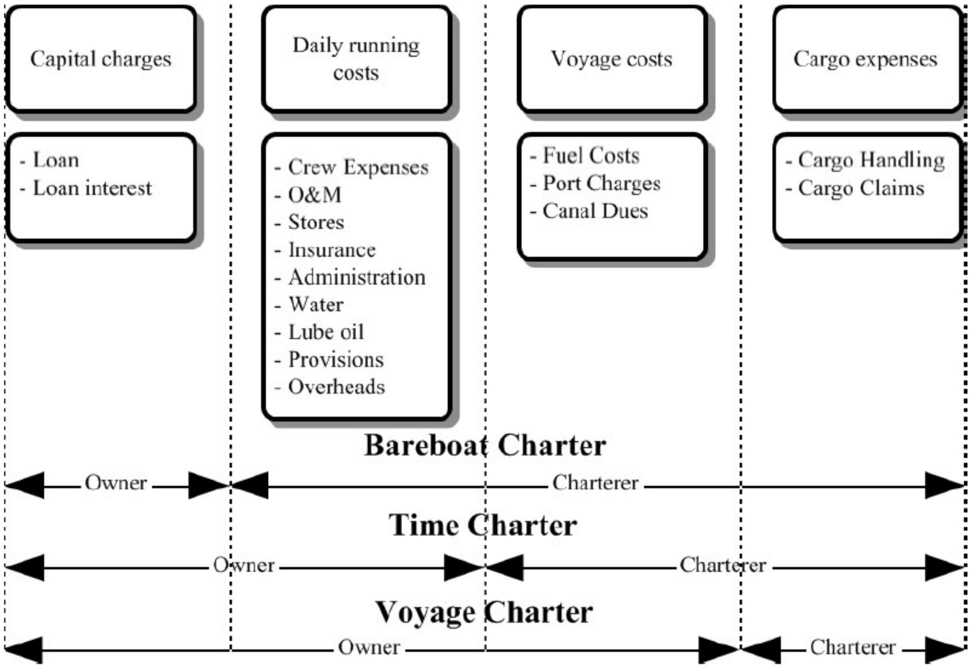

Figure 3-7: Cost distribution of different vessel charter strategies [source (Dalgic, Lazakis, & Turan, 2013)*]*

Typical charters employed in wave and tidal sectors are "Bareboat Charters" thus incurring mobilisation and demobilisation costs as well as many other costs such as admin fees, insurance,

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lubricants, and others listed in Figure 3-7. The additional cost of fuel for dynamic position operations in energetic sites can be considerable.

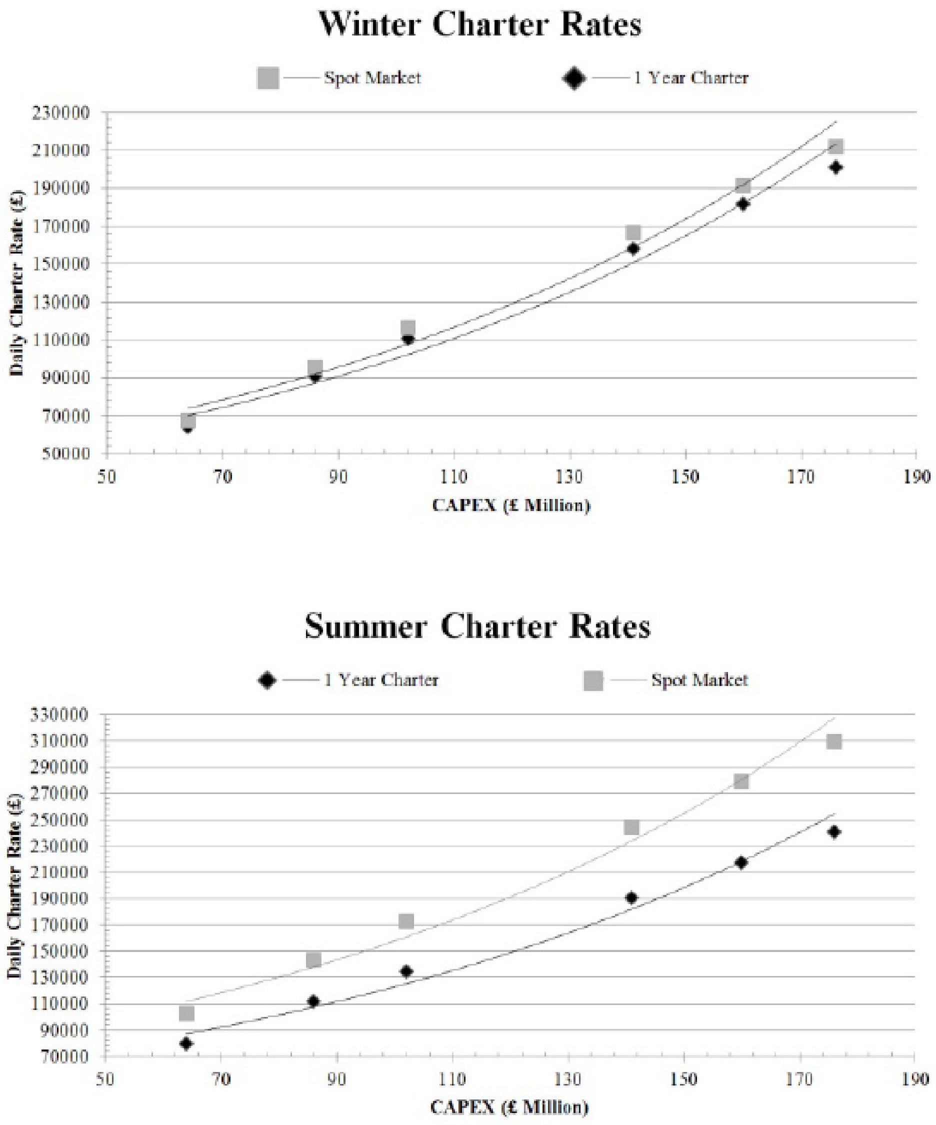

Figure 3-8: Difference is Summer and Winter charter rates[source (Dalgic, Lazakis, & Turan, 2013)]

If the weather is bad some oil and gas vessel are willing to carry out work but if the weather is good everyone is busy. Vessels, like any other equipment hire, prefer long term charters (for example on wave farms as opposed to prototypes) but ultimately wont turn away work if they can factor it into larger value commitments. Due to the fact that spring and summer months are more appropriate for maintenance activities in terms of both milder weather conditions and lower production levels, operators intend to perform maintenance activities in this period. Therefore, the number of available vessels in summer months decreases, subsequently the charter rates of the jack up vessels increases. If there is no alternative but use large vessels for LiftWEC operations then it would appear to be

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advantageous to hire the vessels for longer periods of time. However, there are also some investment risks, which operators have to bear in mind. These risks can be mitigated through sophisticated maintenance approaches and more accurate planning (Dalgic et al., 2013). The majority of those surveyed strongly recommend the use of conventional vessels for offshore operations if possible.

3.4.4 Divers Vs ROV

Divers

The use of divers involves a health and safety as a well as daylight hours requirement. Additionally, there is a legal requirement to use two divers. One tidal device utilised two different companies to challenge each other on feasibility of all operational aspects, of an extremely difficult maintenance operation. The task was successfully completed but at a huge cost. It is essential to have everything is planned out and at all times the diver needs to control their body in the water. Divers also have very brief dive windows, 5 mins to get there, 5 mins to work and 10 mins to return safely to surface (Tidal specific case).

If device is fixed to seabed, and divers are required, then windows are limited as there is rarely no swell. It is recommended to remove divers from the equation if possible. If operations are required at 50 meter water depth then, divers will be extremely cost prohibitive: would need a pressurised diving bell and a week of access.

ROV

Remotely operated underwater vehicles (ROVs) are tethered underwater mobile devices, whose use is now commonplace in the oil and gas industry. ROVs are unoccupied, highly manoeuvrable, and operated by a crew aboard a vessel. It is imperative to design beforehand for the use of ROVs and not to assume they can be utilised at a later stage. For example, by ensuringexternal fixings of device are compatible with manipulators (robot hands). In the tidal energy sector ROVs can increases working window from 5 mins (using divers) to 35mins. In the most extreme tidal sites ROVs can still encounter difficulties in station keeping, but this problem may not be as severe for wave sites if appropriate weather windows are targeted.

3.5 CYCWEC INSTALLATION STRATEGY

The entire CycWEC device shown in **Error! Reference source not found.**Figure 3-9 including struts is completely assembled at port, and can be towed to the deployment location by means of tug boats. At the deployment location the mooring points have been preinstalled and are equipped with marker buoys attached to the mooring points by means of mooring lines. During deployment, the mooring lines of the marker buoys engage in a proprietary strut attachment system that allows the struts to connect to the mooring points without any need for diver or ROV interaction. Once all struts have been attached to the mooring points, the jacking system in the struts enables optimal orientation of the CycWEC in terms of submergence depth as well as alignment with the incoming waves. In addition,

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the struts allow the CycWEC to be lifted out of the water for maintenance, or lowered closer to the ocean floor for storm survival and avoidance of breaking waves.

The nacelles are held in position by two telescoping struts each which are adjustable in length by means of a telescoping jacking system based on a rack and pinion gear system. The struts are attached to four mooring points installed at the ocean floor. The mooring points can be implemented using suction caissons, driven piles, drilled rock anchors or any other suitable technology depending on ocean floor bathymetry. The struts are hinged at the connection point to the nacelle, so that they can be folded to be parallel to the main shaft for transportation and installation. Winches in each opposing nacelle perform the folding action, and the cables connecting the struts to the winches stabilize the CycWEC in the axial shaft direction once the CycWEC is deployed (Siegel, 2019).

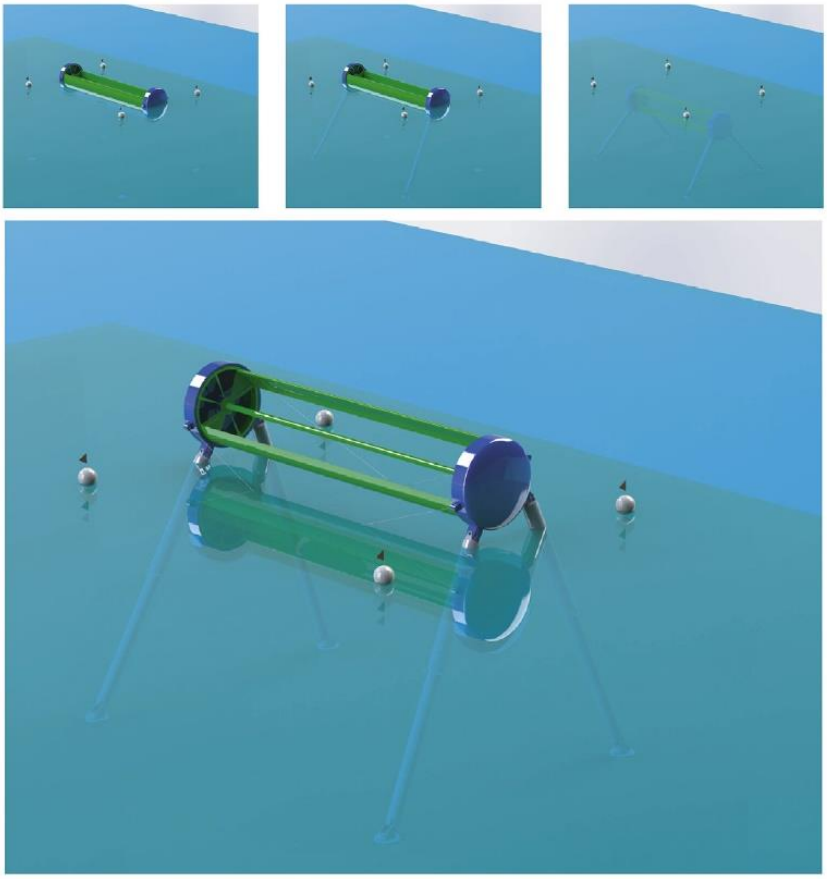

Figure 3-9: Cycloidal Wave Energy Converter towed out for deployment (top left), with two legs deployed (top center), in the operational position (top right), and maintenance position (bottom). The rotor is shown in green, the nacelles in blue and the strut mooring system in gray. [source (Siegel, 2019)*]*

3.5.1 CycWEC O&M Strategy

If the CycWEC becomes inoperational due to major system failure of any type, it can still survive storms with the generator brakes applied and the main shaft stopped. In this survival mode, the loads are actually lower than in operation since the velocity and lift forces experienced by the blades with the shaft stopped is only that induced by the incoming waves, and thus much smaller than the operational load to with the rotational speed of the blade is added. With the blades stopped, the wave induced flow direction relative to the blade will change through 360 with each wave passage, and the blades will experience blade stall alternating with attached flow.

Thus, even in the presence of two failed generators, failed main shaft bearings and failed blade pitch systems the CycWEC can survive storms, which constitutes a large amount of redundancy towards device loss. Since the brakes are spring actuated, no internal or external power is needed for storm survival, and the control system does not need to be operational either.

The support strut jacking system is also redundant in a similar fashion as the CycWEC itself, with two independent gear racks and pinion drive systems operating each strut. As long as at least one of these systems is functional, jacking actions of the strut can be performed, including lifting the CycWEC out of the water for maintenance. The four legs themselves feature redundancy as well, as the CycWEC can be lifted out of the water with three operational leg jacking mechanisms. With the CycWEC lifted out of the water using three legs only, maintenance on one of the legs and its jacking and latching mechanisms can be performed outside of the water, with the leg disengaged from the mooring point and lifted above the water line. The winch systems operating the legs are also redundant, as long as two out of the four winches operating the struts are operational, the entire CycWEC remains operational (Siegel, 2019).

As one interviewee put it “if you need a jack up vessel then you better have a good device”. While the performance characteristics of the CycWEC device do indeed look impressive: Since the installation strategy essentially has a jack up vessel encapsulated in the device, it is likely to incur a heavy CAPEX cost. The overall operational cost of both the intended LiftWEC and CycWEC devices remains to be seen.

4 DISCUSSION AND CONCLUSION

As a result of the interviews carried out, best practices guidelines and design tips of a broader nature as well as more specifically to the LiftWEC device have been documented. Broader design considerations applicable to almost any device include the keywords, simplicity, redundancy and modularity.

Complexity in design is generally undesirable with offshore devices: the more moving parts and number of components that can possibly fail, is likely to incur higher OPEX costs as well as the possibility of downtime in energy production. This problem is often exacerbated with wave energy devices, due the more energetic nature of chosen sites and the decreased number of weather windows, to perform maintenance. If a failure occurs in the winter, it may be several weeks or even months before access is possible. The mantra of simplicity may well be an issue for the LiftWEC device if it relies heavily on control for energy production. The implication being that, should that any of the likely numerous components and sensors, needed for control fail, then energy production will suffer as a consequence.

Redundancy was another frequently encountered keyword that aims to reduce as much as possible the fears laid out in the previous paragraph. Having multiple components (e.g. sensors necessary for control) or ways of connecting multiple components ensuring there is no single point of failure. It is recommended therefore to introduce redundancy on all major components whose failure could affect power production.

Whereas redundancy is a preventative measure well worth undertaking, modularity could be described a curative one in the unwanted event of a failure. If an inner valve, of a section of the device were to fail: rather than spending a considerable amount of time and effort attempting to fix or replace it, if instead the entire section(module) on which the valve fits could be replaced, this would be of huge benefit. Modularity was also referenced in terms of the captor itself, whereby if the foil or the linkage to the structure was modular in such a way as to better absorb different wave frequencies as well as oblique and short crested waves.

The topic of device resilience was discussed, meaning that if the device where to encounter a failure (damage to a foil or an electrical coil for example), production could still continue at some reduced capacity factor. Those surveyed indicated that why this may be possible to do, it is rarely practised due to the likelihood of damaging the remaining part of the device due to excessive loadings etc. Therefore, if this undoubtably useful characteristic is required then it should be explicitly designed in beforehand. This is a topic known as fault tolerant design.

On the subject of the use of divers or ROVs it emerged that as the safety and expense of divers is prohibitive, ROVs would be advantageous. It is important however, to design beforehand for the functional requirements of ROVs, ensuring all external fixings/shackles etc are designed to be compatible with ROV manipulators. Working weather windows significantly increase with ROVs in comparison to divers. Another widely used feature in oil and gas is radio controlled release shackles. Manually removal of shackles involves the use of heaving tooling at sea, which incurs a significant risk, The ability to achieve this function remotely not only reduces the risk but also increases the significant wave height in which the operation can be carried out.

Regarding surface access versus tow away strategies for maintenance, there is no consensus in the community. Surface access would certainly be a benefit for small to medium sized maintenance tasks. However, there is the a concern, that even if access were possible, would it be safe and could the operator be reasonably expected to carry out work during the significant motions that could be encountered (in terms of motion sickness). If the maintenance strategy was to disconnect and tow away, then this operation would have to be carried quickly and preferably with a relatively high H_s threshold to avoid significant downtime. The Pelamis P-750 device could be disconnected and towed back in three hours, which was a highly desirable feature of this technology.

The installation strategy must be meticulously planned beforehand. Several interviewees spoke of the importance of carrying out practice runs, using the same crew, performing the various procedures in a controlled setting. In doing so, they were able to offset considerable risk inherit with installation. If it were possible, to validate the installation strategy at model scale, it would be of huge benefit and this is an area identified as a gap in current research knowledge. The reduced cost of operating at model scale would offset risk and give confidence to the likely success of the strategy, although, it is not envisaged that the practice runs would cease, such is the magnitude of operations, the total number could possibly be reduced.

On the subject of installation complexity, it recommended where possible to plan for the use of conventional vessels such as tugboats, so that vessel availability increases and the total cost decreases. If on the other hand large lifting vessels are required, then the cost will undoubtably increase. The total weight of the device should be regarded as a penalty in terms of both CAPEX and OPEX. The larger the lifting capacity required, the fewer the number of available vessels. The vessel charter market is very much dictated by supply and demand and heavily linked to offshore oil and gas as well as the weather conditions. In general, someone looking for a vessel (the lessee) should regard it as a lessor's market. Vessels are the main cost driver for offshore operations.

The use of active mooring system for survivability was found to be prohibitively expensive as well as likely requiring breakthroughs in technology. The Wetfeet project suggests that submergence through buoyancy chambers is more manageable but still comes with significant difficulties. Several potential methods of resisting the torque generated by the LiftWEC device were investigated. A more detailed financial analysis is necessary before commenting on which system is best and it is likely that the prelimnary configurations will feature both fixed and floating solutions. This work will be the future focus of the operations and maintenance work package: investigating the preliminary configurations and providing more details and their pros and cons.

Finally the author would like to express sincere gratitude to all survey members for their contribution to this document.

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