WAVE ENERGY CLUSTER CONCEPT DESIGN

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Introduction from Wave Energy Scotland

Wave Energy Scotland (WES) has run wave energy technology development programmes for the Scottish Government and the European Union. The programmes are based on pre-commercial procurement and WES has funded 132 projects involving over 300 organisations from industry and academia.

Floating offshore wind projects, as seen in the ScotWind leasing round, are moving towards deeper water locations with significant wave climates, such as off the north and west coasts of Scotland. Economic modelling by Offshore Wind Consultants on behalf of WES suggests that sharing space, infrastructure, services and supply chain with offshore wind developments can significantly reduce the cost of wave energy.

Research conducted by WES at the University of Edinburgh's FloWave facility revealed no significant loss of performance is expected for wave energy converters placed relatively close together.

These findings encouraged WES to seek a design concept for clustering individual wave energy devices together in a way that allows them to be moored and electrically connected as a single entity. While a cluster structure will incur additional cost, WES believes there are benefits that offset this. Advantages include greater capacity density on congested seabeds, fewer moorings, shorter device tethers, reduced dynamic cable lengths, a local equipment room for shared subsystems, improved offshore operations and maintenance opportunities, and an electrical output better suited for integration with floating offshore wind.

WES commissioned Blackfish Engineering Design to help create and explore multiple possible design options to determine if a practical and economically viable solution for clustering WECs could be identified.

CONTENTS

ABBREVIATIONS

Blackfish	Blackfish Engineering Design Ltd
CTV	Crew Transfer Vessel
DP	Dynamic Positioning
ER	Externally Reacting (e.g. reacts main generation loads to an external fixed body or seabed)
FOW	Floating Offshore Wind
LCOE	Levelised Cost of Energy
LER	Local Equipment Room
O&G	Oil and Gas
OSS	Offshore Substation
PA	Point Absorber
PE	Polyethylene
PP	Polypropylene
ROV	Remotely Operated Vehicle
SR	Self reacting (e.g. reacts main generation loads against itself and no external fixed body required)
SB	Submerged Buoy
SPMT	Self Propelled Modular Transporter
T&I	Transport and Installation
UHMWPE	Ultra High Molecular Weight Polyethylene
UV	Ultraviolet
WEC	Wave Energy Converter
WES	Wave Energy Scotland
WTG	Wind Turbine Generator

REFERENCES

Ref 1: ARUP large scale landscaping report (https://www.waveenergyscotland.co.uk/research-strategy/strategic-research/very-large-scale-wave-energy-generation)

Ref 2: Performance Analysis of Multiple Wave Energy Converters Placed on a Floating Platform in the Frequency Domain (https://www.mdpi.com/1996-1073/11/2/406)

Ref 3: Optimal strategies of deployment of far offshore co-located wind-wave energy farms - ScienceDirect (https://www.sciencedirect.com/science/article/pii/S0196890421010906)

Ref 4: Artist's sketch of a system of floater blanket wave energy converters (https://www.researchgate.net/figure/Artists-sketch-of-a-system-of-floater-blanket-wave-energy-converters-WECs-connected-to_fig1_346220030)

Ref 5: Wave Star

Ref6: Ma, Y.; Zhang, A.; Yang, L.; Li, H.; Zhai, Z.; Zhou, H. Motion simulation and performance analysis of two-body floating point absorber wave energy converter. *Renew. Energy* 2020, *157*, 353–367.

Ref 7: Development of a platform-based Wave Energy Converter for the open sea (https://www.sintef.no/en/projects/2022/development-of-a-platform-based-wave-energy-converter-for-the-open-sea)

1 EXECUTIVE SUMMARY

This report provides a description of the work undertaken on behalf of Wave Energy Scotland (WES) to create a high-level concept for a Wave Energy Converter (WEC) cluster. A WEC cluster is defined as a means of installing a number of WECs in a group whereby attaching several WECs to a common structure offers benefits over and above installing the same capacity as individual WECs with their own moorings and cabling.

The risks and challenges associated with installing individual WECs and arrays of WECs are well documented and understood. In recent years, the narrative surrounding co-location of WECs with Floating Offshore Wind (FOW) has been presented as one of the most credible routes to market for wave technology. However, there is some reluctance from FOW developers to include WECs directly on the floating foundations as this presents additional risk on an already relatively unproven technology.

As a result, the concept of clustering WECs in the same location as FOW, but not directly attached to the individual floating foundations has been considered and is the main scope of this project to create a viable concept for clustering. The main purpose of this study is to be able to open discussion and debate with the FOW industry stakeholders, including developers, insurance, certification, ports and harbours, and supply chain.

This project started with defining requirements and then subsequently a 2-day innovation workshop was held with Blackfish Engineering and Wave Energy Scotland. The result of this was a number of cluster concepts and families of concepts that were then assessed at a very high level to determine viability, identify showstoppers and specific technology gaps, assess operational feasibility.

The concepts were reviewed with WES and down selected to two concepts which were given further consideration, namely using rope nets or a lightweight steel hexagonal truss to create a structure upon which to mount WECS. After more consideration, it was decided to only develop the hexagonal steel truss design further.

More detailed engineering assessment was undertaken to create a viable concept model. During this phase, various activities including high level stress calculation, mass and buoyancy assessment, mooring solution assessment, electrical cable integration, assessing T&I and O&M viability, and understanding how different WEC types could be integrated. After completing this work, a rendered image of a group of WEC clusters was created, demonstrating how the cluster structure can be used with three different types of WECs, how cables can be integrated in different ways and how clusters can be electrically connected on the seabed to export power, possibly via a nearby floating offshore wind farm.

This study has identified a number of topics that would deserve further research in order to create technology that can further enable clustering in the future. These include:

- the creation of a large scale self-referencing point absorber WEC.
- a method of joining large steel structures out of port to enable larger structures, or modules, to be connected.
- developing a quick connection technology to attach the WEC to the cluster structure as well as attaching the cluster structure to the mooring system that is suited specifically to this application.
- and creating a taut mooring anchor suited to a wide range of seabed conditions.

The results of this study can be used to engage with the floating offshore wind industry and relevant stakeholders to understand better how this clustering concept can be integrated into FOW farms for the benefit of both the offshore wind and wave industries.

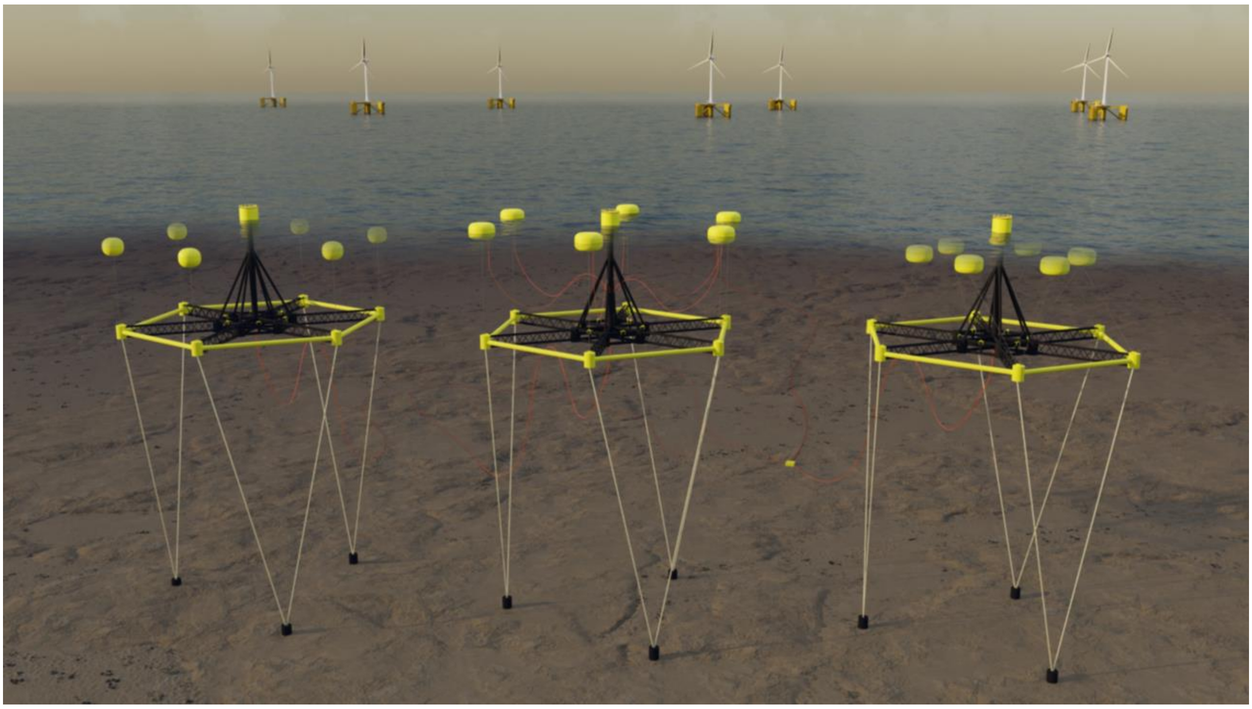


Figure 1 – Rendered image of WEC clusters co-located with Floating Offshore Wind.

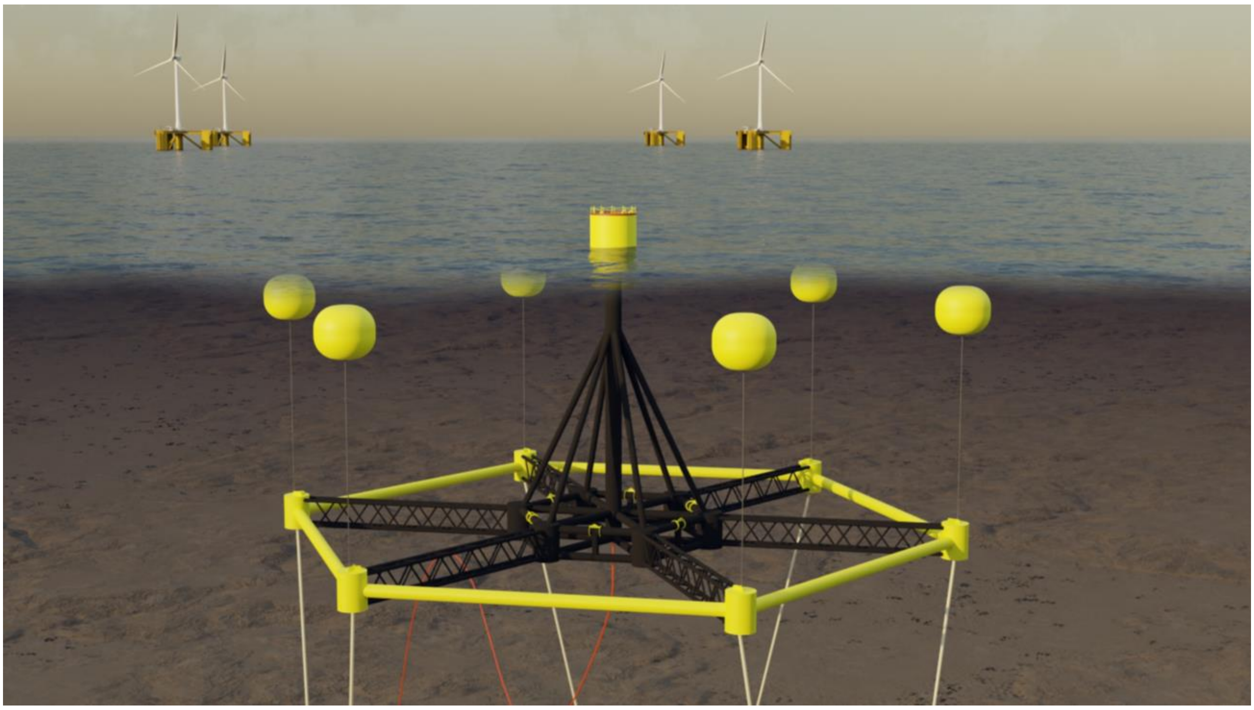


Figure 2 – An illustration of a single cluster deployed with submerged pressure differential WECs

2 BACKGROUND

The idea that WECs can co-locate and share infrastructure with FOW farms is not new and has been discussed in many forums for many years. There are well documented benefits (including Ref 1) to both the wave and FOW sectors to combine or share infrastructure, including reduced costs, increasing yield, and improving consistency of supply. There are clearly associated risks and complexities to this strategy as well.

The concept of clustering WECs again is not new. A cluster is defined as a means of installing WECs onto a common or shared structure, with the aim of benefitting from at least one of the following: reduced number of moorings and anchors, reduced cable lengths, sharing local equipment and subsystems, improved maintenance access, operating at reduced depths and being able to deploy multiple devices simultaneously. A previous landscaping report for WES (Ref 1) proposed a small number of concepts that can be described as clustering, mainly based around a linear structure with multiple WECs attached to it.

More recently, a number of studies have proposed co-location and clustering, but many of these lack the engineering credibility required to gain traction with stakeholders. Well-documented commercial challenges that the wave industry faces to achieve a competitive LCOE mean that many of the proposed WEC concepts will not be viable. Such enormous structures will likely result in high CAPEX and the use of very expensive vessels.

WES understands these opportunities and challenges and as a result, this project was created in order to assess if a viable WEC cluster concept exists to address the challenges and exploit the opportunities. The project consisted of the following phases, established to make the best use of the combined WES and Blackfish team experience:

1. Define requirements and project scope.
2. A face-to-face innovation workshop over 2 days to create and review as many concept ideas as possible. The output was a small number of WEC cluster families for further investigation.
3. Phase 1: assess each cluster family concept in more detail and down select to a single concept.
4. Phase 2: More detailed engineering on the chosen concept and creation of a rendered image of a cluster concept.

This report summarises all the work completed. There is a significant amount of detail and engineering calculations that have been completed that are not described in detail in this report for the sake of clarity.

3 Innovation Workshop

3.1 Requirements capture

An initial review was held with the team to establish the definition and requirements for a cluster and the scope of the project. It was clear from this review that a well-defined set of SMART observations, comments, and narrative. Co-location of individual or solo WECs with FOW farms without some form of infrastructure sharing is likely to be economically challenging. A means of clustering or grouping devices together is more likely to have economic benefits.

- At this stage, the design concepts are not expected to be sufficiently advanced for a quantifiable estimate of LCOE benefits, and attention will be focused qualitatively on LCOE opportunities through narrative and broad design decisions. For example, the anticipated cost increase associated with the combined structure and its deployment should be conceivably less than the estimated savings that can be realised through reduced moorings, Local Equipment Room (LER) access and sharing of vessels, cables and other infrastructure.
- This study is constrained to existing WEC technology and plausible derivatives, so does not include technologies such as Direct Generation Materials. The study will consider generic considerations for a point absorber, attenuator, oscillating surge converter etc.
- The cluster should be a viable form of generating utility scale power. This means a multi-megawatt installation (e.g. 5MW), such that it is compatible with the FOW farm export cable, OSS and other electrical infrastructure.
- It is important to consider how local or shared WEC equipment can be incorporated into the design. Aiming to share electrical power distribution and monitoring equipment between clustered WECs would seem to make sense.
- This study was not constrained by a specific site region, bathymetry or metocean data. It was considered that sea depth should be at least 50m, as this is required for FOW sites, and so a nominal sea depth of 100m was selected.
- Sharing seabed real estate with FOW is the obvious advantage, but there are many other aspects to sharing infrastructure that can be exploited, such as sharing vessels, development teams, consenting and licencing, ports and harbours, supply chain etc.
- Previous engagements have identified a reluctance on the part of the FOW developers to install WECs directly on the FOW WTG foundation. There are already sufficient challenges to overcome in the FOW industry, and adding WECs to the structures is an additional challenge for which there is currently little appetite. Although this solution has been proposed in various images previously, it is not a solution that WES feel is viable in the near future.

3.2 Innovation Workshop Process

The workshop was held in Edinburgh on 17/18 September 2024. There were eight representatives from WES and four from Blackfish. The event was organised and chaired by Blackfish. By holding the event over two days, there was sufficient time to create and consider a lot of ideas, use innovation thinking tools, group and associate ideas, and create some concepts in more detail. The phases of the workshop are outlined in the following sections.

3.2.1 General introduction and scope

A process of structured idea generation was used, with individual thoughts, concepts, ideas, and useful considerations written on individual sticky notes. Different ways of thinking or constraining the discussion were regularly used to initiate different ideas, approaching the problem from different perspectives, and stimulating different discussions. Examples included:

- minimise the problem (how would an ant solve this problem?), maximise the problem (how would a giant solve the problem?), biomimicry (how would nature solve the problem), reversal (how can the exact opposite be achieved?).
- how can specific aspects of FOW infrastructure be shared (support vessels, installation vessels, cabling, moorings and anchors, O&M resources, supply chain, ports, project resources).
- what would an ideal solution look like if only a single operational phase were required (e.g. assembly, installation, operation, O&M, decommission).

By evaluating and discussing the initial ideas and principles, these evolved and led to inspiration of further ideas. By the close of the workshop, over 210 ideas were created. Some of these described an entire concept overview, and many were ideas that were suited to a sub-system or part of a concept that could be combined with others into a complete concept.

The ideas and concepts were grouped according to the main showstoppers, key risks, or important constraints. Time was then spent assessing how or if these issues could be overcome in order to unblock groups of concept ideas. The themes of these showstoppers included:

- Combining different WEC types onto a common structure.
- How to make full use of the sea depth available (energy at the surface and in the mid water column).
- Overcoming concerns associated with inflatable, compliant or folding structures.
- Overcoming concerns associated with a web or mesh structure.
- How to tow or deploy a series of WECs in a long line on a common structure.
- How to create a long structure that can react loads from a series of WECs.
- How to achieve a level of redundancy associated with having lots of small WECs attached to a structure such that the failure of one or a few does not significantly impact the overall yield.
- How a Local Equipment Room (LER) could be incorporated into a structure and what it would need to include.
- How to ensure vessel access is feasible to individual WECs for O&M or swap out purposes.
- Are there opportunities to re-purpose the WEC cluster at end of life (e.g. seaweed farm), or how to work with FOW developers to create other revenue.
- How to overcome the issues associated with large rigid structures at sea that would be required to space WECs apart but are small enough to deploy or assemble.

One of the main outcomes of this assessment was the realisation that a self-reacting (SR) WEC would open up possibilities for the cluster structure. Some prototypes using this design have been tested in previous years (e.g. Marmok, OPT Powerbuoy), but there are no large (>100kW) devices that are entering mainstream pre-commercial development of this type that could be clustered to create a multi-megawatt cluster. As such it is difficult to create concepts using a hypothetical self-referencing WEC, particularly a self-reacting point absorber WEC, without a baseline design.

Once all the ideas had been reviewed and the common issues discussed, the next phase was to develop some of the concepts that appeared to have more potential or were favoured by the team. Some concepts had been mentioned multiple times across different ideas or in different discussions, and so justified a more detailed review. Four families of concepts were considered in detail for 1-2 hours each. These concepts were:

1. Rope mesh structures, connected at a number of nodes. These could be smaller meshes to connect 5-10 devices, or more extendable meshes that could connect >10 devices. The mesh would be anchored to the seabed using a number of moorings that is fewer than the number of WECs. A LER could also be attached to the mesh. This solution assumes Externally Reacting (ER) WECs and that the mesh structure reacts the WEC loads and provides position mooring.
2. Large mesh structure with self-referencing WECs. Based on an assumption that enormous mesh structures exist (large fishing and aquaculture nets), this structure would be based on attaching SR WEC devices (either attenuator or Point Absorber (PA)) as the load bearing capacity and stiffness of the mesh would not be able to support high forces and as such the mesh would act as a station keeping device. This concept could be further developed to create a “carpet” with hundreds of smaller devices (<10kW) attached, with the benefits of providing elevated levels of redundancy.
3. Low mass steel structures, such as truss or space frame structures, or tensegrity structures. Various shapes of space frame could be used to provide station keeping, react loads and act as deployment and recovery tooling. Spaceframe designs could articulate to enable deployment or in-port assembly, using the tensegrity principle if applicable. The structure would be rigid once deployed, using a number of moorings to react loads to the seabed.
4. Linear structures, along which are installed several WECs. These concepts utilise a horizontal, linear, neutrally buoyant structure. The linear structures provide station keeping, and potentially can react loads but are probably more suited to SR WECs. The layout of the linear structures would be connected to an LER, either in a set of parallel lines or in a radial spoked shape for example. Other layouts would be possible.

It is also possible to combine many elements of all of these concepts, as will be explained throughout this report.

3.2.2 WEC Type

The discussion above makes it clear that the WEC type has an enormous influence over the cluster structure concept. However, within the scope of this project it is important not to constrain a particular cluster concept to a specific WEC developer. As a result, a number of developers were identified that have created viable, pre-commercial, large scale devices that could be considered to have scalable solutions for a multi-megawatt cluster structure. In reality, this means a clear plan to a 300kW-500kW device, or larger. As a result, it was agreed that cluster concepts should aim to be viable for at least one of the Mocean, Carnegie, Corpower, AWS, or IDOM approaches. For the purposes of this project, individual cluster concepts should be compatible with at least one these device approaches. As further developers will continue to enter the market in the future, other devices under development, such as Crestwing and Wavepiston, may also be considered, so as to understand the wider applicability of proposed cluster concepts.

3.2.3 Discontinued ideas

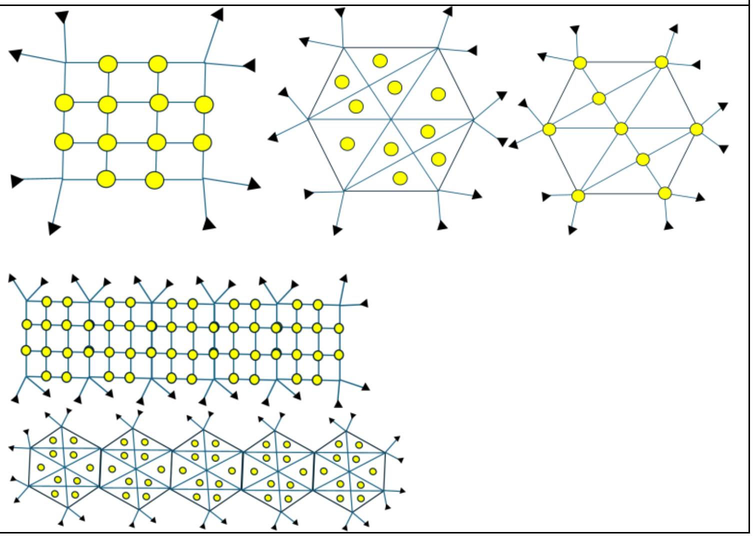
Several concepts or ideas were considered not to be viable by the end of the workshop. These include:

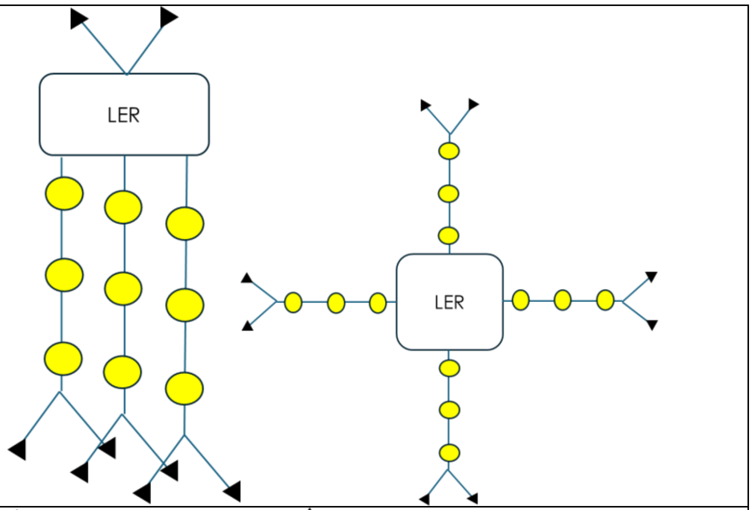
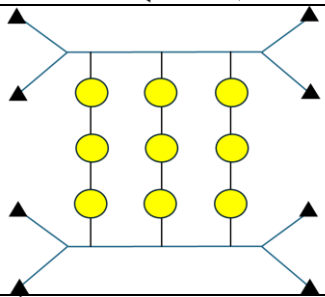
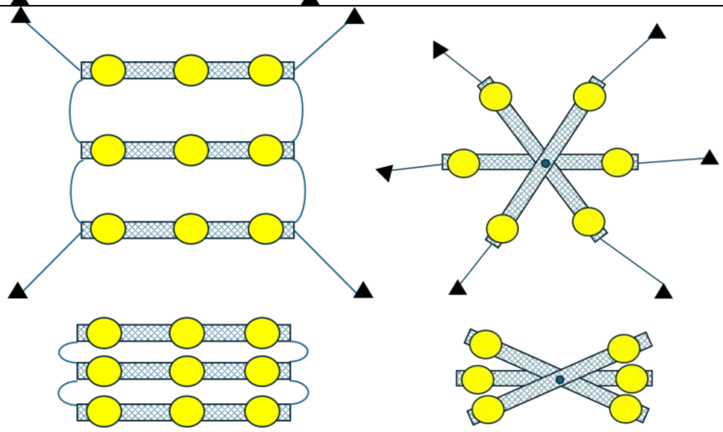
- Inflatable structures or components to aid deployment, allowing a small structure in port to be expanded when deployed and contracted when recovered. As well as concerns about the ruggedness and reliability of inflatable materials, the impact of failure can be catastrophic and very difficult to mitigate.
- Using a FOW platform with or without an integrated WTG – this solution lacks the structural efficiency and optimisation to the needs of wave energy.

- Using a cluster to affect wave behaviour – creating constructive or destructive interference to reduce oncoming waves to FOW platforms, or increasing wave height for adjacent clusters. This is considered extremely difficult based on the very wide spectrum of wave period that would need to be accounted for. This would need significant amounts of research.
- Packing a number of WEC devices into a smaller storage unit, and then deploying at sea and allowing the devices to separate by themselves. This was considered unviable due to the close nature of the WECs, likely impact with each other and the large size of the storage unit.
- Changing the structure or WEC spacing depending upon the wave climate in order to maximise performance. In a similar way to affecting wave behaviour, changing the position of the WEC according to the wave climate is very challenging.

3.2.4 Conclusion of the workshop

The most promising ideas were collated and discussed in more detail. The ideas and families are shown at a very conceptual level in Table 1. At this stage, no engineering calculations had been performed on these concepts, and any reasonably qualified engineer would be able to quickly challenge their viability. To address this, following the workshop they were assessed in more detail by completing some Order of Magnitude calculations and identifying showstoppers, solutions that are reliant on technology that does not exist, and areas of considerable risk.

Family / concept name	Description	Sketch
Rope meshes	Could be square or hexagonal. Mesh modules could be connected to make a longer, patterned structure with shared moorings. Diverse ways to arrange WECs that are attached to nodes or in between nodes.	

Linear structures	LER structure used as an anchoring structure for linear arrangements of WECs around it. Arrangements could be parallel or radial around the LER.	
Linear structures type 2 – clusters attached to a pre-installed mooring system	Pre-installed horizontal moorings, connected by parallel linear arrangements of WECs.	
Lightweight steel structures	There are various layouts possible including: Collapsable linear parallel, Collapsable hexagon, Circular "pen" structure, and a Square grid.	

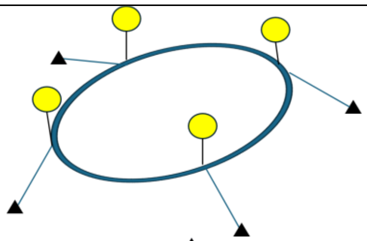
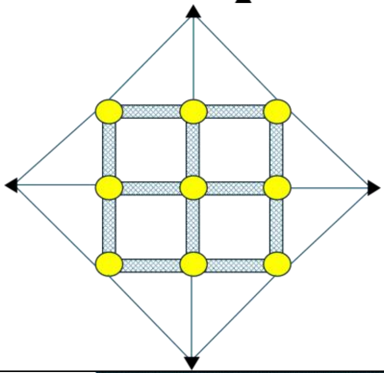
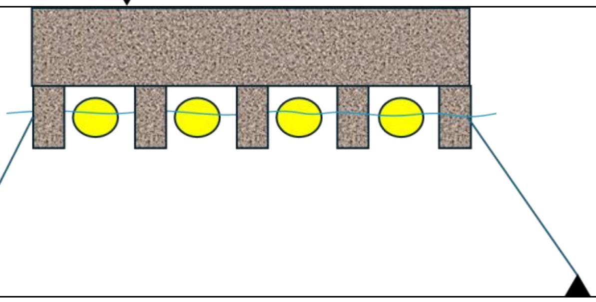
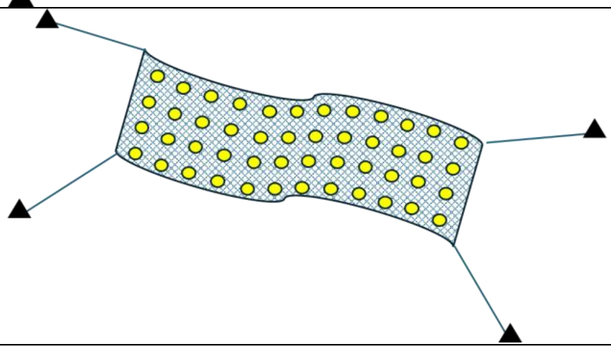
		 
Large concrete structures	Buoyant structures with integrated WECs	
Large mesh	Multiple tiny SR WEC devices integrated onto a large, flexible structure	

Table 1 – Summary of workshop output

It was agreed that each of these concepts should be considered in more detail during the next phase of the project.

3.3 Previous work done

As context to this study, it is worth noting some other concepts and previous work that has been done in this field.

WES commissioned a report (Ref 1) looking at Very Large-Scale Wave Energy Generation. One of the outputs from this report was the concept of clustering smaller devices together. This report did not go into the detailed arrangement of the cluster structure or the actual layout, but did propose a high level concept of a cluster on a linear truss structure, as shown in Figure 3.

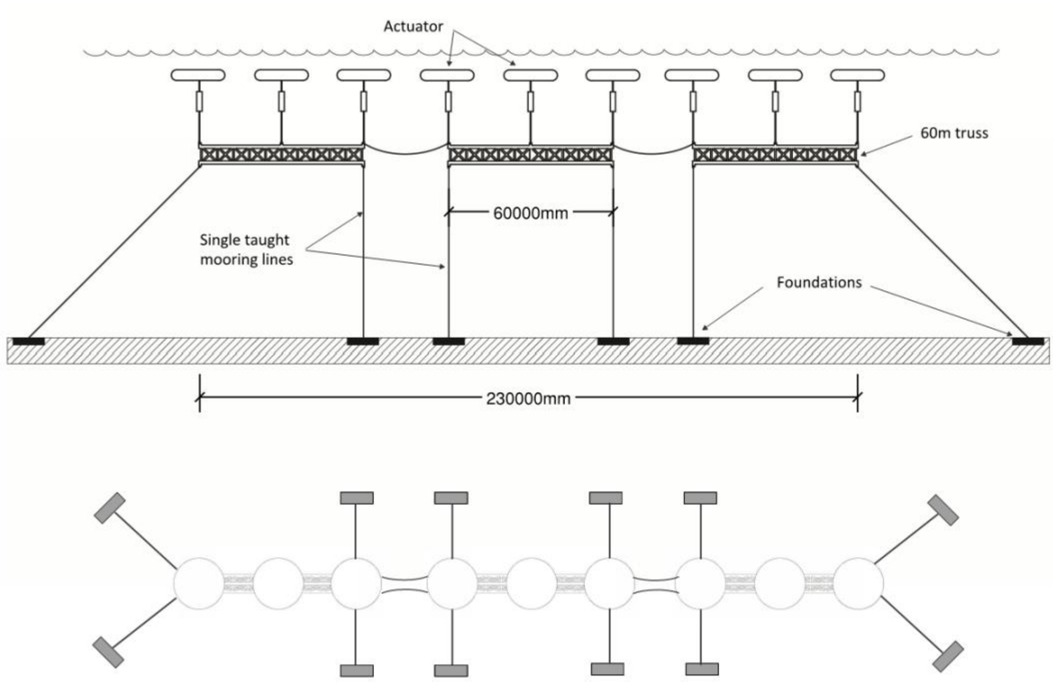


Figure 3 – Representation of WEC cluster as illustrated in Ref 1.

Some other studies have been undertaken and have published images of clustering or offshore structures, some of which are included in Figure 4. Whilst each of these offers a vision of a future cluster of WECs on a shared structure, many of them are artists impressions with little consideration of the detail, practicalities or real issues that would be faced with such a structure.

As a result, whilst acknowledging that these concepts exist, this project has been focussed on deriving a cluster concept that is considered to be physically viable, with critical engineering aspects considered in some detail.

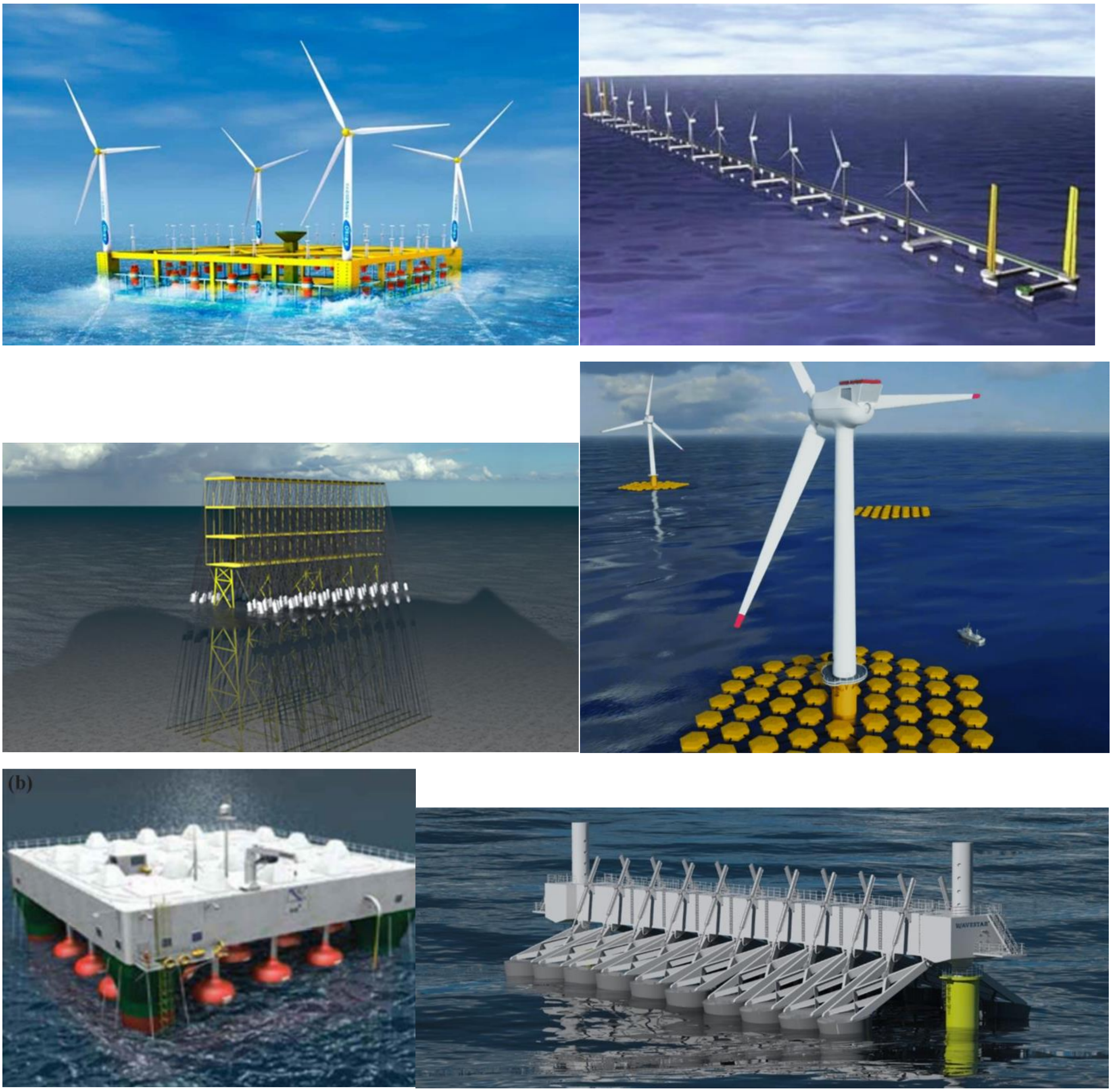


Figure 4 – A variety of other WEC cluster and array concepts,

Clockwise from top Ref 1, Ref 2, Ref 3, Ref 4, Ref 5, Ref 6:

4 PHASE 1 ASSESSMENT

4.1 General approach

For the families of WEC clusters chosen, each concept was considered in more detail as described below. Basic hand calculations were completed, and each concept was considered against a number of topics to identify the main technological or operational risks. The topics and questions considered were:

- WEC Spacing – Assuming a PA of 10m in diameter and 30m centre to centre spacing, how feasible it is to create a structure to hold a number of WECs at this spacing?
- Loads – Based on preliminary and anonymised load data available to the team, a PA vertical load for a 300kW device was assumed to be 1MN. How feasible is it to react a load of this order of magnitude into the cluster structure?
- LER – It was generally considered that the LER would be a key part of the cluster architecture. Can an LER be integrated or does it need to be a separate structure?
- Port and harbour operations – No specific ports, harbours, or geographical sites were considered, but how practical is it to assemble and deploy the structure in a reasonably sized port, using typically available infrastructure? Is it necessary to assemble the structure at sea?
- WEC type – The cluster concept should ideally be suited to multiple WEC types. In this context, common WEC types were considered, along with the types of WEC that currently have well-developed concepts for 300-500kW device size.
- WEC replacement – Is it possible to replace a WEC on the cluster, and what would be a feasible method of doing so? Will the method rely on divers and ROV operations in large seastates?
- Mooring configuration – What is a likely mooring configuration that is feasible? Can the number of moorings be reduced so that there are benefits over installing individual WECs?
- Identify obvious technology gaps – Are there obvious technological gaps that are not solvable currently? Is it conceivable that some development work could overcome these issues or are they fundamentally too difficult to solve in a realistic time frame?

As a result, the study of each family created a matrix that summarised the teams' considerations in each of these areas. For some of the categories, it was considered that these could be scored (red / amber / green) in order to easily identify the critical issues and difficulties. Some of the categories are difficult to score meaningfully and so have a narrative to describe the issues and the teams' analysis and opinions.

4.2 Rope Net Structures

The rope net structures concepts offer some advantages that are appealing. These include:

- Lightweight and neutrally buoyant ropes that could provide deployment savings.
- Scalable and adaptable to distinct types of WEC according to the structure of the mesh (e.g. square vs hexagonal).
- Provide inherent flexibility to mitigate peak loads.

Some of the main points considered are described in more detail below.

A mesh will inevitably be domed in shape, as it is extremely difficult to achieve a flat mesh structure without a lot of moorings. As an inherently 3D shape, there will be elements of the mesh that are flatter than others, as shown in Figure 5.

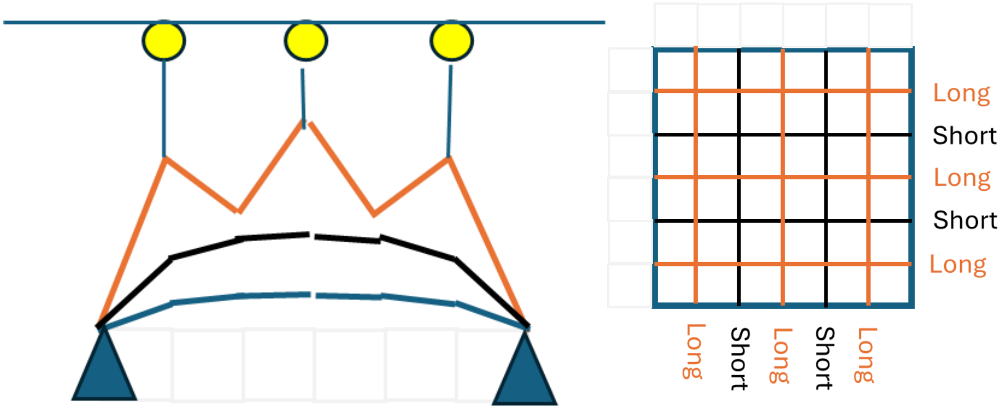
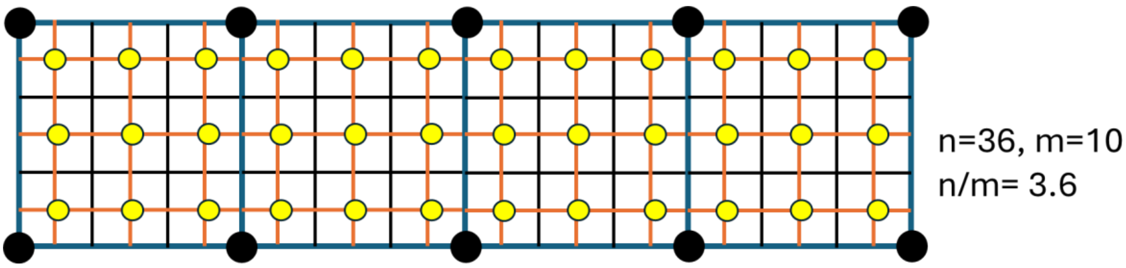


Figure 5 – Layout of rope net concepts

A mesh structure on its own will have a certain number of WECs (n) per mooring (m). By joining mesh modules in a pattern with shared moorings, it is possible to improve this ratio, but this comes at the expense of sharing moorings between modules and the risks of deployment of two clusters in close proximity. Figure 6 indicates how the n/m ratio can be improved by patterning the mesh. There is an obvious caveat to this patterning in that it is assumed that this cannot be done in two dimensions due to increased WEC interactions. Increasing the width in the downwave direction of the incoming waves will mean a greater number of WECs positioned in the wave shadow of others in the cluster, with the assumption that this will result in a loss of performance. As a result, the 1-D pattern, with a maximum of three WECs in the wave direction is considered to be the baseline limit, despite the n/m benefit of larger patterns.



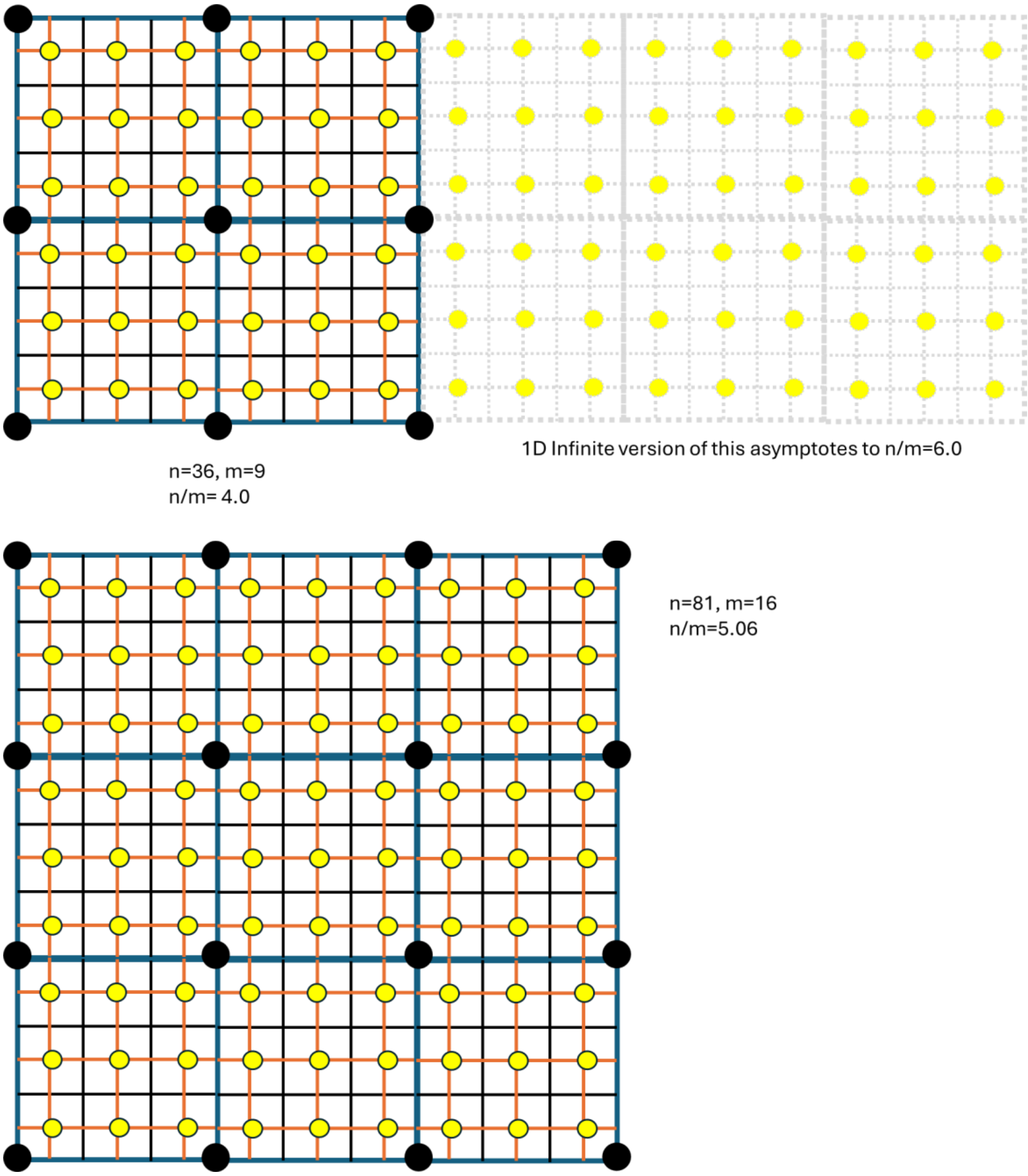


Figure 6 – Rope net pattern concepts

Once some analysis of the loads in the individual ropes is undertaken, it quickly becomes apparent that using a horizontal mesh structure to react vertical loads associated with PA WECs is difficult. It is assumed that each of the WECs is providing a vertical load of 1MN, and with a WEC spacing of 30m, a 6x3 WEC mesh is 180m x 90m. Figure 7 (right) indicates a scenario where the net is attached to moorings from the seabed so that the mesh can be installed at the correct height for the sea-depth, although in reality for a single mesh these mooring lines would be angled. This illustration raised the question of how to calculate the exact shape of the mesh and where the highest midpoint would be situated in the water column compared to the corner points.

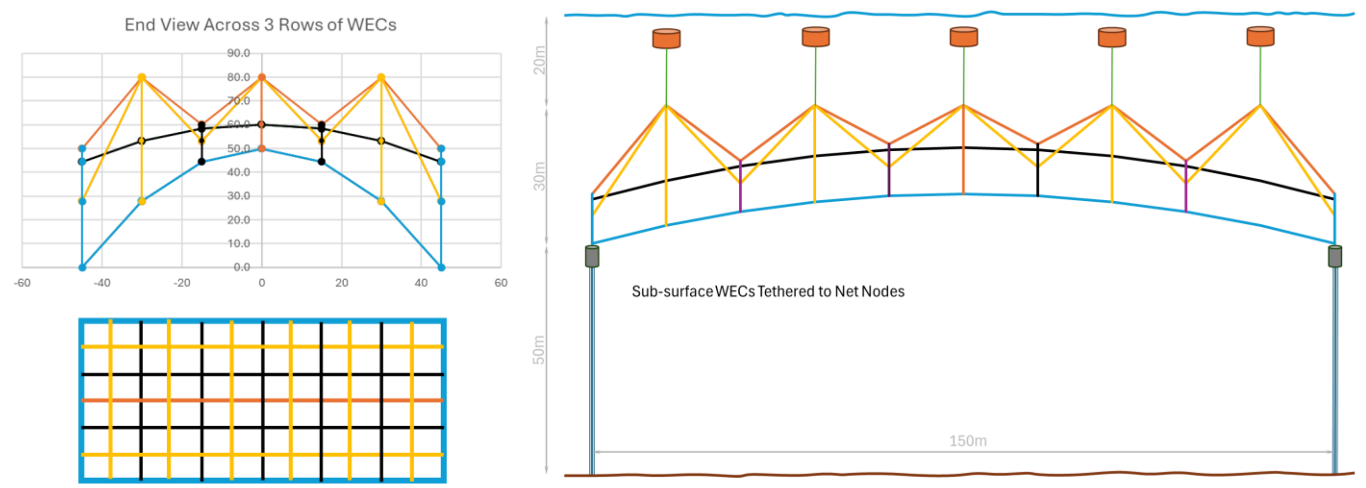


Figure 7 – Different elements of rope net structures and depth constraint

It is not trivial to calculate the mesh shape but it is possible to iteratively solve using the assumption that the midpoint of the mesh will be the highest point, and that the angle of the mesh must increase towards the seabed at each node. Figure 8 (left) shows the iterative pathway from the centre node of the mesh towards the corner used to solve the shape of the mesh. From Figure 8, it can be seen that the height of the mesh (not including the moorings from the seabed) is at least 25m for a 6x3 mesh. This does not include the height of the WEC attached to the mesh at the midpoint, which could easily be on a 10m mooring tether. As a result, the total depth required for a submerged WEC attached to a 6x3 mesh could be up to 45m. This is compatible with installing in 100m sea depth sites once vertical moorings are considered.

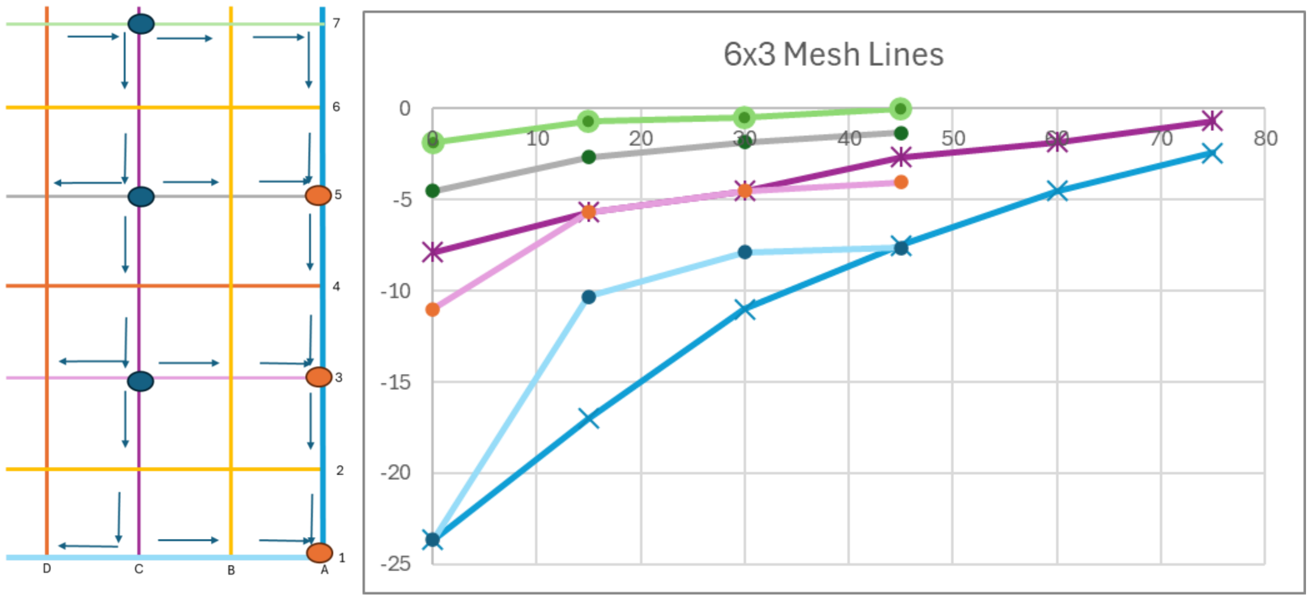


Figure 8 – Analysis of a 6x3 rope net mesh to calculate depth

The following calculations were completed based on the assumption that a suitable rope exists for this application.

Ropes with very high minimum breaking load are available (generally approaching 2000te MBL for 150mm UHMWPE ropes), but this is not to say that these types of rope are suited for this application.

The choice of rope material would require a much more in-depth study, but likely choices include:

- Polyester (PE): Cost effective and good if dynamic loads are low, high strength, high abrasion resistance, but stiffer than other choices so less suited to dynamic and shock loads.
- Nylon: More elastic than PE so better for dynamic loads, high strength and abrasion, marine growth, and UV resistance, but can absorb water and lose strength when wet.
- Polypropylene (PP): Is a cost-effective material, but has lower strength compared to nylon and PE.
- Ultra-high Molecular weight Polyethylene (UHMWPE): Very high strength, low stretch and high stiffness, so may not handle dynamic loads as well. Also, the most expensive material.

The use of braiding, double braiding and protective jackets would need to be considered for abrasion, UV, and marine growth resistance.

It is well documented that moorings fail from time to time, and as a result redundancy is a necessary consideration. The O&M implications of a submerged, load bearing rope net structure are not to be underestimated. Replacing individual rope lengths, inspection, deployment, and connection whilst preventing entanglement are all significant issues that are not trivial to overcome, although not impossible.

4.2.1 Assessment summary and scoring

Category	Traffic lights	Narrative
Loads / rope sizes and feasibility	(amber)	High MBL ropes are available, but the fundamental principle of reacting vertical loads onto a horizontal structure moored in the corners is a difficult engineering issue to overcome. For a 500kW ER WEC, loads might be as high as 15MN on a single tether to the WEC. This is not possible to react into a single node on a mesh.
Technology gaps / showstoppers	(red)	Rope capacity for ER PA WEC. Connecting large ropes / large numbers of strands at 4-way junctions and maintaining load-sharing. Multiple ropes per line would likely be possible to ensure equal load sharing, but this increases cost and complexity. Annual net inspections: Would need an efficient way to inspect all these lines. This is not trivial and might require development of autonomous crawling inspection and rope repair technology.
Specific risks	(amber)	Tight spacing increases risk of marine operations (and damage to assets). DP vessel likely necessary. Performance detriment to WEC due to the reaction point stiffness. Risk that cost benefit is even worse than expected. Cost of ropes not assessed in detail.
Cost / Benefit	(red)	Cost savings on mooring installation partially offset by cost of the net. Cost savings further offset by increased inspection time and expected performance decrease.

		Rope net approach might start to look worthwhile for very much deeper sites >200m, though these locations may have longer export cables and transit times. Concept might suit niche, deep ocean island locations sites around the world.

Category	Narrative
WEC type - ER or SR?	This analysis looked at ER type. The basis was a C4 CorPower device with a single vertical reaction mooring. The spacing assumed in this analysis was agreed at the start of the project (30m). This is significantly closer spacing than CorPower suggests (125m). See notes on spacing.
Mooring – most suitable type rope or chain?	The net is likely to be subject to constant motion and so UHMWPE (e.g. dyneema) ropes would be more durable than chain. Chain links would likely wear due to constant motion.
Replacement Strategy	Net remains installed for life of farm. WEC intervention is individual. A quick connector is an essential part of the solution.
Spacing	30m spacing is very tight for marine ops. Vessel could either use DP or pick up farm mooring points. Wider spacing would require greater depth or even stronger lines. Rope feasibility already challenged.
LER	Scheme does not lend itself advantageously to an LER solution. LER would be moored adjacent to the grids and collect power from a suitable number of WECs assigned to each LER. No obvious advantages for WEC electrical connections which would still require a high degree of flexibility.
Deployment operations	Install corner moorings. Manufacture net on shore. Install net on moorings. Install WECs individually to the reaction points on the net.

4.3 Lightweight steel structures

Within this family of cluster designs, three separate structures were identified as concepts.

1. Submerged ring structure.
2. Collapsible, articulating structures.
3. Fixed spaceframe structures.

These will now be discussed individually in more detail.

4.4 Submerged ring structure

The basis of this is to use a ring structure to provide spacing between WECs but use the moorings under each WEC to take the loads. In this way, the number of moorings per WEC is not necessarily reduced, but the effective seabed is raised and levelled, which offers some simplification of the marine operations, and provides a location to connect the LER with shared infrastructure. A few images of the concept development are shown in Figure 9 and Figure 10.

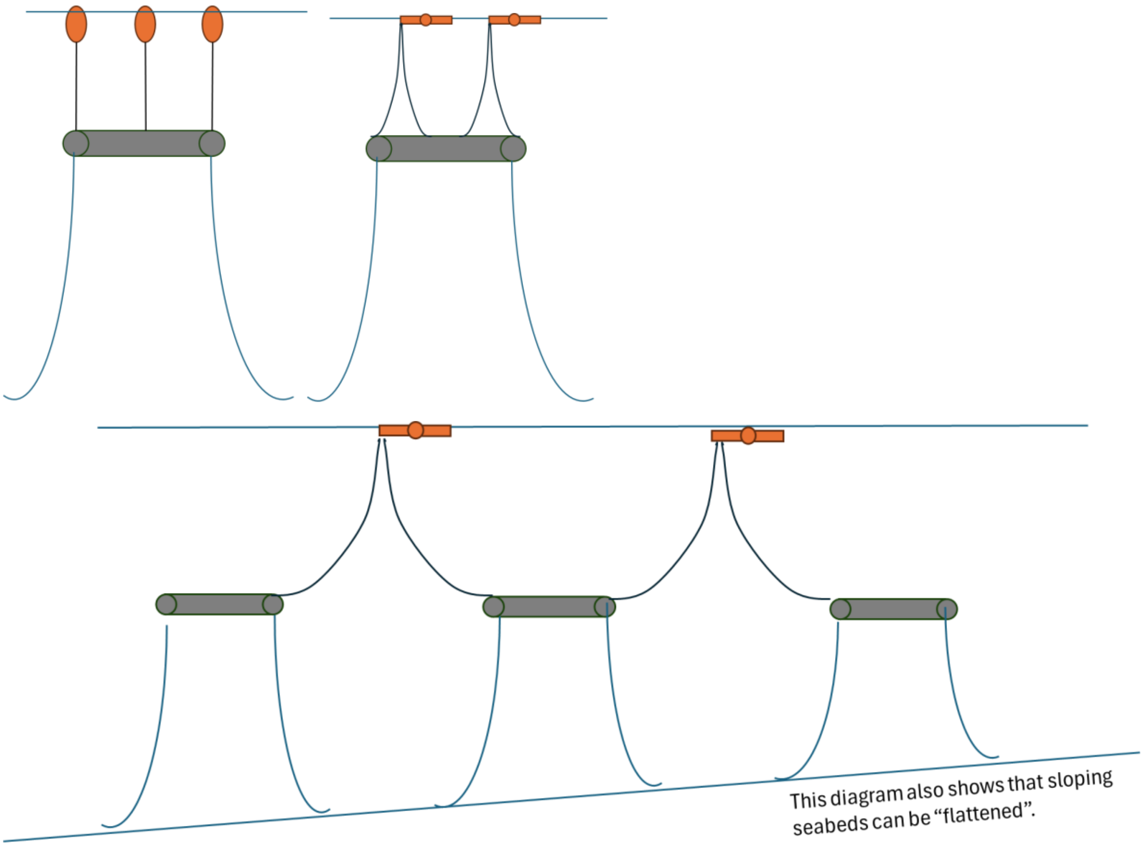


Figure 9 – Overview of ring concept

Ring structures can be compatible with more than one WEC type, and can also be linked together.

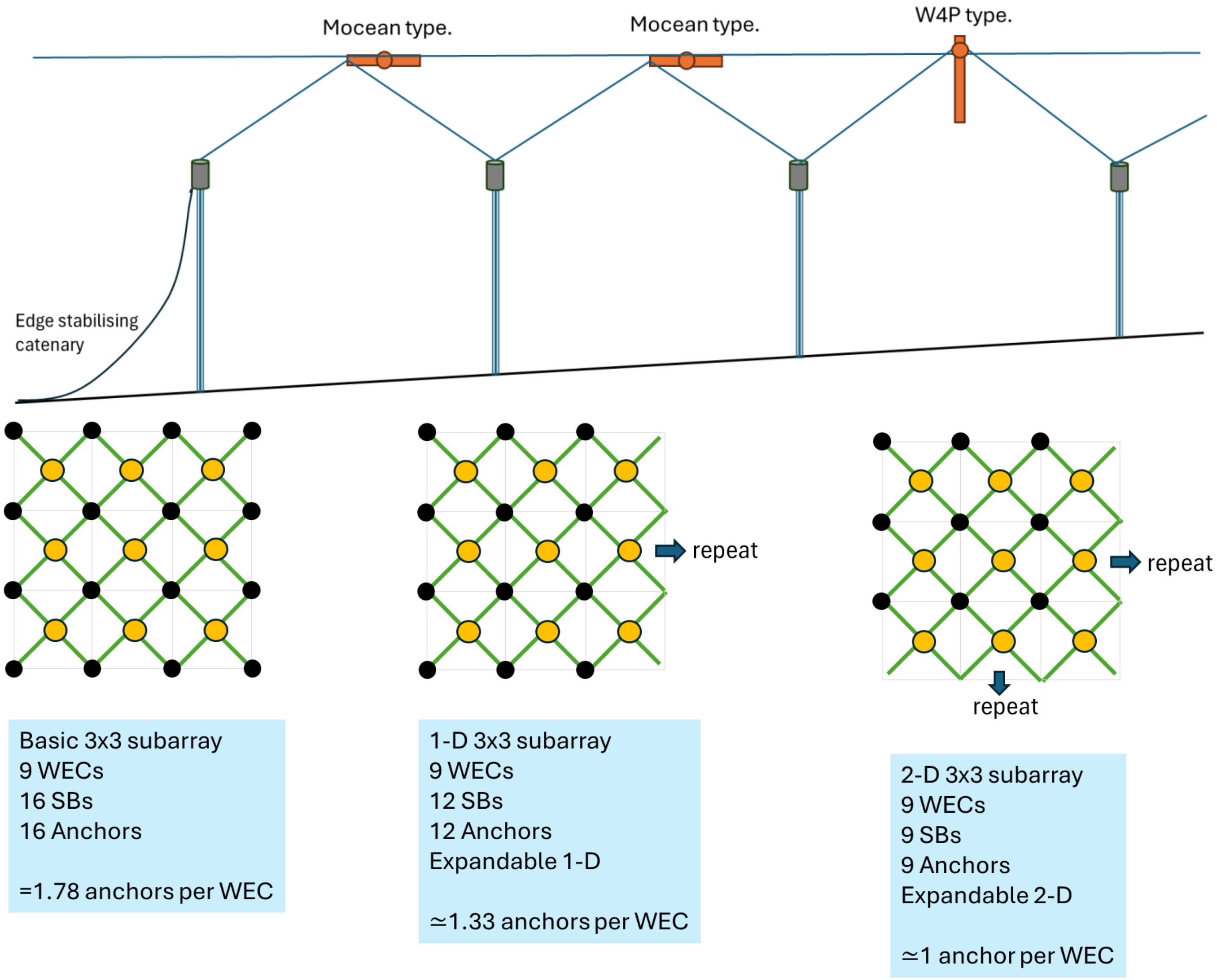


Figure 10 – Development of ring into submerged buoy cluster

If linked together as shown in Figure 10, the immediate challenge is to explain clearly what the ring structure really offers and why a simple submerged buoyancy (SB) structure is not proposed instead. At best, the solution results in one WEC per anchor, so it is marginal if the benefit of this system would outweigh the additional cost of intermediate submerged buoyancy given that the LER is difficult to integrate.

If a ring is used, this needs to be structurally sound, even if it is only acting as spacing for the WECs and it is not required to react mooring loads or significant bending moment. In order to be manufacturable, it might be easier to build in straight sections. This begins to look very similar to a hexagonal fixed structure, which is discussed separately in section 4.6.

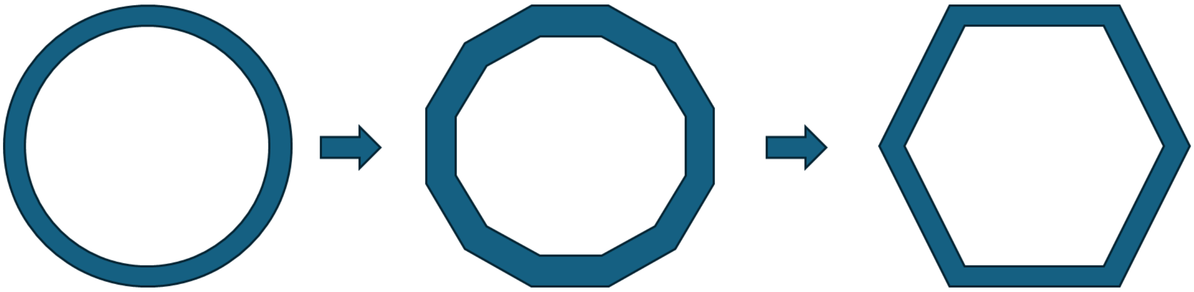


Figure 11 – Development of ring into hexagon concept

4.4.1 Assessment summary and scoring

Category	Traffic lights	Narrative
Loads / member sizes and feasibility		Loads likely to be feasible and within the normal bounds for mooring lines. Based on the single buoy study for the Waves4Power device, the submerged buoys look to be of a feasible size. One aspect that will start to erode this margin is understanding the dynamics of such a multi-body system, but the starting point is good.
Technology gaps / showstoppers		Durable connection system required to connect WEC mechanically and electrically to the structure. The size of this connection system not explored yet. Daisy chaining the connections might bring benefits. Connections needed back to the LER. Single connection to each appears simplest but requires a quick connection technology.
Specific risks		Tight spacing and multiple taut lines increases risk in marine ops (of damage to assets). DP vessel capability likely needed. Scaling up looks to be possible.
Cost / Benefit		Cost savings on mooring installation due to reduced number per MW installed. However, no clear benefit from installing as a cluster. This approach may start to look worthwhile for very much deeper sites at >200m. There is a benefit by being able to install on non-horizontal seabed, but likely to only be feasible in gently sloping bathymetry. An effective connection design would provide opportunity for swapping WECs and enhance availability. Might suit niche sites around the world, such as deeper ocean islands, etc.

Category	Narrative
WEC type - ER or SR?	This analysis concluded this scheme would only suit SR WECs. Examples considered were a Mocean type device and a Waves4Power device with four taut moorings in a pyramid arrangement. The spacing assumed in this analysis is not consistent with other schemes (100m vs 30m). This addresses access issues but makes farm density incomparable. See notes on spacing.
Mooring – most suitable type rope or chain?	The submerged buoys would be moored by vertical taut lines to a suitable anchor (pile, rock anchor or mass). The WEC moorings to the submerged buoys are envisaged to be taut (stretchy) synthetic lines. No specific sizing calculations have been done on mooring sizes but because these are station keeping moorings and not generator reaction moorings it is expected they will be within norms.
Replacement Strategy	Submerged buoys, taut moorings and quick connection remain installed for life of farm. WEC intervention is individual.
Spacing	Order of 100m spacing based on Waves4Power mooring scheme. The concept looks to be scalable to larger spacing and might be scalable down to reduce spacing. The scheme would benefit from having a buoyant quick connection that connects to the moorings and is left behind when a WEC is swapped.
LER	Scheme does not lend itself advantageously to an LER solution. An LER would be moored adjacent to the grids and collect power from a suitable number of WECs per LER. No obvious advantages for WEC electrical connections as they are so dynamic.
Deployment operations	Likely that each SB would be individually deployed to its anchor, perhaps with WEC mooring lines pre-connected. WECs would then be connected up last.

4.5 Collapsible, articulating structure

A WEC cluster structure will inevitably be large when deployed, so the concept that allows it to be much smaller when in port and larger when deployed is attractive from an assembly and marine operations point of view. A few concepts were considered, but for each of the ideas there was always a single technical aspect that was considered very difficult to overcome, namely the creation of an articulating joint when the following requirements are assumed:

1. It can articulate during deployment.
2. It can be locked once deployed without using bolted joints, divers, ROVs, or complex mechanisms to provide a secure lock, whilst reacting shear or bending loads during operation.
3. It can still articulate a number of years later for recovery without having been used in the meantime, without requiring divers, ROVs, or the use of complex mechanisms liable to failure.

As a result, this concept was not considered a viable option and was discounted.

4.6 Fixed spaceframe structures

Building upon the conclusions from the rope nets and submerged ring concepts, the fixed spaceframe concept developed quickly into a fixed hexagonal structure with a number of WECs attached to it. Loads of 1MN were assumed to be acting either on the edge nodes, or in the case of a CETO device, spread across a number of nodes.

Some basic hand calculations resulted in initially selecting a large diameter tube for the structure, Ø1850mm x 30mm wall thickness diameter. This results in bending stresses around 175MPa, which is plausible, but does result in a very high internal buoyancy. To reduce this, a natural development is to look at truss structures, utilising the space from the neutral axis to provide additional bending stiffness, as shown in Figure 12.

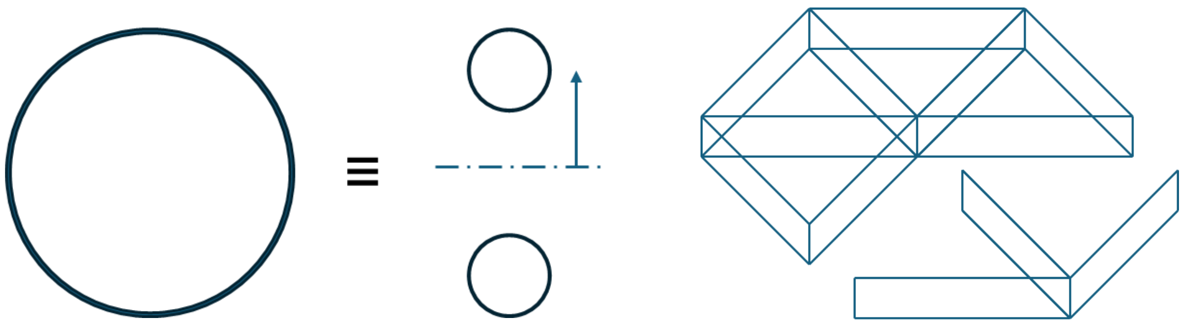


Figure 12 – Illustration to improve stiffness and reduce mass and buoyancy.

A review of the different arrangements created a range of different scenarios to clustering WECs onto the same structure, including a single triangular module that could be replicated into a much larger repeated pattern.

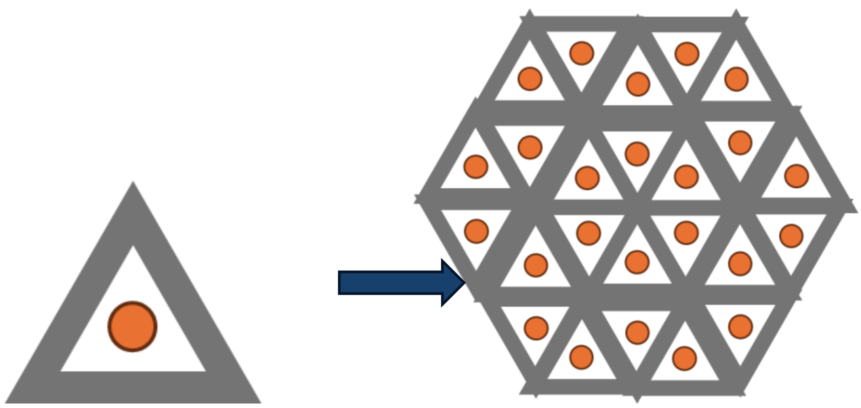


Figure 13 – A modular approach to lightweight steel structures

This appears to have a high steel usage, so by reducing some of the interlinking members, a structure like those shown in Figure 14 could be created.

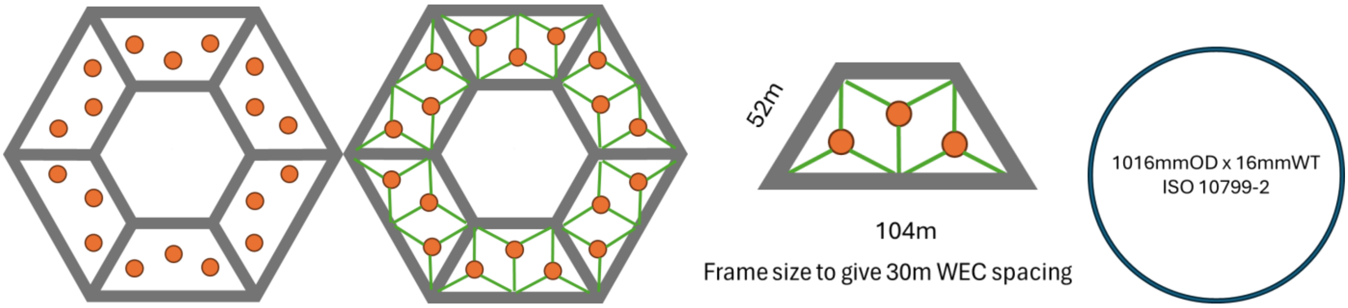


Figure 14 – A large-scale (5MW) cluster concept

Although conceptually possible, the amount of steel to react the loads associated with this number of WECs is large. Also of significance is that the entire structure would be approximately 300m wide. This could be mitigated by joining the modules together away from port, but the same issues as discussed with collapsible space frames exists, namely the ability to create a joint that can be assembled and disassembled at sea without using divers or ROVs, and that does not rely on complex mechanisms. As a result, it was considered that this structure was too large to be practical.

The further development of this concept is to reduce the size to something that is plausible. The layout in Figure 15 shows how 6 WECs could be attached to a single structure, either standard ER PA WECs or something more like the CETO device with multiple moorings. A basic beam structural analysis shows that the external members are not highly loaded and that the central part would need more structural rigidity, but this was considered relatively straightforward to implement. Further assessment showed that using a pair of beams of Ø500mm x 10mm results in a structural mass of 275te with a net buoyancy of 100te. This is important as it is assumed that the structure must not be reliant on the WECs to provide a stable and buoyant platform.

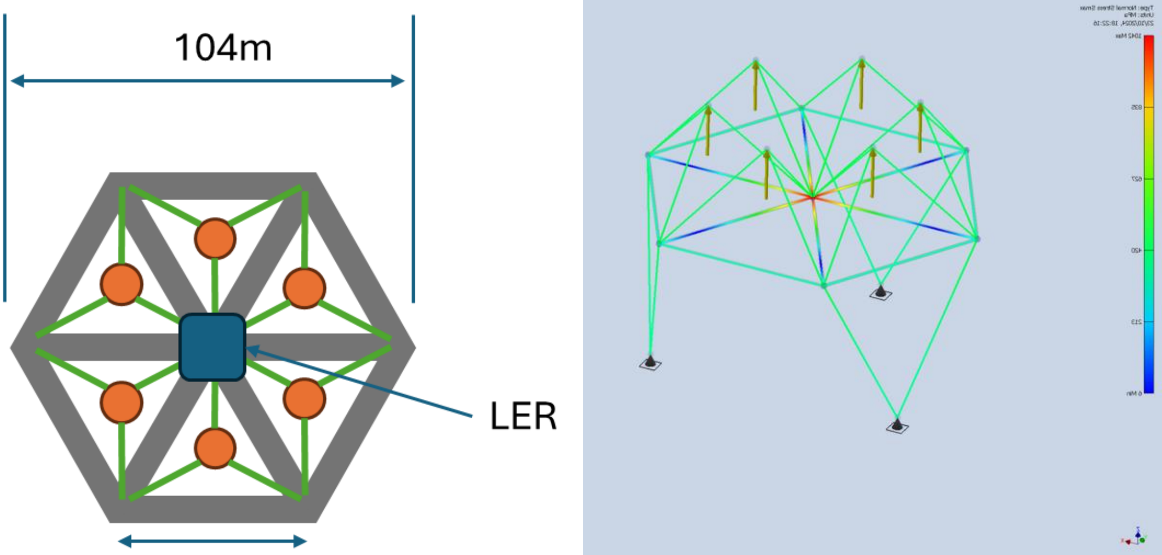


Figure 15 -A reduced and more practical hexagonal structure concept

4.6.1 Assessment summary and scoring

Category	Traffic lights	Narrative

Loads / member sizes and feasibility		Loads appear to be feasible and within the normal bounds for mooring lines and readily available pipe sections. One aspect that will start to erode this margin is understanding the dynamics of such a multi-body system, but the starting point is good.
Technology gaps / showstoppers		Large structures need to be assembled and deployed, which will require large port access and large vessels, but these are in line with FOW port requirements. Quick connection technology required, but these are available in various forms or can be developed.
Specific risks		Tight spacing makes marine ops higher risk (of damage to assets). LER is surrounded by WECs – vessel size for access or crew transfer is limited. DP capability likely needed. Spacing might need to increase to allow use of wind industry standard crew transfer vessels. Although size is feasible for industrial nations, port facility size requirements might be limited elsewhere (though not relevant for scope of this study). Joints made while afloat might address this, but will add cost and risk.
Cost / Benefit		Cost savings on mooring installation looks likely to be partially offset by the cost of the hex ring structure. This will change with seabed type and depth. The attractiveness of this scheme improves as sites get deeper and more difficult to operate in, but it is considered more viable in ~100m sites than other schemes reviewed so far.

Category	Narrative
WEC type - ER or SR?	This scheme would suit a ER-WEC type with multiple connections back to the structure to spread the load. The basis was a CETO type device with three taut moorings in a tetrahedral arrangement. The scheme might also suit a taut moored SR-WEC but the spacing might be too close especially for weather-vaning WECs. The spacing assumed in this analysis was kept consistent with other schemes (30m). This might be too close in reality (see notes on spacing).

Mooring – most suitable type rope or chain?	The hex ring would be moored by any conventional means suitable (taut) for the local conditions and bathymetry. The WEC moorings to the hex ring are envisaged to be taut (stretchy) synthetic lines. No specific sizing calculations have been done on mooring sizes, but because these are station keeping moorings and not generator reaction moorings it is expected they will be within norms.
Replacement Strategy	The hex-ring remains installed for life of farm. WEC intervention is individual. Disconnection of WEC will be technology specific and depends on whether the tethers are a consumable / replaceable item. Optimum would be for surface operations only for WEC swapping.
Spacing	30m spacing is very tight for marine ops. The scheme looks to be scalable to a limited degree to larger spacing. Spacing increase would require a tubular space frame design.
LER	Scheme has obvious benefits for LER platform, as it could be located centrally within the system. Access might be limited for large vessels, but crew transfers to LER would be possible. Having each WEC connected directly to LER would seem to have advantages over daisy chained schemes.
Deployment operations	Anchors and hex structure pre-connected with WEC tethers depending on the technology. LER and hex ring could be pre-assembled and installed in one operation.

4.7 Horizontal strings of WECs

The concept of connecting WECs together on a horizontal structure was suggested in many forms throughout the workshop. Concept arrangements included linear parallel, radial, and circular, either as a pre-deployed structure or as a deployable system with pre-attached WECs.

The concept of radial or circular structures was discounted early on, as it is difficult to arrange WECs to meet the oncoming waves in all conditions as well as maintaining optimum WEC performance and providing a more space efficient solution. Therefore, only the concept of linear horizontal strings was developed further.

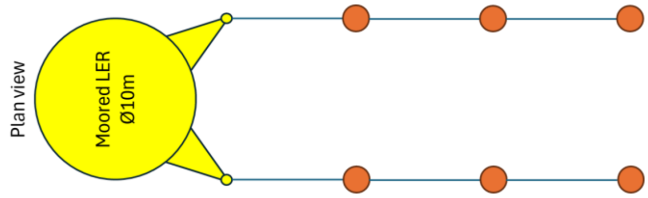


Figure 16 – High level concept of horizontal string concept with an LER

The concept is characterised by having surface or near-surface horizontal lines radiating from a moored LER. There are multiple WECs on each line, but with the parallel line arrangement requiring wide enough spacing between WECs, this does imply a very wide LER structure, which might not be achievable.

Once this solution is considered in more detail, creating a viable but efficient mooring solution is not trivial. Although a horizontal string can easily be moored at the LER and the end of the line, it is likely that each individual WEC will require some additional lateral restraint to maintain the required performance level. As a result, the concept develops into a more complex layout as shown in Figure 17. These ideas show how the WECs can be laterally restrained against each other, how the solution could be adapted to several types of WEC, and how additional moorings can be used to provide lateral stiffness.

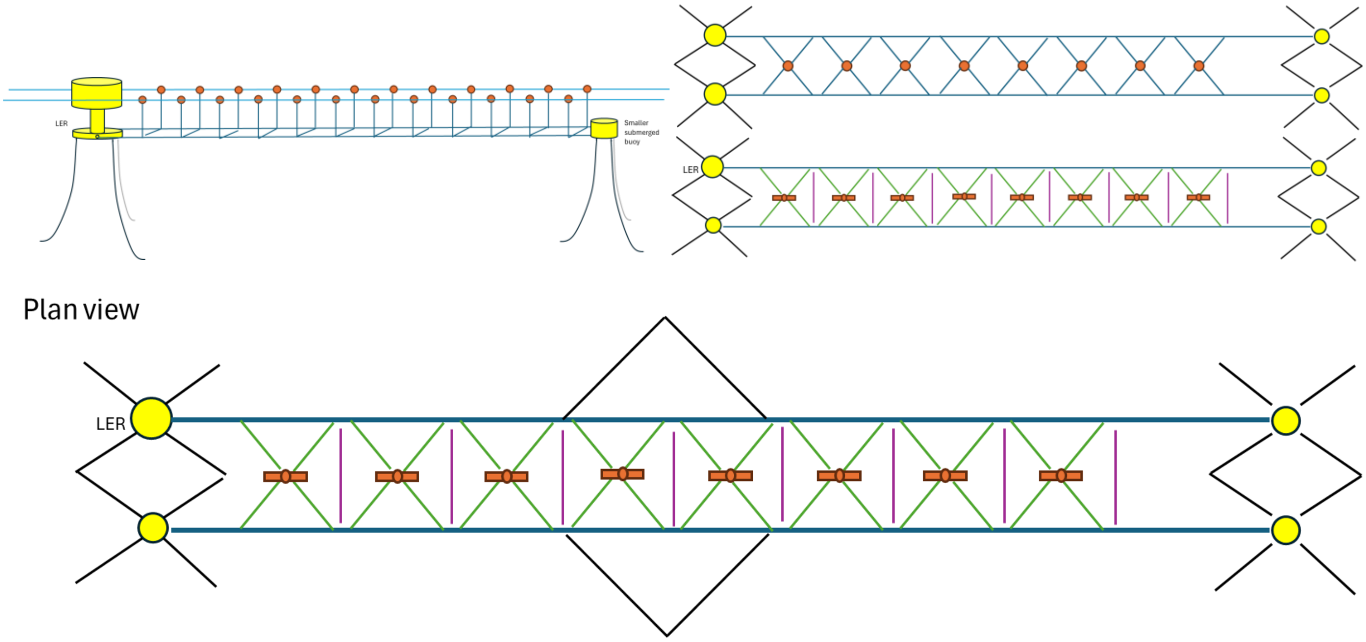


Figure 17 – Concepts to stiffen horizontal string layouts

Once these moorings are considered, along with the issues of managing the electrical cables from each WEC along the structure to the LER, it is clear that this type of concept has some significant challenges.

The structure of the horizontal strings was considered, noting that they must be flexible enough for the environment, rigid enough to hold the WECs in the correct location, and provide buoyancy or be at least neutrally buoyant. To create a cluster with sufficient generating capacity (e.g. 10 off 300kW – 500kW WECs), the ropes running along the length of the cluster would not be strong enough or rigid enough to withstand the possible combined loads, based upon the calculations undertaken as part of the rope nets concepts. Therefore, these strings would need to be steel or composite pipes, such as hollow drill string pipe, which is designed to take significant axial loads, but these structures would be at least 250m long, which is extremely difficult to handle from a vessel. Additional buoyancy would likely be needed, as well as complex cable management along the structure which would allow for individual WECs to be deployed and recovered.

A further concept was considered, which would allow the cluster structure to be unrolled from a tool for deployment, so that the two main lines of the structure would not require two separate vessels to deploy. This would rely on a rope type structure to provide the flexibility to be rolled and WECs would need to be deployed once the cluster structure was installed. Although ambitious with many development risks to overcome, it could provide a basis for deploying a wide structure to minimise the use of large vessels, but it is considered too conceptual for the purposes of this study.

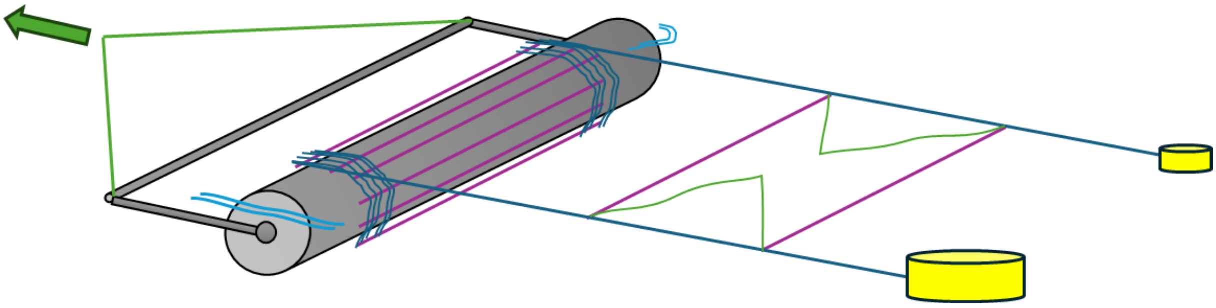


Figure 18 – Deployment concept for horizontal strings

4.7.1 Assessment summary and scoring

Category	Traffic lights	Narrative
Loads / member sizes and feasibility	Green	Loads appear to be very feasible and within the normal bounds for mooring lines and readily available pipe sections. One aspect that will start to erode this margin is understanding the dynamics of such a multi-body system, but the starting point is good. Loads might be potentially reduced as multiple WECs move out of phase, resulting in load cancellation at the mooring.
Technology gaps / showstoppers	Amber	Durable connection design between WEC and structure including power connection, mechanical interface, and sufficient buoyancy is challenging. Sizing of this has not been explored in this study Connections between the rigid elements. Durability. Design for maintenance. Cable management Annual inspections. Would need an efficient way to inspect all the elements. Not trivial due to number of items and limited sea state windows. Deployment with standard vessels challenging due to width between strings – significant innovation needed.
Specific risks	Green	Tight spacing makes marine ops higher risk (of damage to assets). DP essential. Scaling up looks possible, but limited by practical installation of >250m long structures
Cost / Benefit	Green	Cost savings on mooring installation looks likely to more than offset the cost of the ladder structure. An effective quick connection design would open opportunities for swapping WECs and enhance availability. Possibility of rapid installation of an array using the roller system, which could offer large benefits.

Category	Narrative
WEC type - ER or SR?	This analysis concluded this would only suit an SR type WEC. The basis was a Mocean type device with four taut moorings in a pyramid arrangement. The spacing assumed in this analysis was kept consistent with other schemes (30m). This might be too close (see notes on spacing).
Mooring – most suitable type rope or chain?	The end buoys and LER would be moored by any conventional means. The WEC moorings to the horizontal string are envisaged to be taut (stretchy) synthetic lines. No specific sizing calculations have been done on mooring sizes, but because these are station keeping moorings and not generator reaction moorings it is expected they will be within norms.
Replacement Strategy	Buoys, strings, taut moorings, and quick connection remain installed for life of farm. WEC intervention is individual.
Spacing	30m spacing is very tight for marine ops. Vessel could either use DP or pick up farm mooring points. The scheme looks to be scalable to larger spacing. The scheme would benefit from having a buoyant quick connection that connects to the moorings and is left behind when a WEC is swapped.
LER	Scheme makes obvious use of the LER platform as one of the buoys for the system. Obvious advantages for WEC electrical connections utilising the string for routing, but a reliable cable management system along a flexing string is complex.
Deployment operations	If the members of the string “ladder” are flexibly jointed or if the main rails are from rope rather than rigid, then it is conceivable that a long length of ladder could be pre-assembled and folded for transit then stretched out for deployment. This might require temporary buoyancy until the quick connections are fitted. Might require very wide vessel, or bespoke barge or bespoke installation “tool”. The flexible joints would require significant care to ensure their durability. The width of the rungs of the ladder could be 30m+ depending on required taut mooring geometry. This is very wide for handling.

At this point, it is important to mention one specific WEC type that does utilise horizontal strings for an array, but in a very specific way. The WavePiston concept uses a series of vertical flaps that move horizontally along the string, but instead of generating electricity the concept pumps seawater to shore for electricity generation or desalination. This concept was discussed and agreed to be conceptually viable, but its current form does not provide the solution of a WEC agnostic cluster that could be deployed in FOW sites far offshore, as the distance to pump water would be too great. It is conceivable that the concept could be adapted to enable an offshore generation substation to be installed for electrical generation or desalination, but this is considered to be sufficiently far from the original scope and intent of the WEC cluster study and is very specific to a single concept.

Figure 19 – An artist's impression of the WavePiston concept, with a number of parallel horizontal strings with wave flaps mounted on each string.

4.8 Other concepts

Other concepts were considered but have been quickly discounted. These are discussed at a high level below:

A "carpet" with a high number (>500) of small devices (<10kW). This was not considered to be practically viable and would rely on small SR WEC types. The advantage of this concept is that a high degree of redundancy exists, so that several devices could fail without compromising the output. However, for exactly the same reasons that small WECs are generally not economically viable compared to large devices due to the scaling laws of wave power, this system may only become viable when direct generation materials become available.

Using a FOW platform, with an integrated WTG. This is a concept that has been well published by many organisations in the past. In the context of this project, it is considered that adding WECs to an early-stage technology platform such as FOW is an unnecessary risk that developers will not want to accept. The clustering solution provides an alternative solution for FOW developers to share infrastructure without adding additional technical risk to the individual WTG platforms. Use of the FOW platform without the WTG was also not considered as this solution lacks structural efficiency and optimisation aligned to the needs of wave energy.

Large, buoyant, concrete structures that include multiple installed WECs were considered. The mounting of WECs onto a concrete structure is not a new concept and has been previously used for mounting WECs into shore-based infrastructure. In this project it was considered that this solution would not be viable as a cluster solution as the CAPEX is likely to be significant compared to the energy yield that would result.

Tensegrity structures, which are based on a system of structural elements held in place with a number of cables in tension, were considered, as these offer significant advantages in terms of structure mass and potential deployability. Consideration of these combined them with collapsible structures, where the structure could be deployed and expanded by using tensioned cables. Additionally, it was considered that the external ring of a hexagonal structure could be replaced with tensioned cables. The main disadvantage of this system is the reliance on achieving and maintaining tension without depending upon complex subsea winches and cable / chain stopper systems, which will likely creep over time. As a result, tension monitoring and automated re-tensioning systems would need to be developed, there would be inherent reliability risks associated with these. Cables would also need to be well protected from corrosion, biofouling, and abrasion, which would certainly be challenging for high tensile steel cables.

4.9 Down selection to single structure concept and justification

At the end of phase 1, a down selection process was used to identify the favoured concept from all of the options. At this point, both rope nets and lightweight steel structures had been demonstrated at a high level to provide the most conceptually plausible solutions, albeit with some significant challenges that still need to be overcome. The layout of each solution that was considered in more detail is shown in Figure 20 and Figure 21.

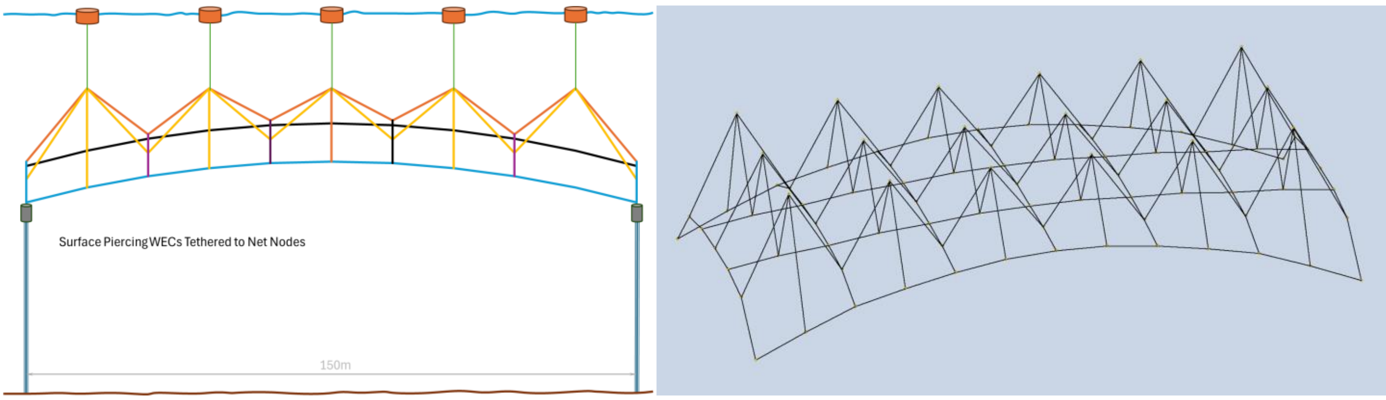


Figure 20 – A more detailed analysis of a 5x3 and 6x3 WEC rope net mesh

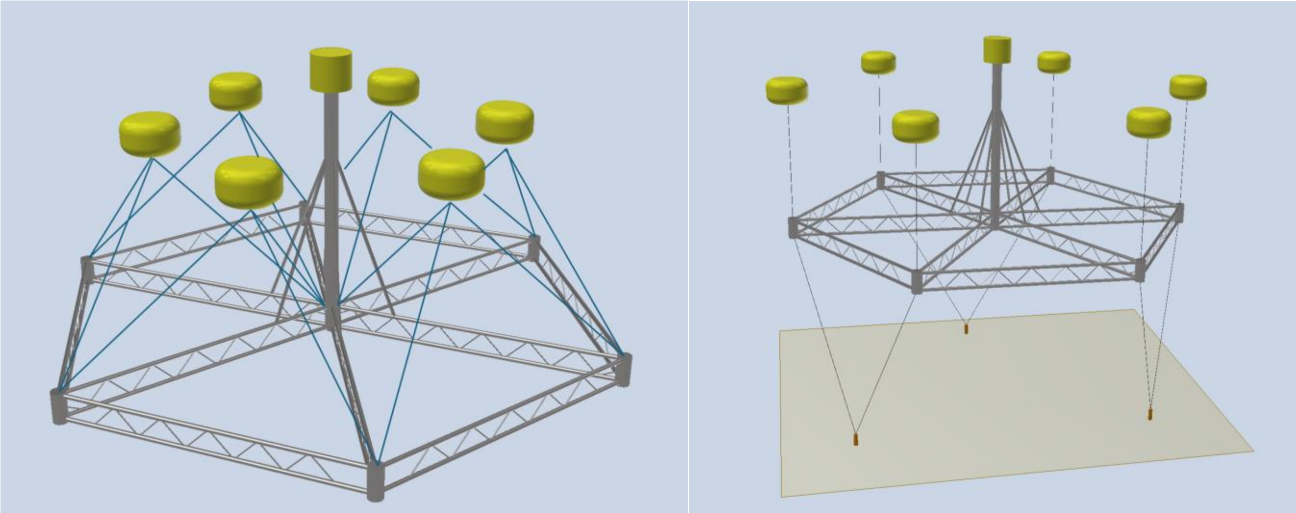


Figure 21 - A more detailed illustration of the hexagonal steel structure either with single or triple point moorings to PA WECS

Further assessment to choose between the two concepts was completed, which resulted in choosing the lightweight, hexagonal structure, based on the following justifications:

- The stress analysis completed for the steel structure indicated that this structure is viable when considering the ultimate loads from a 500kW ER PA WEC. Stress values below 150MPa are achievable in a high-level concept design, which could easily be reduced with appropriate structural optimisation. No fatigue analysis was considered.
- The net structure, although technically viable in terms of peak loads, is fundamentally a horizontal flexible structure under the influence of vertical loads. The steel structure moored solution is able to transfer the vertical loads directly into the moorings, which results in the structure not having to withstand significant bending loads.
- The nodes of the rope mesh are likely to result in significant technical risks, as they must ensure that load is equally distributed throughout the structure. Nodes with multiple ropes terminating onto a steel masterlink or potential rope equivalents (e.g. Lankoloop), along with the considerations of corrosion, biofouling, abrasion, and UV degradation are all potential technical risks that may be difficult to mitigate.
- The integration of the LER onto the rope structure is not trivial. A totally separate structure could be used, but this increases the dynamic cable management risks and the number of moorings. The hexagonal structure offers a suitable, static, location that allows the LER to be rigidly fixed (relative to the structure) whilst also allowing the LER to be accessed with vessels, and reduces the number of dynamic cable connections between the WEC and the LER).

As a result, phase 2 focussed on developing the lightweight steel structure into a more viable solution.

5 PHASE 2

5.1 Description of work completed

Having selected the hexagonal steel structure as the most promising concept, further work was completed to improve the solution to overcome some of the initial concerns from Phase 1. These were:

- Increasing the overall rigidity and ruggedness of the structure, to make it more visually plausible that it could survive in the offshore environment.
- Improving the central LER integration to spread loads around the central node and into the spokes.
- Assessing the stress of the structure with symmetric and asymmetric loads applied from the WECs. The assumption of 1MN vertical load was still applied in this phase.
- Consideration to improve the fabrication and associated O&M costs, such as corrosion protection, bio fouling, painting, and weld inspection.
- Integrating more than one type of WEC on the same structure, as ensuring viability for at least two WEC types is important.
- Consideration of the mass and buoyancy of the structure.

As a result of these considerations, the following improvements and amendments were included.

The spoke structure was improved to a quadrilateral truss structure. This was an iterative evolution, first to a triangular structure before subsequently reaching the quadrilateral truss. This arrangement provides far greater stiffness of the structure, but at the penalty of increased steel usage and associated painting and welding costs.

Addition of an internal hexagon to provide a base structure for the LER support multi-legged structure.

Sizing of an LER to accommodate electrical equipment for 6 WECs. A 7m diameter room, with two floors was considered to be a practical size, to allow equipment installation, suitable flooring and a realistic internal working space envelope, power electronics and control cabinets for each WEC, combined switchgear equipment, and additional LER environmental control systems. The LER is circular to avoid the worst of wave slam loads.

Increasing the size of the nodes to make the structure positively buoyant, so that is floats with a sensible draft during towing when there are no WECs are attached. The nodes could be further improved with the use of heave plates to mitigate movement and WEC loads if required, or alternatively ballast could be added to add additional inertia.

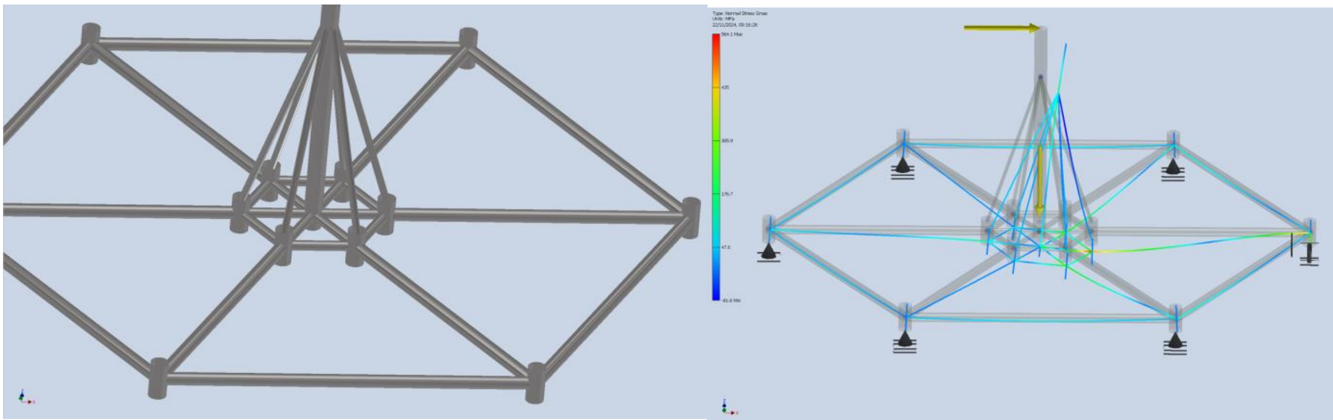


Figure 22 – Initial structural assessment - ***Larger single tubes still do not provide sufficient stiffness. Nearly all load is reacted by a single member with peak stress >500MPa***

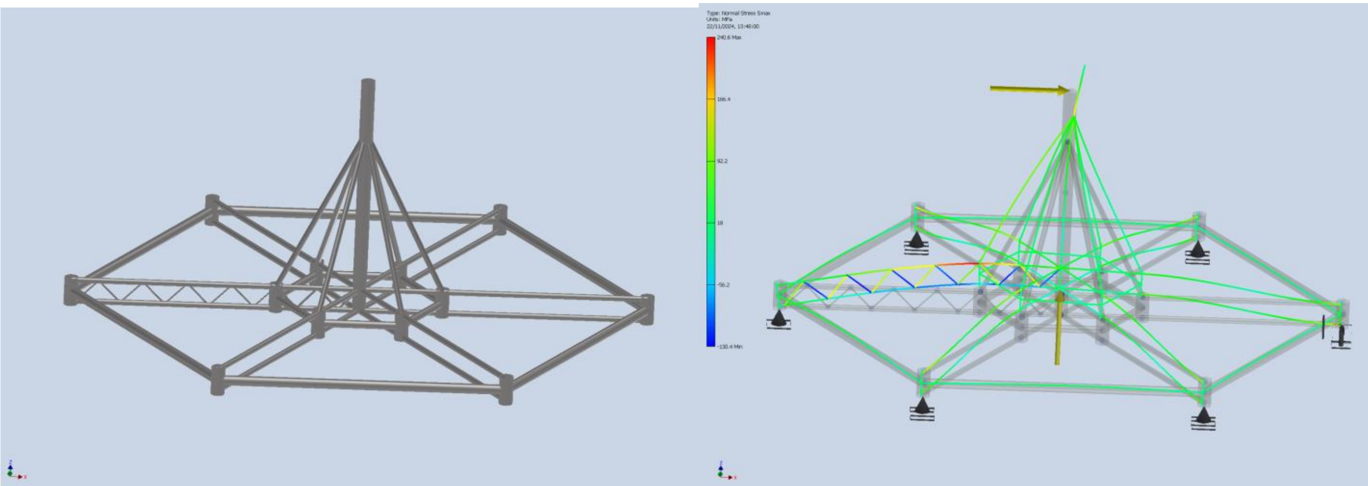


Figure 23 – improved structural performance using truss structures - ***A similar principal stress direction, but stress is vastly reduced to 250MPa. Truss structure only shown in a single leg for simplicity***

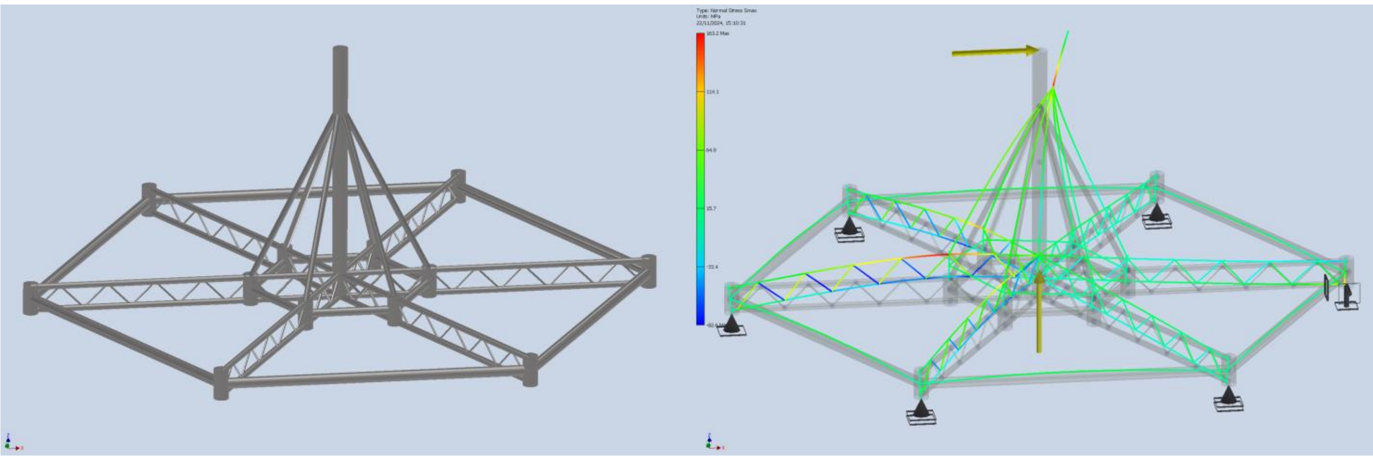


Figure 24 – Improved structural performance with truss structure on spokes ***A fully modelled truss structure shows stress further reduced to 150MPa and spread across multiple spokes***

Further improvements were made to simplify the internal hexagon structure at the centre of the platform, as the truss structures in this region are not required.

Mooring lines and dynamic electrical cables have also been added to demonstrate how these would be connected. A taut mooring has been assumed as a baseline in order to minimise the cluster structure excursion, as well as keeping the mooring system footprint as small as possible. Clearly other mooring systems are applicable (catenary, semi taut), and the preferred option would be chosen based on the particular site, seabed geology, bathymetry and metocean data. Basic pad eye connections have been modelled, but these would be further improved during detailed design. The dynamic cables have been assumed to be “lazy S” profiles to allow WEC movement without damaging the end cable connection. More detailed analysis of cable fatigue would be essential, and the final routing of the cables may well look quite different depending upon the WEC movement, cable exit point and cable fatigue considerations.

5.2 Resulting cluster concept

The conclusion of this project is summarised in Figure 25, to Figure 28. The images illustrate:

Three identical cluster structures, but with three different types of WEC, demonstrating the concept can be adapted to various WEC types.

Cables are shown in more detail on the central cluster, but various cabling options are available. Cables are removed from the other clusters for clarity of the remaining system.

Clusters can be electrically connected at a subsea hub, located in proximity to the cluster farm. This subsea hub could then be connected to a co-located FOW farm offshore substation.

The anchoring system is assumed to be relevant to a taut mooring system, based on a rocky geology with drilled anchors. Other anchoring systems for sand, clay and loose rock systems are available.

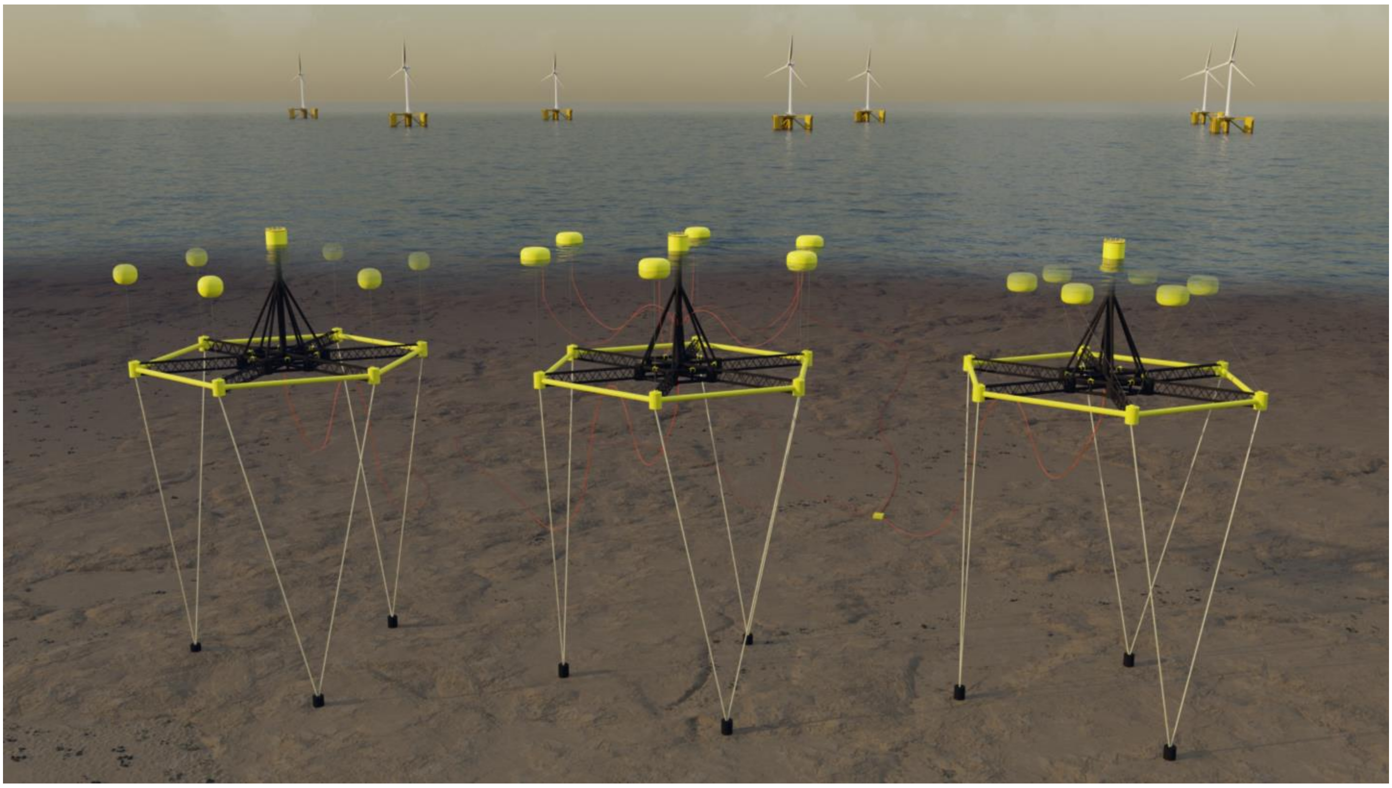


Figure 25 – Visualisation of cluster concept, demonstrating applicability to different WEC types (from left to right, submerged pressure differential, point absorber, and submerged point absorber) and co-location with a FOW farm.

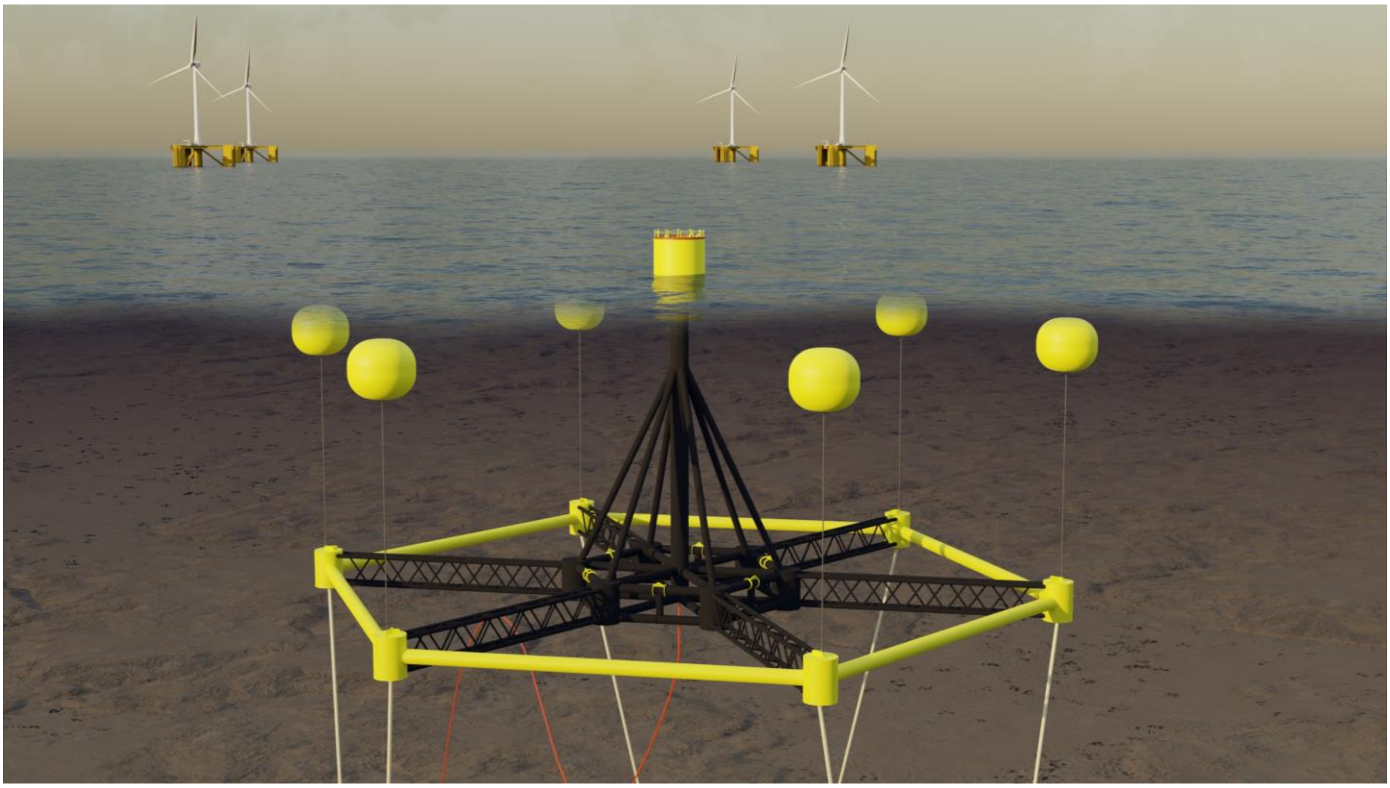


Figure 26 – Single cluster concept, with submerged pressure differential WECs

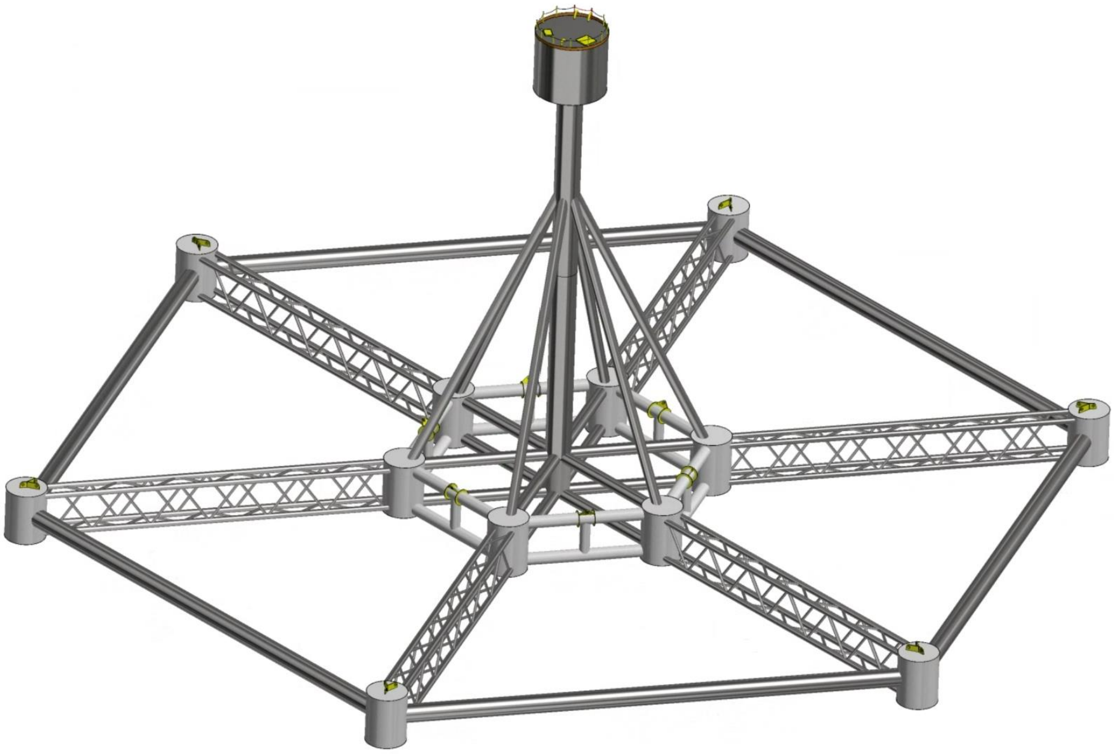


Figure 27 – CAD image of cluster concept framework

Figure 27 shows the overall structure, with a mass of 850 te and a net buoyancy of 2400 te, prior to any buoyancy modification or tuning, resulting in a net buoyancy of 1550te. The large diameter nodes can be ballasted as needed with concrete, steel, or water to reduce buoyancy, but this high amount of net buoyancy will also act as a stabiliser for the taut mooring system to improve the stability of the system when in operation. These figures do not include the mass or buoyancy of any of the attached WECs, which would add additional buoyancy.

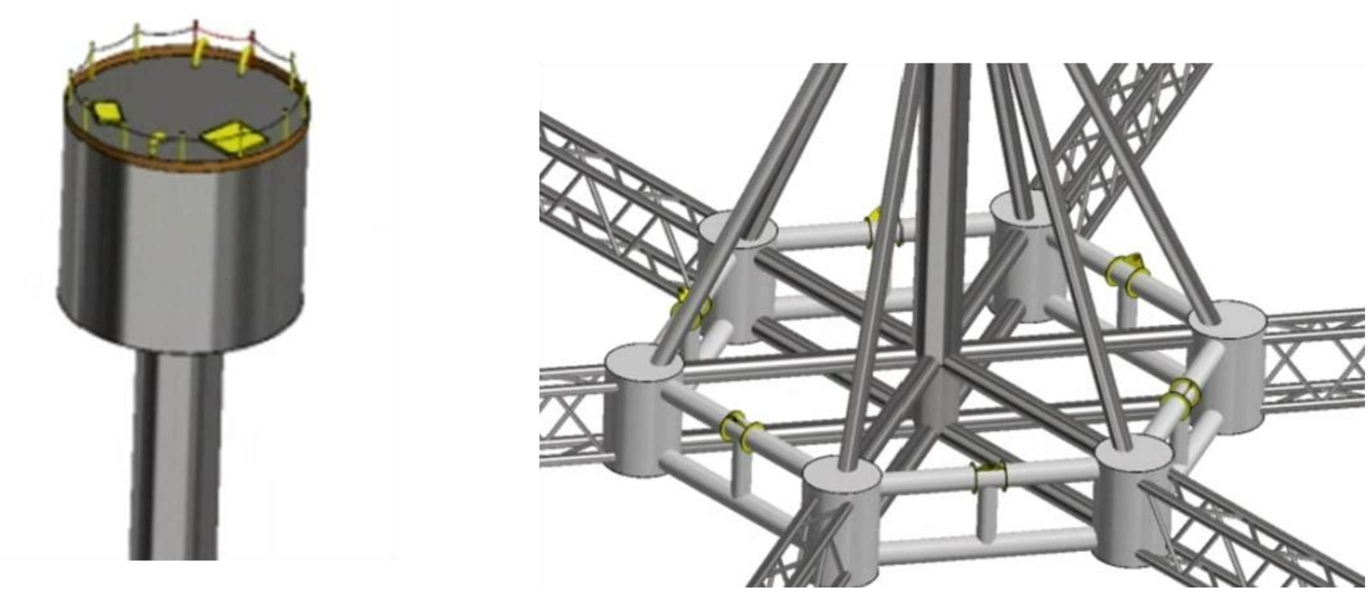


Figure 28 – LER and Central region, showing more detail

Figure 28 shows some of the high-level details that have been illustrated, including padeyes for the moorings, the WEC tethers and operational features for the LER, such as boat landing, platform, hatches etc).

5.2.1 Operational and logistics details

More detailed aspects associated with manufacture, assembly, deployment, and operation of the concept are outlined in this section.

The manufacture of the steel structure would use relatively standard steel fabrication procedures. This is a large structure (100m diameter), but this is not larger than many other offshore jacket and rig structures and there are many examples of the manufacture of such structures at port or quayside facilities, using existing supply chains and fabrication techniques.

Installation into the water would likely involve SPMT or similar, either down a slipway or onto submersible buoyancy platforms or barges, or using facilities with very large cranes, such as ring cranes. Clearly this is not something that would be available at all ports but, given the timeframe of WEC cluster development and the likely development of the FOW industry in the meantime, it is justifiable to assume that ports, quaysides and marshalling areas suited to FOW structures could also be suited to this type of WEC cluster structure.

This argument is also very valid for the port operations. Whilst there are many ports that are too small for such a structure, the development of FOW structures prior to WEC clusters means that any port with the quayside, laydown area and vessel type suited to FOW marine operations would also be highly likely to be suited to this structure. Issues surrounding capacity to do both simultaneously would need to be overcome, but that is not within the scope of this project.

Deployment is assumed to be a tow from port. The structure will be buoyant, mainly achieved through the sizing of the members that make up the structure. The large amount of buoyancy around the edge of the structure will provide stability during towing, but this has not been assessed dynamically as part of this project.

Deployment and recovery at site would not be trivial but would in principle be similar to a buoyant TLP or spar buoy structure and a taut mooring system, which is common in the FOW and O&G sectors.

The O&M strategy for this cluster concept can be considered from two aspects. Firstly, minor maintenance requiring access to the LER only, and secondly more major maintenance requiring the removal and replacement of a WEC.

For minor maintenance that can be undertaken in the LER, access is obtained by using standard Crew Transfer Vessel (CTVs), as used widely in offshore wind. A standard boat landing and ladder has been included, and modern access to work systems could easily be deployed in this instance, such as the Pict Lift to Work system. Depending upon the type of WEC used, the amount of access space for a vessel to approach the centre in between the WECs differs and this would need to be considered in detail with a marine operator. Even if the WECs are submerged, there is still a hazard associated with a CTV being over the top of a submerged WEC.

For more major WEC maintenance, this will rely on a tow to home strategy for individual WECs. In some circumstances, access to an installed WEC can be managed, but by the nature of the WECs being in an energetic site, the assumption should be to avoid access to a WEC at sea as a baseline. Access increases risk, but this does need to be considered in the overall context of reducing tow to port operations for very minor failures, if straightforward maintenance at sea can be safely managed. This argument therefore concludes that a quick-connection technology is required to facilitate easy removal and tow to port for individual WECs. Some quick-connect mooring and electrical connection systems exist as prototypes, and they could be developed further for this cluster concept. Fundamentally, the connection and recovery process as well as the O&M strategy should aim for a hands-free operation, with vessels not requiring pushing up against the WECs or require personnel or equipment transfer. There will be situations where this is required, but these should be minimised.

Maintenance activities for the structure, for example inspection of steelwork, mooring connection management, corrosion, and biofouling inspection, replacing internal power cabling, replacing anodes, etc, would at least require ROV operations. These activities will be largely similar to those that are needed for a FOW structure and similar techniques would be employed using FOW best practice. Technology development for automated inspection and possible repair using AUVs is available, and by the time WEC clusters are installed is likely to be a standard solution.

Lastly, for the entire WEC cluster structure recovery, this would be a major operation requiring similar vessels and durations as the deployment process. This would be considered in a very similar way to the FOW platform O&M strategy. At this stage in FOW development, there is a clear intent that the platforms will not be brought back to port for maintenance, mainly due to the vessel costs involved and the turbine down time that would result. However, it is worth noting that few developers have finalised O&M strategies in detail at this stage.

5.2.2 Cost – benefit assessment

A detailed cost – benefit assessment was not part of this project scope. However, the design has been created with the cost benefit in mind.

For this to be a viable concept, the benefits associated with clustering must outweigh the increased costs. These benefits can be qualified as CAPEX, OPEX, DEVEX or risk.

A cluster such as the one proposed would provide benefits by:

- Reducing the number of moorings compared to installing WECs individually, and those moorings would be specifically designed for attachment to a large structure, rather than attaching to a very dynamic WEC.
- Shortening the WEC moorings, which are likely to be more complex due to the need to manage the highly dynamic nature of the WEC.
- Shortening the dynamic electrical cable, as this no longer has to go to the seabed.
- Reducing the risk and cost associated with trenching and laying electrical cables on the seabed, as this is reduced by a factor of 6. It is envisaged that individual WECs would probably still be connected to a local subsea hub, so this cost is considered similar.
- Reducing the complexity of equipment on each WEC, by locating maintainable equipment in the LER, which can be accessed using standard CTVs and access procedures.
- Reducing overall O&M and inspection costs by concentrating WECs in a smaller space envelope. O&M activities could be more easily shared between WECs and the LER.

These must be offset against the additional costs, which include:

- Manufacture, assembly, deployment and installation of the hexagonal steel structure.
- Ongoing O&M costs associated with the structure, such as inspection, anode replacement, and biofouling removal.
- The likely use of larger or more vessels for the deployment than would be required for an individual WEC.

A more detailed assessment would be required to quantify these over the lifetime of the cluster to determine the balance of benefits compared to the costs.

5.2.3 Assumptions, constraints, limitations

Various assumptions have been made throughout the development of this proposed cluster arrangement including:

- The cluster is conceptually applicable for a variety of different WEC types, and the concept is based around a surface piercing single mooring PA, a single mooring submerged pressure differential device and multi-mooring submerged PA type.
- Basic stress calculations have been completed based on an assumed 1MN peak load from a 300kW-500kW capacity WEC. Some of these loads are scaled from smaller scale WECs using basic wave scaling laws, or from data available from developers.
- Dynamic cable routings have been suggested, but options exist for other solutions. Internal cable routing within the hexagonal structure is possible but affects the WEC connection and disconnection unless a quick connection system is used at the WEC / mooring interface. It is preferred to avoid the use of wet mate or dry mate connectors unless incorporated into a dedicated and automated quick connection system.
- No dynamic analysis has been completed, so mooring ropes have been sized using order of magnitude calculations assuming a peak load from the WECs. Additional loading from system dynamics has not been considered.
- An operational story board for installation and recovery of the structure has not been completed in detail, but the installation of the submerged structure is expected to be in line many FOW structures.
- It has been assumed that the port will be large enough to assemble and install the structure. The structure is approx. 100m in diameter, which will be larger than many ports have capacity for, but this structure is a similar order of magnitude in size to many jacket structures and FOW foundations that have been or will be deployed. WECs will not be attached until the structure has been installed at site.
- The cluster is sized to contain six off 300kW – 500kW WECs, with a total power of 1.8MW to 3.0MW. It is feasible that these WEC ratings can be increased, and it is also possible to install more WECs per structure, as long as the size of the structure is still within the practical fabrication, assembly and deployment limits of ports and vessels.

6 FURTHER WORK

6.1 Next steps

There is clearly significant further design work required to develop this into a costed and manufacturable solution, which would be a significant piece of work. However, the purpose of this study is to create a concept and to present an image that can be used to engage with relevant industry stakeholders to inform discussion and debate about the role of clustered wave power co-locating with floating offshore wind and how this can best be done. As a result, although many detailed engineering tasks are needed to consider every aspect of this concept from a technical, operational, and commercial point of view, the recommended next steps for this work are very much focussed on using the outputs of this work to:

- Start engagement with all the relevant stakeholders.
- Identify common concerns and risks across the industry, as well as specific issues with individual. stakeholders that would affect the implementation of WEC clustering in particular situations.
- Understand how different developers consider the integration of WEC clusters in different ways.
- Understand how the insurance and certification bodies will approach WEC clustering.
- Understand the specific risks associated with ports, harbours, marine operators, and the O&M strategy.
- Assess the supply chain impacts of creating such a structure.
- Whilst this platform is not a FOW structure, it does share a lot of common properties and can certainly share a lot of resources and strategies with FOW platforms. Examples include ports and harbours, supply chains, lifting equipment, and O&M strategies. Engagement with FOW developers is important to understand how they are planning these activities and therefore how this WEC cluster concept can be developed and improved further.
- Creating a more detailed cost model to better assess the cost benefit of these structures, compared to installing individual WECs.

6.2 Recommendations

This study has developed a very high-level concept of a WEC cluster solution. Throughout the project, several issues have been identified that could become enablers for this technology if they were available in the future as commercial solutions.

- A large-scale (>300kW) Self-Referencing Point Absorber WEC. This would allow smaller steel structures to be used and may even open up the possibility of using rope nets as the cluster structure.
- A method of joining large steel structures out of port, so that these structures could be constructed in modules with integrated WECs, towed out of port and then integrated together into a combined structure in a sheltered location, prior to deployment. This could be done using large semi-submersible barges, but a more cost effective, proven, and viable offshore connection system could enable improvements to this concept. In particular, this could lead to an increase in the size of the structure, the number of WECs and ultimately the amount of power generated per cluster.
- The creation of a quick connection system that is compatible with this cluster technology. Having a quick connector installed at the top of each mooring rope would enable individual WECs to be removed and towed or lifted back to shore, as at sea maintenance should be the aim of a commercially viable, offshore, production solution to achieve the required reliability. Some quick connection systems exist but would likely need some improvement or adaptation to be relevant to this application.

- In common with FOW structures, the loads and size of catenary moorings may well prove to be at the limit of existing mooring capability. Extremely large diameter and long catenary mooring chains are expensive, cause a supply chain constraint and reduce the density of cluster installation at sea. The development of taut or semi-taut mooring and anchoring systems that are adapted to a wide range of seabed conditions will ensure that WEC clusters can be installed across a large swathe of seabed without needing to change anchor system depending upon the subsea geology that can be very variable across relatively small sites.