D6.2 - Analysis of different potential configurations of rigidly inter-moored devices

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Table of Contents

Table of figures

Table of tables

EXECUTIVE SUMMARY

This report presents Deliverable 6.2 of the WETFEET H2020 project – Report on analysis of different potential configurations of rigidly inter-moored devices (compact aggregates) in what concerns loads, motions, risk of collision and performance.

It consists of an introductory description of the benefits of having inter-connections between devices, in this case, rigid connections, in order to decrease the cost associated with the installation and also maintenance operations of mooring and electrical cables. To reduce such cost is seen as a necessary breakthrough in order to make wave energy a more competitive and readily available and achievable technology.

After an initial description of the moorings systems for wave energy devices and its main elements, the main parameters and evaluation factors are introduced and analyzed. These consist mainly of cost, performance, used seabed area and environmental impact and risk of collision or failure.

Some of the technologies that have already been suggested that explore the idea of shared rigid connections between devices is presented and analyzed. It is seen that mostly they divide in to main categories, either sharing a connection to a common infrastructure or having some sort of rigid connection between different devices, either by the form of a system of bearings or by a stiff metal rod link.

Having these considerations in mind, six different configurations are proposed and analyzed in terms of the parameters highlighted in the initial sections for the case of an array of five devices. These are compared with the reference case of individually moored devices.

The deliverable concludes with the suggestion of which rigidly inter-moored arrays should be further investigated, namely through numerical and experimental analysis, in the future tasks of this work package.

LIST OF ACCRONYMS

IST	Instituto Superior Técnico
MRE	Marine Renewable Energy
O&M	Operations and maintenance
OWC	Oscillating Water Column
PTO	Power Take-Off
TLP	Tension Leg Platform
WEC	Wave Energy Converter

1. INTRODUCTION

1.1. Context and Motivation

The wave energy industry is currently held back by numerous technological issues relating to reliability, survivability and high development and operational costs. Within the framework of the WETFEET H2020 EU-funded project, a set of different breakthroughs has been identified to address the main obstacles that have been delaying the commercialization of wave energy. The WETFEET project aim is to create breakthroughs in four main areas: survivability, operation and maintenance (O&M), power take-off devices (PTO) and arrays. Two devices are used as case studies: the Symphony, developed by Teamwork Technology, and the oscillating water column (OWC) spar buoy developed by Instituto Superior Técnico (IST), Lisbon.

The extensive exploitation of the offshore resource will most likely take the form of arrays, similar to what happens for wind energy. The advantages of having multiple devices grouped together in arrays are multiple.

The combination of the power output of several converters will have a smoothing effect on the total absorbed power therefore making it more suitable when inserting it into the grid, which is a common issue affecting the installation and integration of renewable energy sources technologies in the power grid. Another advantage is the scale cost reduction effect of having multiple structures sharing common infrastructure and resources, such as electrical cable connections and power converters or simply the same sea area.

The chosen array geometry will depend on several factors such as the one which, considering hydrodynamic interferences, grants optimal power production for the dominant expected sea state of the location where the device is installed. Besides this, the economy of the moorings and of the electrical cables, together with the available sea area and seabed profile, are also significant factors. It can even be discussed, if these factors are not in the end the most deciding ones.

Even if there is some compromise in the total power absorption, and therefore, the financial revenue, given that the costs of mooring and electrical cables can be very significant, especially because of the high installation cost, with very specialized vessels and equipment's, it is foreseeable that in the end, in terms of LCOE, they can be more significant factors.

It is possible that many of the first arrays will be placed in regions in proximity of shipping, fishing or other areas of sea use and, therefore, limitations in sea space may dictate that the devices need to be relatively densely packed. This will mean that the 'footprint' of the mooring should be constrained, to ensure that the moorings from each device do not interfere.

Significant cost reductions are required for marine renewable energy to become competitive. Aside from the deployment of arrays, one key area that has been identified as having potential for cost reductions is the mooring system ([1]). A clear challenge therefore exists to design mooring systems which can satisfy their primary role of station keeping while being

affordable and durable. This is especially true for the case of wave energy, in order to help its breakthrough to a competitive technology.

It is then fundamental to study the differences in the mooring design for the specific case of floating WECs, the influences of the moorings in the device performance, and finally, to analyze what are the more suitable mooring design criteria for devices when placed within arrays, in proximity with other devices, sharing similar sea bed areas and infrastructures.

As is the case of any floating oil and gas platform, free floating wave energy devices are subject to drift forces due to waves, currents and wind, and therefore they have to be kept on station by moorings.

It is important to take into account that the moorings are a critical element, whose failure can destroy the whole system. So, instead of being perceived simply as an additional cost in the overall economics of device, moorings should be in fact designed as an integral element of the system throughout its entire design phase.

Moorings play an essential role in extreme sea waves, as they are the ones that prevent the device from drifting away resulting in loss or, worse, destruction of the device(s). This means they must be designed in such a way that they are capable of providing enough freedom for the energy extracting motion(s) in normal operation conditions, but at the same time a stronger restraining force and stiffness for waves in extreme storm conditions.

In order to share infrastructure and also to take advantage of the influence of hydrodynamic interactions on power production, close separation distances between MRE devices positioned in arrays is proposed. The close proximity between devices means that particular considerations must be made regarding the design of mooring, electrical and hydraulic infrastructure. One aspect to take into consideration is the mooring system compliance.

This is important to reduce the risk of mooring line entanglement and device collisions and to allow suitable clearances between the devices for any vessel access during installation, maintenance and decommissioning procedures [2].

A densely packed WEC farm would also require short mooring lines providing a small footprint area to allow for the installation of multiple devices. This would be in contrast to typical offshore oil and gas installations where the footprint area is mostly not restricted, and only obstacles like pipelines, riser, etc. need to be considered, since they are not allowed to touch each other [3].

The requirement of a small footprint area and a small excursion for WECs would result most likely in the use of heavy mooring lines within a simple catenary mooring arrangement. As a consequence, such mooring arrangements would become stiff, resulting in higher natural frequencies. Within the preliminary mooring design these are the factors that require greatest attention in order to establish a mooring that provides the optimal arrangement between the footprint area, excursion, and natural frequency [3]. Another option could be the use of synthetic ropes, but there is still little experience on this, besides that this introduces a a high pre-tension in the device and a very stiff system.

In terms of guidelines, the separation distance specified in the DNV-OS-E301 Position Mooring guidelines [4] between offshore accommodation units and fixed equipment is suitably large for that given application, but not applicable to MRE devices which are unmanned during operation. An alternative and more suitable approach suggested in the DNV-OS-J103 Design of Floating Wind Turbine Structures guideline [5] is to base the separation distance on the maximum possible surge or sway displacements during normal operation and in the case of a failure in one of the mooring line (assuming that the mooring system has built-in redundancy).

Another aspect to take into account is that for an array of considerable size it is unlikely that the site will be heterogeneous in terms of sediment or rock type or seabed feature across the site. Therefore, a uniform approach to mooring and foundation design may not be suitable and several designs may be required [2].

Also, across an array it is likely that the loads experienced by moorings and foundations will differ, either due to hydrodynamic interactions or to the level of exposure to the incident conditions. Hydrodynamic interactions occurring between devices could result in loads being applied to the array mooring or foundation systems which are different from an individual device.

Shared mooring system infrastructure would be a way of reducing capital costs and to reduce the number and difficulty of installation and decommissioning operations for MRE devices. The concept is not entirely new, with array-type moorings and shared anchor points used for aquaculture systems [2].

On the benefit side, less bottom-mooring line represent:

- Reduction mooring costs and offshore operations required.
- Smaller sea bed area required.
- Reduction environmental impact on sea bed.
- Increase range of possible "array optimal distances" coming from optimization routines.
- Reduction of the lifecycle transit distances through shared maintenance efforts.

However, some risks can also be associated to this mooring strategy. Namely,

- Reduction of bottom connections increase risk in survivability.
- Complication in maintenance operations.
- Difficulty to increment the number of devices in a pre-existing array.
- Difficulty in controlling dynamics of several inter-linked devices.
- Lower production due to negative hydrodynamic interferences.
- Risk of entanglement.

The objective of this deliverable is to analyze the feasibility and the subsequent different options of having the wave energy devices rigidly connected between each other, in order to reduce the number of necessary bottom moorings and associated installation and O&M costs.

The outcome is a report on analysis of different potential configurations rigidly inter-moored devices (in compact aggregates) in concerning loads, motions, risk of collision and performance.

The aim of Work Package 6 is to identify and quantify the potential for sharing mooring lines within an array as a cost reduction strategy. To achieve this goal, different tasks and subtasks are proposed. In the one related to this deliverable, Task 6.1, different array configurations are to be investigated and proposed for evaluation and assessment (in the subsequent tasks), in terms of loads, motions and performance. The assessment will be performed through a series of numerical modelling simulations and laboratory scale testing.

Task 6.1 leads to two deliverables: D6.1 covering the feasibility analysis of a flexibly moored array and D6.2 covering the feasibility analysis of different potential configurations of rigidly inter-moored devices. The full cost evaluation of all the breakthroughs proposed in WP2 – WP6 will be addressed in WP7 Multi-disciplinary assessment for large-scale deployment.

It should be noted that the aim of WP6 Task 6.1, reported here, is not to suggest the best mooring system for the chosen device, nor is it to suggest the optimum array geometry, or test site. The aim is to select configurations worthy of physical and numerical modelling that are likely to lead to implementable lessons in the design and engineering of arrays of devices.

2. ARRAYS OF DEVICES

Current technology is still not mature enough in such a way that parks or arrays of wave energy devices are already installed. However, it can be predicted that offshore wave energy parks will be formed by several groups of units, each having a typical power between hundreds of kW to a few MW. The total instantaneous power will be the sum of the power of each unit that forms the array. This way, since waves are irregular in height, period and direction, it can be expected that the power delivered by the park to the network will be somewhat favorably smoothed by the combination of devices in array.

3. SEABED MOORING OPTIONS

Mooring research specifically for offshore renewable energy and especially for WECs is still maturing, with most of the mooring experience still coming from ships and offshore platforms.

A classification for wave energy devices can be made in terms of moorings function regarding the role or influence of the mooring:

Reactive mooring - mooring provides a reaction force and the PTO exploits the relative movements between the body and the fixed ground. The resonance of the system is designed to match the wave periodicity. An example of this kind of device is the Seabased device.

Passive mooring - the only purpose of the mooring is station keeping and the movements have a limited effect on the device efficiency. The mooring resonant period is designed to fall far from the wave forcing periods. Some examples of this kind of device are the OEBuoy, the Wave Dragon and the Pelamis.

Active mooring - the system stiffness is important for dynamic response and may alter the resonance conditions. The mooring resonant period is designed to fall far from the wave forcing periods. Some examples of this kind of device are the point absorbers e.g. WaveBob, PowerBuoy, etc.

3.1. Anchors

An anchoring or mooring system consists of: (1) the mooring line that transmits the forces from the moored structures to the anchor, (2) the attachment point on the structure, and finally (3) the anchor itself. The anchor provides the majority of the resistance to the motion, or holding capacity, although some contributions exist from the portions of the line which are buried in or lying on the sea, especially if the mooring line is made of chain.

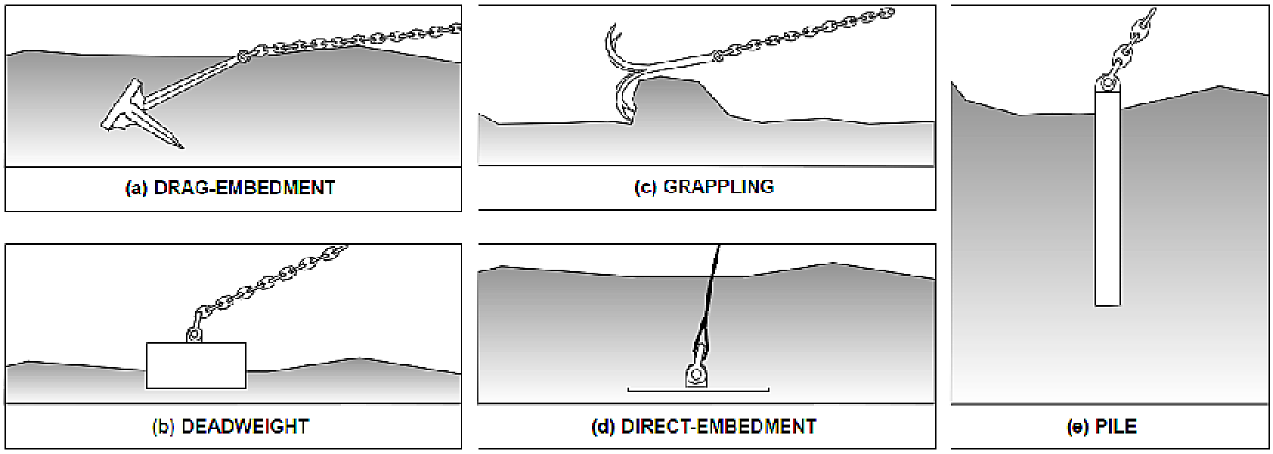


FIGURE 3-1 EXAMPLE OF THE EXISTING DIFFERENT KIND OF ANCHORING SYSTEMS [6]. A) DRAG EMBEDMENT ANCHORS, B) DEADWEIGHT, C) GRAPPLING, D) DIRECT-EMBEDMENT, E) PILE FOUNDATION.

Different kinds of anchoring systems exist (Figure 3-1), which have mostly been developed initially for ships and more recently for offshore oil and gas structures. The selection of the anchor to be used can depend on several factors, which can be group in three main types:

- **Seabed:** the type of soil and the sea floor sloppiness;
- **Loads:** the direction of the loading and the load range;
- **Economics:** the initial, installation and maintenance cost.

These factors can be determining when designing the anchor to be used, depending on the available conditions. Figure 3-2 indicates the applicability of the different anchors according to the different factors. For example, deadweight anchors are not considered appropriate for a seabed with a slope higher than 10º. Also, drag-embedment anchors per example, are only applicable for some kind of soils, namely softer soils and if the direction of the load is not important and well defined.

Item	Deadweight	Pile	Direct-embedment	Drag-embedment	Grappling
Seafloor Material					
Soft clay, mud	++	+	++	++	o
Soft clay layer (0-20 ft) over hard layer	++	++	o	+	o
Stiff clay	++	++	++	++	o
Sand	++	++	++	++	o
Hard glacial till	++	++	++	+	
Boulders	++	o	o	o	+
Soft rock or coral	++	++	++	+	++
Hard, massive rock	++	+	+	o	++
Seafloor Topography					
Slope < 10 degrees	++	++	++	++	—
Slope > 10 degrees	o	++	++	o	—
Loading Direction					
Omnidirectional	++	++	++	o	o
Unidirectional	++	++	++	++	++
Large uplift	++	++	++	o	++
Lateral Load Range					
To 100,000 lbs	++	+	++	++	++
100,000 - 1,000,000 lbs	+	++	+	++	o
Over 1,000,000 lbs	o	++	o	o	o

++ Functions well
+ Functions well, but not normally the best choice
o Does not function well

FIGURE 3-2 APPLICABILITY OF THE DIFFERENT OF ANCHORS ACCORDING TO DIFFERENT FACTORS, NAMELY SOIL AND LOADS [6].

Another factor will be the water depth. Due to costs, installation procedure and proprieties of the anchors, for very deep waters, more specific anchors might need to be used.

3.2. Catenary Mooring

In catenary mooring, the lines consist of free hanging catenaries where the restoring force is generated by the line's own submerged weight. Their behavior is well-known and uplift at anchor is usually designed not to occur. It is most suitable for applications in which device motions are permitted in several degrees of freedom.

Heavier chains can be used for the lower sections of the mooring. In calm conditions these sections will rest on the seabed and are only lifted if the mooring loads from energetic device motions are sufficiently high. It should be taken into account that the interaction of the chain with the seabed will have an impact in the marine species located in the vicinity of the mooring system. Additional floater and sinker components can also be used for example to provide a 'lazywave' mooring geometry, similar to umbilical cables, for increased horizontal compliance which may reduce the mooring loads [7].

The typical scope, which is the length of the mooring line in relation to the water depth is around 2.5 [7,9], which means somewhat large footprint areas are needed. This kind of system usually has low stiffness.

Slack mooring has the benefit of being in general very reliable in high waves, without great dimensioning requirements. Parts of the mooring, together with the moored body, move with the waves. The floating body is not fixed to one rigid position, but is prevented from drifting too far away. This in contrast with tight moorings, where the body is kept in a steady location, requiring very strong mooring lines in order to survive high waves.

Having survivability in mind, slack mooring seems then to be the best choice for wave energy converters [8]. The problem then may be if the energy absorption is significantly reduced because of the mooring damping. On the other hand, with tight mooring, absorbing energy might be easier, but there is the problem of dimensioning and survivability. It seems the best thing would be [8] if it were possible to have the floating converter tightly moored in smaller waves, and slack moored in storms and higher waves.

The analysis in [9] also supports that the most appropriate mooring is the catenary system, in line with previous analysis from other researchers ([10]-[12]). Albeit having its downsides, such as, greater length and weight, other factors, such as easy installation, lower cost, or the fact that it is less affected by the corrosion, tend to make it the best option in most cases.

3.3. Taut Mooring

In taut spread mooring the restoring force is related to axial stretching rather than geometric changes of the entire mooring system, as is the case of catenary chain. In this case, the mooring lines reach the anchoring point with an angle and therefore the anchor must resist both horizontal and vertical forces and hence drag embedded type anchors, per example, are not suitable. In the particular case of TLP (tension leg platform), the lines are perpendicular to the seabed.

Ropes constructed from polyester [13] have been successfully used for platforms located in deep and ultra-deep water locations. These have particular advantages compared to steel components, including low cost and mass and load-extension properties that can be used to reduce peak loadings. However, unlike steel components, synthetic materials have nonlinear load-extension properties that are time- dependent [14]. Changes to the compliance of these materials are possible over the life-time of the component and this should be considered in

the design. For example, after manufacture the initial loading of certain ropes results in permanent extension and this should be accounted from the start, in the design stage [2].

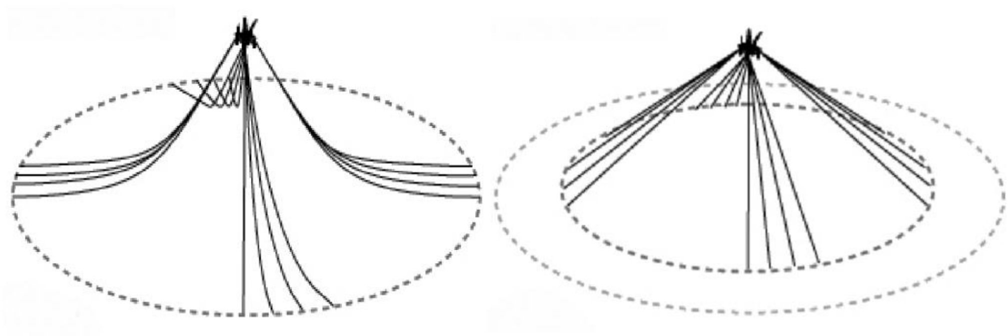


FIGURE 3-3 COMPARISON OF CATENARY AND TAUT MOORINGS SYSTEMS IN TERMS OF USED SEA BED AREA.

Compared to the catenary systems, smaller lengths are usually required (Figure 3-3), with a scope of around 1.5 [7,9] and, therefore, smaller footprint area (~ 40% less). However, these kind of systems have high stiffness, which might be a major drawback since it means they are less compliant with environmental loads.

Also, in taut cables, there is no tangential contact with the seabed, so mooring line tension may be increased significantly by little movement of the floating body and this steep increase of mooring tension may affect the safety of the mooring system. The possibility of large and potentially damaging peak or snaps loads occurring should be considered.

This also means that, because the displacement of a taut-moored device will be limited by the compliance of the mooring lines, unless a large mooring footprint is specified, the device can become submerged in large waves or at locations with high tidal ranges ([19]).

4. MOORING ANALYSIS

Three main aspects are borne in mind relevant when considering and comparing mooring design options:

- **Cost:** from the material but also from the installation
- **Footprint area:** occupied by the array and the mooring lines
- **Environmental impact:** in this case related to the mooring lines, anchors and installation procedures.

Also some consideration should be given to the risk of failure and collision associated to a specific design. This should look at the risk of collision in storm extreme conditions or in the

case of a mooring failure. Finally, outside of the mooring analysis, in the final design process the impact in terms of power performance of the overall array should be considered.

All of these different aspects are further analyzed next.

4.1. Mooring costs

An important aspect of mooring systems is the costs or fraction of cost compared to the total investment. The function and capital cost of the mooring system can impact the feasibility of certain choices and may exclude particular systems [2].

Moorings and foundations can represent a significant proportion of the overall capital cost of a project and must therefore be within the scope of the project total budget.

If for offshore oil and gas platforms the cost of the mooring system is around 2% of the total investment, for wave energy devices the cost is estimated to be higher, around 10% ([12], [15], [16]) or even higher at around 20-30% of the WEC total cost. It was estimated to be for example, up to 30% for the Seabreath device [17]. Another aspect to take into account is that the profits obtained by the oil and gas offshore industry are much greater than those expected from wave energy electricity production. Therefore, the mooring system has a marginal cost in offshore installations, but a significant cost for wave energy devices. Therefore, the optimization of the cost and performance of mooring systems can have a big impact on the effectiveness and attractiveness of this energy source.

The cost of the mooring lines can be treated as a linear function of their total combined length and the maximum tension they have to withstand. This approach defines the cost to be proportional to the total mass of the lines, because the required cross-sectional area will be proportional to the tensile strength. Some sources [9, 10] suggest the line cost to be based on a factor of $0.42 /m-kN which is multiplied by the total line length and the maximum steady-state line tension. This gives final line cost results that fall within the range of costs spanned by [18], [19], and [20].

A similar approach states that the cost of the mooring lines can be related directly to its weight [11]. The line cost is based on a factor of 0.265€/N which is then multiplied by the total weight of the mooring cable (which will in fact be similarly related to the weight per meter and the line length).

For anchors, the cost can be modelled as a linear function of the maximum load on the anchors. A fixed per-anchor installation cost can also be included. Anchor costs (and line angle criteria) examples are given in Figure 4-1.

Anchor Technology	Line Angle	$/anchor/kN (line tension)	$/anchor (installation)
drag embedment	0°-10°	100	5000
vertical load (VLA)	10°-45°	120	8000
suction pile	45°-90°	150	11000

FIGURE 4-1 ANCHOR COST MODEL [9].

The added inclusion of the installation costs and line purchase costs can be seen as nonlinearities in the cost function. In fact, the installation cost is expected to be a big percentage of the total cost since it will most likely require the use of very specific and expensive ships, rented by the day. The number of days required for the installation will depend on the weather conditions and on the complexity of the installation. This mobilization cost will largely depend on the available infrastructure in the area of the installation but as a guideline, it has been suggested [10] the value of 50,000 €/day. However, these costs are not considered in this initial evaluation since there values are highly variable and project dependent.

A Summary Report produced in August 2012 by the Technology Innovation Needs Assessment (TINA) [21] estimates possible reductions in levelised costs for wave and tidal mooring systems of up to 50% and 40% respectably by 2020 and 85% and 60% by 2050. The report also indicated estimations on the different percentages of the cost in terms of the different phases of the installation process. As can be seen in Figure 4-2, higher installation costs are expected for tidal devices but in opposition, smaller operation and maintenance costs.

	Cost of Energy (Wave, Tidal)
Foundations and moorings	10%, 10%
Installation	10%, 35%
O&M	25%, 15%

FIGURE 4-2 APPROXIMATE PERCENTAGE COSTS IN RELATION TO THE TOTAL COSTS, OF FOUNDATIONS AND MOORINGS IN RELATION TO INSTALLATION, OPERATIONS AND MAINTENANCE COSTS [21] FOR BOTH WAVE AND TIDAL INSTALLATIONS.

It is important to take into account that cost savings made through informed component choices may be counter-acted if their installation, maintenance and decommissioning of equipment is costly [7]. The risk of bottlenecks occurring can be reduced by adequate planning and reducing the reliance on costly procedures (e.g. dive teams).

Since a significant contribution of the total costs of a WEC comes from moorings, and within these, a high percentage comes from the installation of the cables, reducing the number of cables connected to the bottom and simplifying the installation could prove highly beneficial.

4.2. Footprint area

In terms of footprint area, it should be recollected that it is possible that many of the arrays will be placed in regions in proximity of shipping, fishing or other areas of sea use and, therefore, the 'footprint' of the mooring should be as much as possible constrained.

A densely packed WEC farm would also require short mooring lines providing a small footprint area to allow for the installation of multiple devices. This would be in contrast to typical offshore oil and gas installations where the footprint area is mostly not restricted, and only obstacles like pipelines, riser, etc. need to be considered, since they are not allowed to touch each other [3].

The requirement of a small footprint area and a small excursion for WECs could result in the use of heavy mooring lines within a simple catenary mooring arrangement. As a consequence, such mooring arrangements would become stiff, resulting in higher natural frequencies.

In terms of guidelines, the separation distance specified in the DNV-OS-E301 Position Mooring guidelines [4] between offshore accommodation units and fixed equipment is suitably large for that given application, but not applicable to MRE devices which are unmanned during operation. An alternative and more suitable approach suggested in the DNV-OS-J103 Design of Floating Wind Turbine Structures guideline [5] is to base the separation distance on the maximum possible surge or sway displacements during normal operation and in the case of a failure in one of the mooring line (assuming that the mooring system has built-in redundancy).

As stated before, the typical scope, i.e. length over water depth, for catenary mooring systems, is around 2.5, which means somewhat large footprint areas are needed. For taut moorings systems on the other hand, smaller lengths are usually required, with a scope of around 1.5, and, therefore, smaller footprint area (~ 40% less).

A wave energy device will normally have at least three mooring lines (if not weathervaning), equally 120º spaced around the device. If we consider an array, given that suitable distances between devices and between mooring lines, in order to avoid collision, are needed, this can represent the need for large sea bed areas per absorbed MWh of energy.

Considering just one device, for a given water depth H, and a given scope Scp this would mean a total line length of $3HS_{cp}$. If one considers for the case of a slack line, that the distance to anchor D is about $D = (S_{cp} - 1)H$ this means a total circular footprint area for one device of

$$A = \pi[(\mathrm{Scp} - 1)\mathrm{H}]^2.$$

Although not all of this area will be occupied by the device, with its motion, also the mooring lines will move occupying an area around the one in the static case (see FIG??). If one thinks of the need to define clearance distances from these for safety reasons, this total area can approximately be considered.

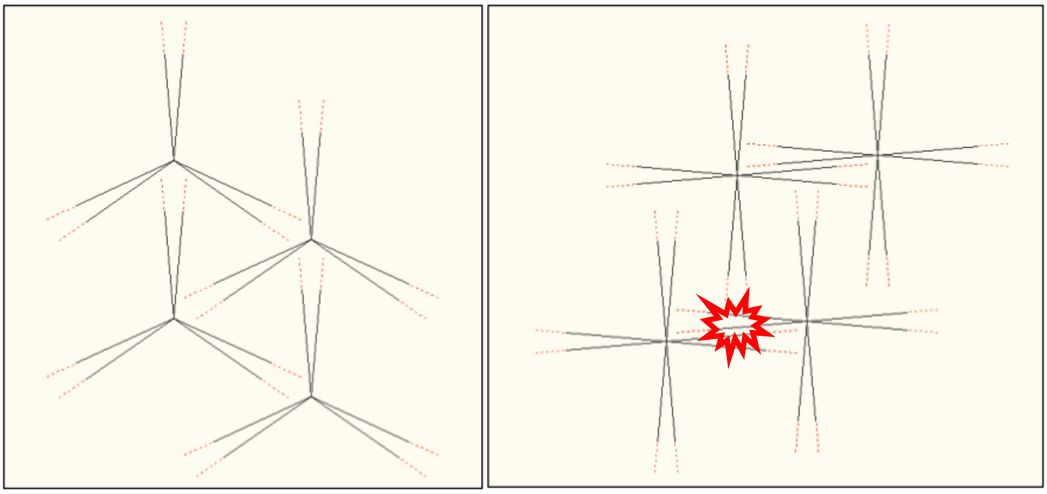


FIGURE 4-3 MOORINGS ARRAGMENTS IN ARRRAYS.

For the case of an array it is more difficult to quantify, as some of this areas can overlap, as long there are no risk of collision between mooring lines. Even so, if one considers a 10% overlap on the circular area, for the case of an array of N devices, this will represent a total area of

$$A = 0.9 \times N \times \pi[(\mathrm{Scp} - 1)\mathrm{H}]^2.$$

This total amount of seabed area can significantly be reduced if the number of bottom moorings are reduced and inter-moorings between devices are used instead. It should be noted that array hydrodynamics optimization routines, in general, do not consider the device moorings and therefore, the resulting optimization layouts may be difficult, if not impossible, to implement due to moorings positioning or collision (Figure 4-3). Inter-connections would allow to have the devices closer together (compact aggregates) and permit to increase range of feasible optimization layouts.

4.3. Environmental impact

The presence of wave energy devices causes impacts on the marine environment, which can be physical, chemical and biological. For example, the pile driving or any seabed soil drilling of a foundation activity is a source of noise and sediment moving, which will impact the fauna living in the area.

This disturbance is related to a direct physical effect on the substrata (e.g. sediment penetration, removal, abrasion, disturbance or recovery with concrete mattresses

installations, etc.) leading to an alteration of seabed habitats. Habitat removal affects infauna (organism living within the sediment) for mobile sediment (usually sands) and epifauna (organism attached to coarse sediments and rock) for coarser sediments like gravels, pebbles and cobbles [26].

Footprint issues associated with anchorages, moorings and foundations are related to sediment disturbance and therefore habitat alteration. The environmental impact of foundations and anchors is directly related to the area of seabed contact under the footprint of the foundation structure. But it is furthermore acknowledged that the area covered by the over shallowing foundation structure itself can also alter the seabed. Despite no direct contact (e. g. seabed located beneath the lattice of a steel jacket but not under one of the footings), the presence of an artificial structure modifies surrounding water and sediment flows, which in turn may alter the sediment granulometry and therefore alter seabed communities [26].

Besides, although not fully well documented, the risk of collision between ships and marine mammals can exist although it is unlikey [24]. Also, the installation operations enhance the number of vessels and marine infrastructures that usually contains oil, lubricants and other chemical substances.

In terms of environmental impact, the main aspects to consider are the following:

- Minimization of disturbed/covered seabed area as well as depth of seabed penetration to minimize impact on the sea bed.
- Reduction of mooring lines to avoid wildlife entanglement / entrapment / collision.
- Avoidance of hazard substances in mooring structure materials (e.g. antifouling paints, concrete leaching).
- Optimization of moorings maintenance activities to minimize vessels use (avoidance of gas emissions and noise disturbance).

This indicates that there can be a highly beneficial gain in terms of environmental impact in reducing the number of bottom mooring lines, both in terms of sea bed and biological impact but also in terms of pollution related aspects.

Although a quantification of this impact is hard to measure, a connection can be made to the number of lines and number of anchors and also the total sea bed footprint area.

$$\boldsymbol{Env.Impct.} = \boldsymbol{EI_{lines}\, n_{lines}} + \boldsymbol{EI_{anchor}\, n_{anchors}} + \boldsymbol{EI_{footprint}\, A}$$

EIlines, EIanchors and EIfootprint are factors that could be defined in a way to assess the environmental impact of each type. The higher the factor, the higher the impact of that given characteristic.

4.4. Power performance impact

The best disposition of the devices within the array is still an open question, since several different factors influence this, including the interference between devices but also the mooring system and the electrical cables connections.

If the devices are too closely placed, some hydrodynamic interference between them can be expected to exist. The simple presence of a body, even if stationary, changes the wave field around it by diffraction. Besides that, the oscillatory motions of the bodies produce radiated waves which will also interfere with the wave field. The two effects, diffraction and radiation, will perturb the wave field of the neighboring bodies, originating complex phenomena of mutual (constructive or destructive) interference.

A first initial evaluation of the performance of an array of identical WECs can be obtained in the frequency domain by considering optimal conditions. The gain factor q can be defined as

$$\boldsymbol{q = \frac{P_{array,max}}{N_d P_{max}}}$$

where Parray;max is the maximum time-averaged total power in optimal conditions, absorbed by Nd devices in the array, and Pmax is the maximum power absorbed by a single device. The gain factor q is a measure of the effectiveness of the array, indicating if and when it may be more advantageous, from a total absorbed power point-of-view, to have the devices placed in array. This factor was initially designed to evaluate impact in terms of array physical geometry disposition but can also be considered for the comparison of the different arrays with inter-connections.

In Ricci (2012) [22], results, based on a frequency domain analysis, and assuming optimal values for the PTO damping coefficients, indicate that “an array does not necessarily impair the performance of the individual devices, and may significantly improve it if the array geometry is suitably designed for the frequency of interest".

McIver (1994) [23] has suggested that a possible improvement to maximize the energy absorption could be achieved with unequal spacing between the absorbers. Concerning arrays of equally spaced absorbers, however, simulations with random irregular waves seem to indicate that the device performance becomes practically independent of the spacing, if it is larger than about four radii [22].

4.5. Risk of failure and collision

In terms of risk of failure and collision, this are a somewhat more subjective and not as easily quantifiable, parameters. This risk of failure and collision is a way of trying to assess the impact of line breaking or the risk of collision, within the array. This relates to the physical disposition and attachment of the devices. What can be expected the behavior to be, if one of

the mooring line, attached to the bottom, or inter-connecting devices, breaks. Also, by looking at the motion restriction imposed to the devices, what is the risk of collision between devices.

For the case of rigid connections between devices in fact, there is no actual risk of collision between devices, since a break in the connection should be seen as an actual structural failure, and therefore the assessment should rather be on the structural demands that are placed in the connections and structure and in the bottom mooring lines securing the overall structure.

5. RIGID MOORING CONFIGURATIONS

5.1. Existing rigid mooring concepts

The concept of rigid connections between devices is not entirely new. Several technologies have already been suggested that bring the idea of shared rigid connections between devices. Some of these devices have never left the design stage others have been tested at small scale in wave tanks and some have been tested at almost full scale in open sea. Some examples are briefly presented next.

Fo3

The Fo3, developed by Norwegian entrepreneur Fred Olsen, consists of a generic floating wave energy device, which basic concept consists of several axisymmetric point absorbers oscillating in respect to the same floating platform under which they are placed.

In its concept, it consists of several (12 or 21) heaving floaters attached to a 36 by 36-meter rig and by means of a hydraulic system, the vertical motion is converted into a rotational movement that drives the hydraulic motor. This motor in turn powers the generator that is expected to produce up to 2,5MW.

In this case the rigid connection consists of the shared floating platform.

FIGURE 5-1 - FO3 WAVE ENERGY DEVICE.

MightyWhale

The Mighty Whale, which was launched in July 1998 by the Japan Marine Science and Technology Center, is a steel floating structure, 50 m long and 30 m wide and which carried three air turbine generator units. Each air chamber is connected to a Wells air turbine that drives an electric generator. It was anchored to the bottom of the sea with six mooring lines; four lines on the seaward side and two on the lee side.

In this case the rigid connection consists of the shared floating platform where the three oscillating air chambers reside.

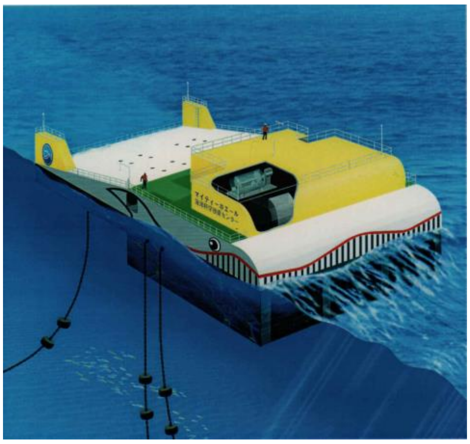


FIGURE 5-2 – MIGHTY WHALE DEVICE.

Oceanlinx

The Australian company Oceanlinx deployed in 2010, off Port Kembla, Australia, a one third scale grid connected model of their most recent OWC device, the Mk3, which (like the Kaimei three decades earlier) is a floating platform with several OWC chambers (in this case eight chambers) each with an air turbine. During the tests only two turbines (of different types) were installed. The tests took place off Port Kembla, Australia, in 2010, with two grid connected turbine generator sets of different types.

The structures of the floating OWC prototypes briefly described above are slack-moored to the sea bed and so are largely free to oscillate (which may enhance the wave energy absorption if the device is properly designed for that) [25].

In this case the rigid connection consists of the shared floating platform where the air chamber resides.

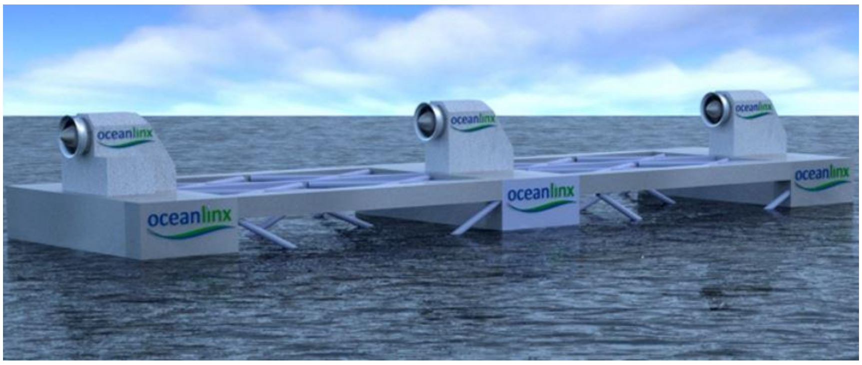


FIGURE 5-3 OCEANLINX DEVICE.

WaveStar

The Wavestar machine, developed by Wave Star ApS, draws energy from wave power with floaters on movable arms that rise and fall with the up and down heave motion of waves. Each individual float is attached by an arm to a shared platform that stands on legs secured to the sea floor. The motion of the floats is transferred through hydraulics into rotation of a generator.

Most noticeably, being able to raise the entire installation along its pillars, this system has a high endurance for rough storm conditions. So far, this method has not yet been deployed at full scale. A 1:2 scaled installation has been built at Hanstholm with a nominal power of 600 kW. Production is thought to be scaleable up to 6. Another major benefit of these types of exploitation is the minimal contact with water, placing any delicate machinery and electrics out of reach of most corrosion or physical forcing of the waves (with the exception of green water loads).

In this case the rigid connection consists of the shared seabed fixed platform.

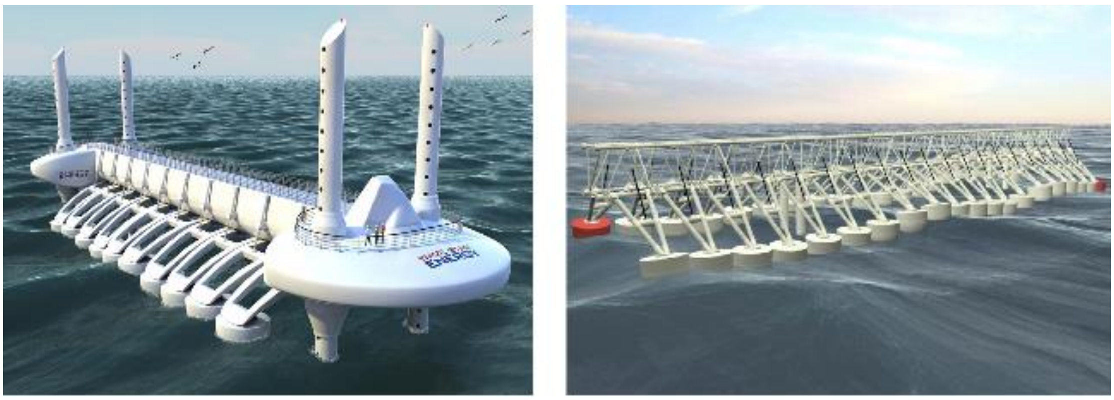


FIGURE 5-4 - WAVE STAR DEVICE.

Salter's Duck

The nodding Duck, created by Stephen Salter, in the 1970s and early 1980s, consists of a cam-like floater oscillating in pitch. Although the later version proposed a solo duck, the first versions consisted of a string of Ducks mounted on a long spine aligned with the wave crest direction, with a hydraulic-electric PTO system. In this case the rigid connection consists of long spine bearing system.

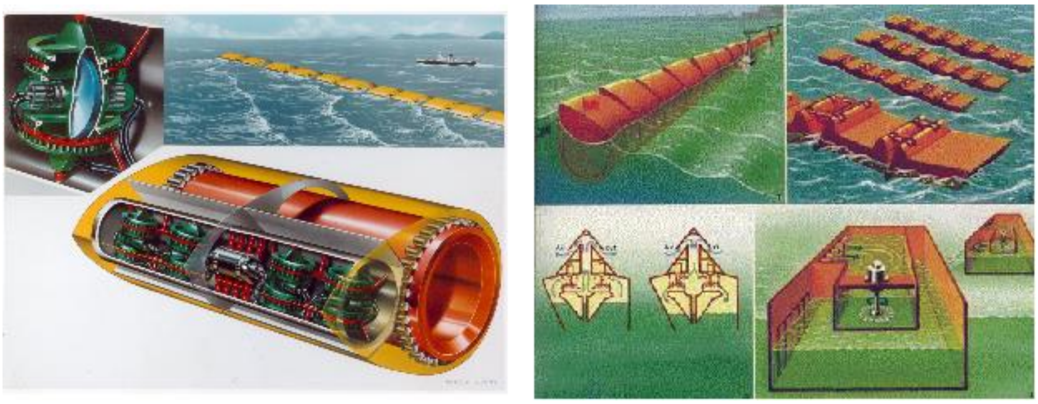


FIGURE 5-5 - SALTER'S DUCK CONCEPT.

Pelamis

The Pelamis, developed in the UK, is a snake-like slack-moored articulated structure composed of four cylindrical sections linked by hinged joints, aligned with the wave direction. The wave- induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors driving three electrical generators. In this case the rigid connection consists of a system of hinged joints.

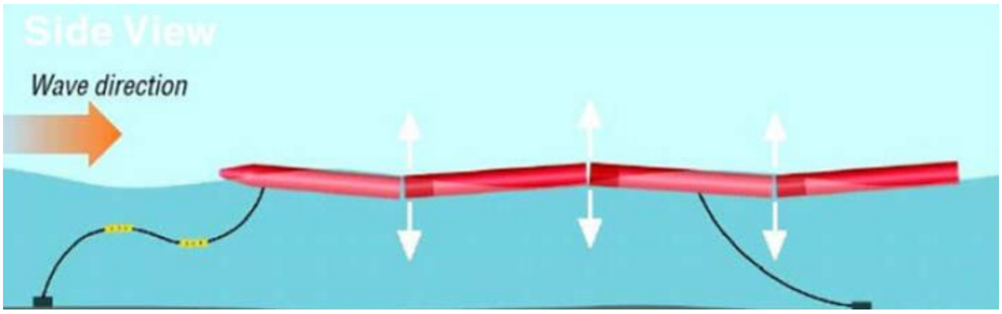


FIGURE 5-6 - PELAMIS WAVE ENERGY DEVICE CONCEPT.

SeaWEED

Each SeaWEED unit consists of four modules connected by truss structures. The four module array includes a non-energy producing nose module in the front, followed by two energy

producing modules, with another non-energy producing module at the rear. The movement of the modules rising and falling over passing ocean waves drives 4 on-board double acting hydraulic rams that feed electrical generators.

The SeaWEED is designed to be anchored to the seafloor by a mooring of a three-point catenary slack mooring system at the front of the device and a single leg slack mooring system at the rear.

In this case the rigid connection consists of a system of truss structures.

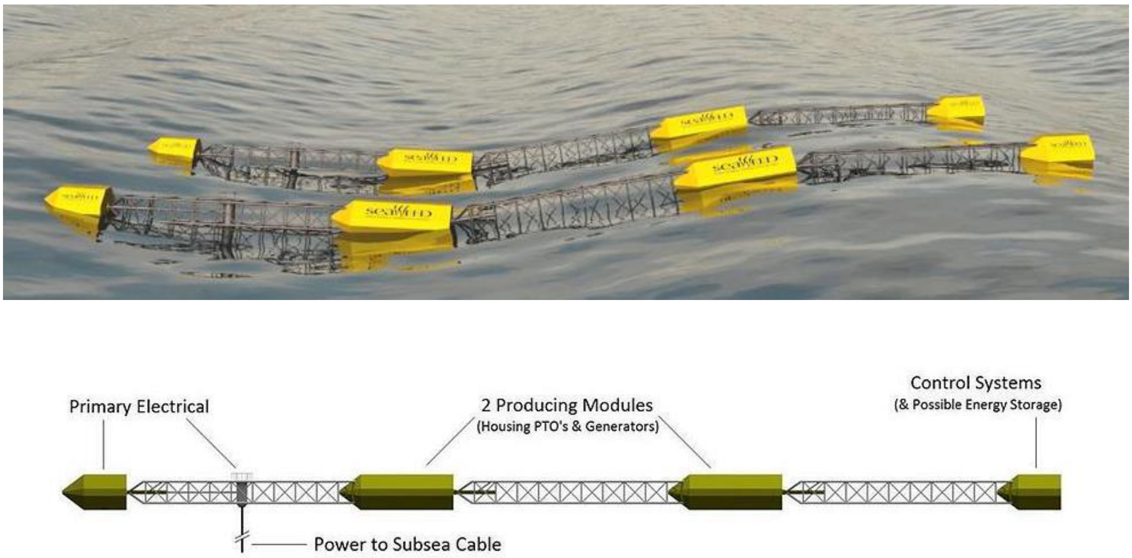


FIGURE 5-7 - SEAWEED WAVE ENERGY DEVICE.

Langlee E1 WEC

The Langlee E1 device is a semi-submersible floating installation which is designed to be floating at the water surface while most of the unit is under water. Four mooring lines keep the device in position. Two water wings swing back and forth with the waves and are directly connected to generators.

This device consists of two hinged flaps attached to the same floating structure. Via PTO systems, the relative motion between each flap and the structure is converted into useful energy.

In this case the rigid connection consists of shared floating platform and the respective bearing system associated to each device.

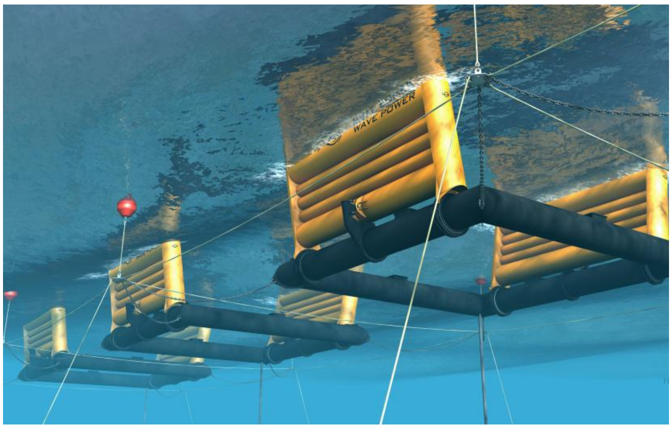


FIGURE 5-8 - LANGLEE WAVE ENERGY DEVICE.

WaveNET

WaveNET arrays are made up of interconnected SQUID units which react to the motion of the waves to generate electricity. Each SQUID unit comprises a hollow central riser tube connected to 3 buoyancy floats by linking arms. The connections between each of these components is made of 6 identical fully articulated pumping modules. In this case the rigid connection consists of a system of linking arms with a bearing system. This system works in shallow water and is placed directly on the seabed.

FIGURE 5-9 – WAVENET ENERGY DEVICE CONCEPT.

Manchester Bobber

Similar to the FO3 concept, the Manchester Bobber consists of a rig with semi-submerged floats which move vertically with the passing of waves operating a pulley which spins a fly-wheel connected to an induction electricity generator. The difference to the FO3 concept lies in the structure that is lying on the seabed though a single shaft. In this case the rigid connection consists of the seabed standing structure.

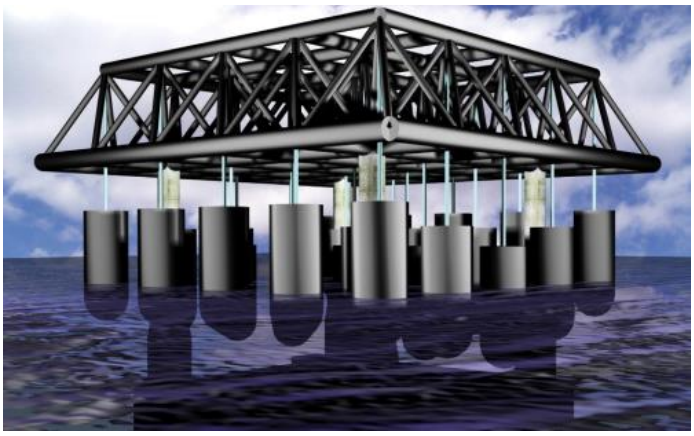
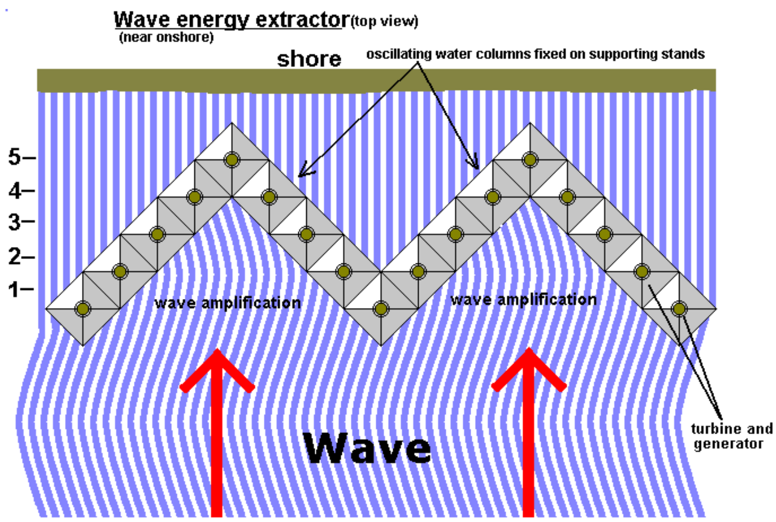


FIGURE 5-10 - MANCHESTER BOBBER CONCEPT.

Wave Energy Extractor

The system consists of a series of oscillating water columns, pyramid shaped, which are strongly inter-linked in a shape of a saw tooth wave (90º angle between the corners). Each of the oscillating water columns has its own air turbine and generator on the top. The system is fixed on a supporting stand that is constructed from the sea bottom.

The arrangement of the oscillating water columns provides a wave amplification effect and so it can utilize the maximum wave energy. Since the cancellation of upward and downward forces of the waves are cancelled by the adjacent water columns, there is no need for the huge mass to the oscillating columns like ordinary oscillating water columns. The only requirements are good materials and the interconnections between the oscillating water columns. In this case the rigid connection consists of the physical interlink between chambers.



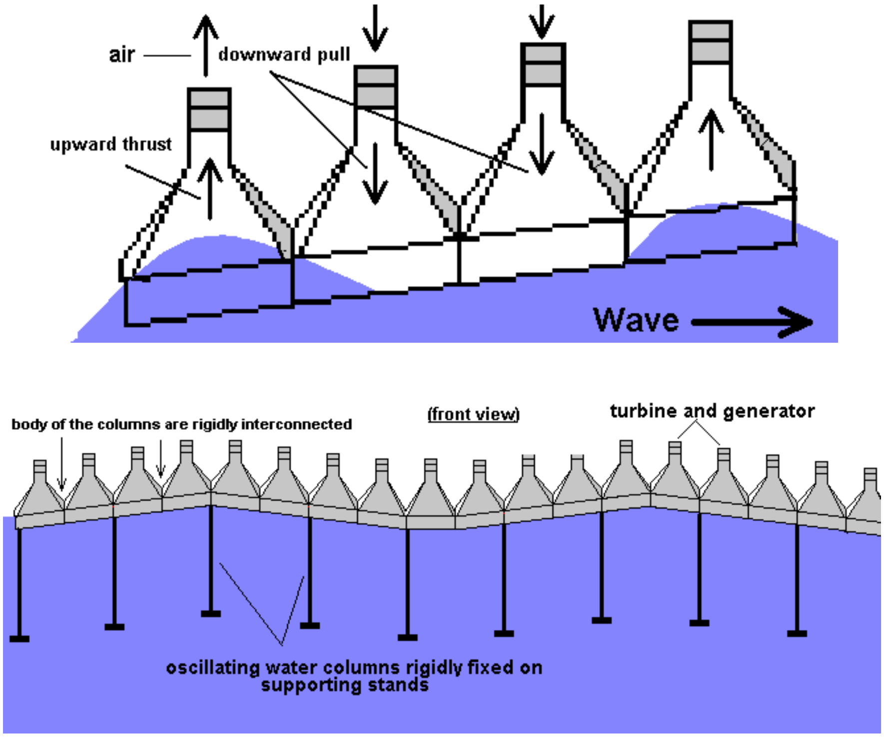
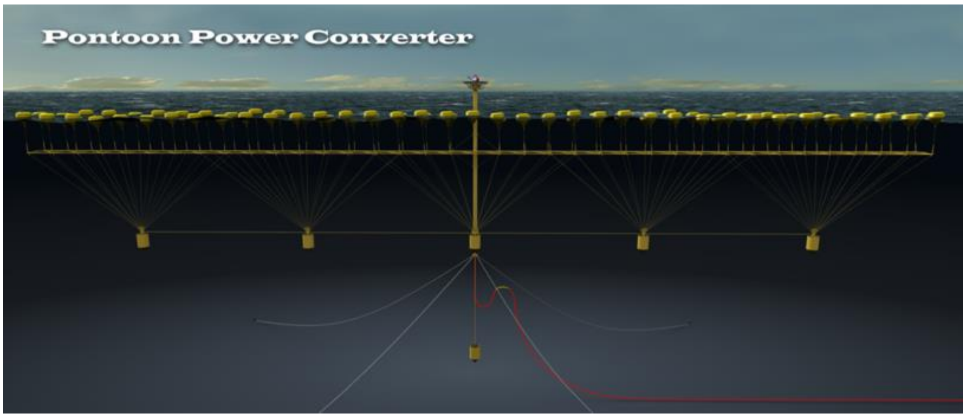


FIGURE 5-11 - WAVE ENERGY EXTRACTOR CONCEPT.

Pontoon Power

The Pontoon Power Converter, is a multibody floating WEC, based on working pontoons, with hydraulic pumping cylinders, and hydroelectric turbines and a generator mounted on a patent pending ballasting and load-bearing structure. The total buoyancy force from the buoys is balanced by net gravity forces of the bridge and the ballast baskets. The platform is thought to be attached to the seabed with slack moorings.

In this case the rigid connection consists of the physical interlink between chambers.



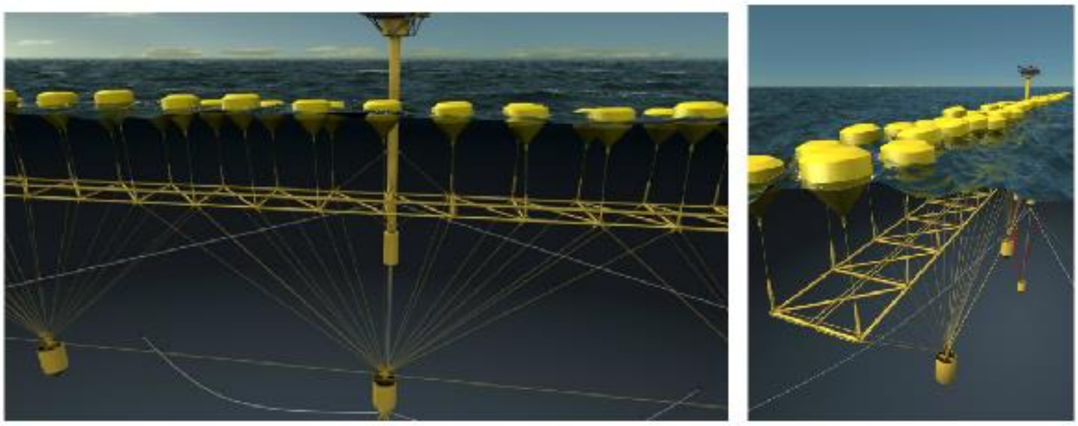


FIGURE 5-12 - PONTOON POWER DEVICE CONCEPT.

5.2. Rigid Connections

Different existing wave energy concepts and technologies have been presented which have in common either sharing a connection to a common infrastructure or having some sort of rigid connection between different devices, either by the form of a system of bearings or by a stiff metal rod link.

A common shared structure system is proposed for the Fo3, Might Whale, Wave Star, OceanLinx, Manchester Boober, Wave Energy Extractor and Pontoon Power concepts.

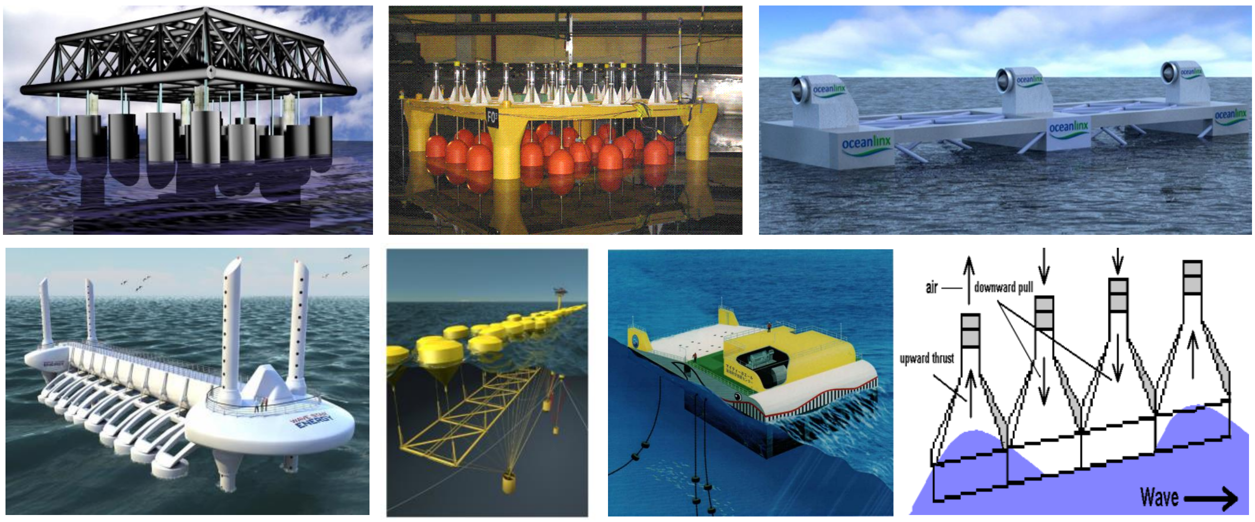


FIGURE 5-13 WAVE ENERGY CONCEPTS WHERE SEVERAL DEVICES SHARE A CONNECTION TO A COMMON STRUCTURE OR ARE PHYSICALLY CONNECTED TO EACH OTHER.

Bearing systems are proposed for the Pelamis, SeaWeed, OceaNET, Langlee E1 and Salter duck concepts.

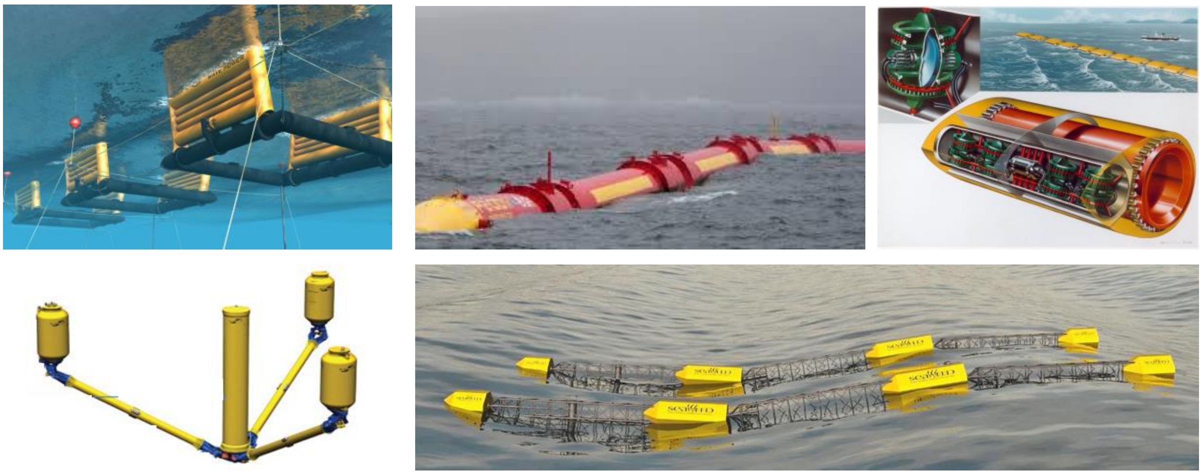


FIGURE 5-14 WAVE ENERGY DEVICES WHERE SEVERAL STRUCTURES OR DEVICES ARE CONNECTED TO A SYSTEM OF RIGID CONNECTIONS.

These systems however are prone to many issues in their most weak point, the bearing system. These systems are also hard to implement experimentally and therefore are decided not to be the ones proposed for further analysis

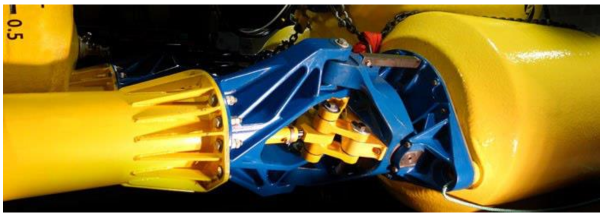
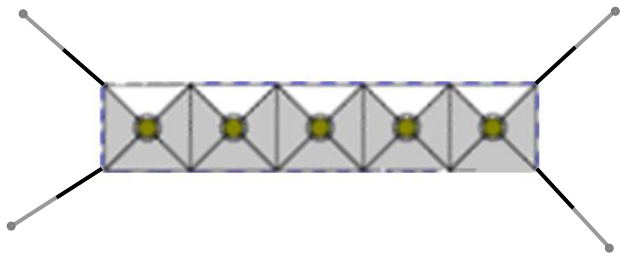


FIGURE 5-15 BEARING SYSTEM IN THE WAVENET CONCEPT.

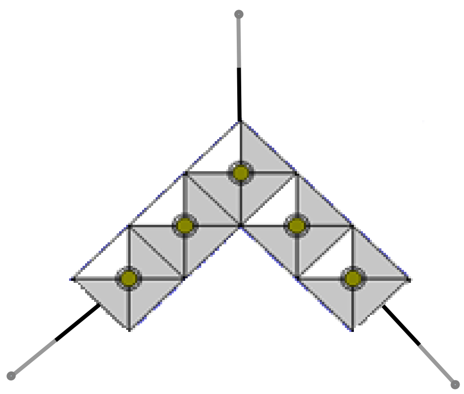
From the different possible concepts, the ones that seem more promising are the ones where oscillating air turbines share a common structure, as is the case of the Mighty Whale, Oceanlinx and Wave Energy Extractor or a concept as the Pontoon Power where many floating bodies share a common structure. These concepts are possible to install in offshore deep water locations and are scalable to any given number of devices. Concepts like the Fo3, Manchester Bobber or the Wave Star are similar but the fact that the reference structure requires to have legs standing on the bottom mean that they are suitable only for near shore locations besides of shadowing effects that can come from the standing legs structures affecting the performance of some of the devices.

Having these considerations in mind, the following configurations are proposed as base cases for further analysis, where a group of five devices is either physically attached to other(s) [A-C] or is attached by means of a physical steel rod [D-F]:

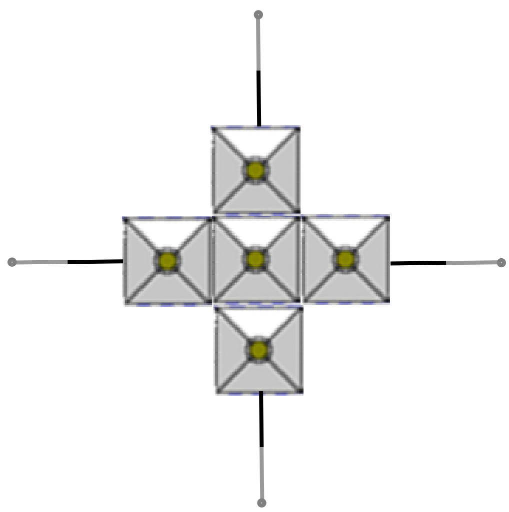
(A)



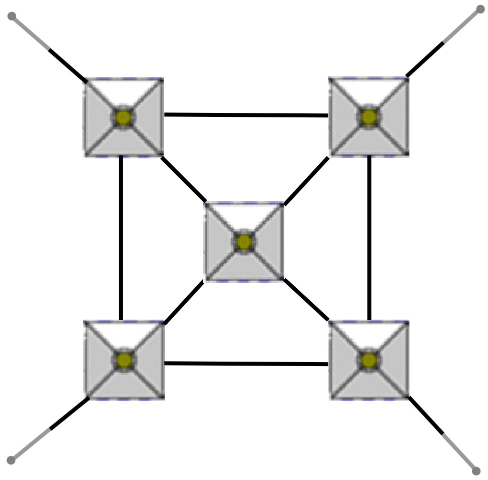
(B)



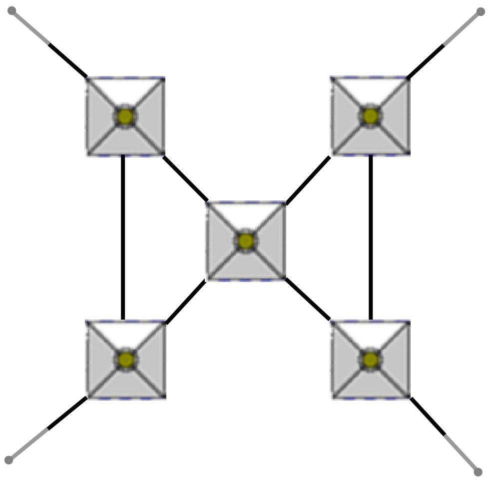
(C)



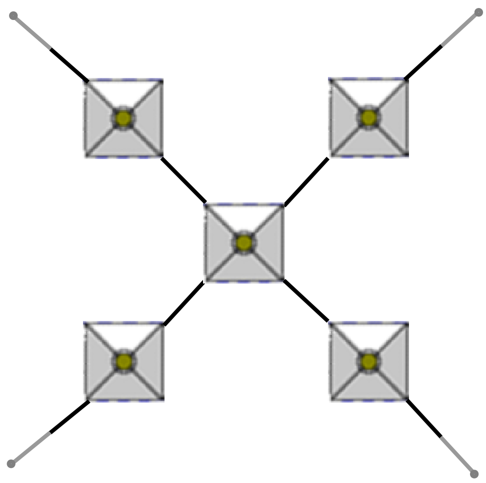
(D)



(E)



(F)



The configurations are shown in plain view (from above), depicting the bottom mooring line connection (in two colors) or the physical connection between devices (if they exist).

The first three set of configurations (A-C) are for devices physically attached to each other. Configuration A is a linear set of devices, configuration B is a v-shape array and configuration C is a more compact array set. The three remaining configurations (D-F) are for a set of five devices connected through iron rod links.

Given the decision to study five devices different arrangements are possible. The cross arrangement (D-F) was chosen because it is the one that is more compact, allows for different degrees of connectivity between devices with the use of different number of links and is mostly symmetric and independent on the wave direction.

6. CONFIGURATIONS ANALYSIS

Five devices were decided to be considered for testing. The criteria for this is to have a number of devices that would fit in the wave tank at a reasonable scale while at the same time to have a sufficient number of devices that would be interesting and scalable for a large array.

The different configuration considered are compared considering the relevant evaluation parameters mentioned before: cost, environmental impact and performance and risk indicators and the ones that seem to be more promising are advised for further analysis and testing.

For the cost, the total bottom mooring line length and number of anchors are considered together with the length or total expected steel weight material. In terms of environmental impact, the relevant parameters will be the number of anchors, number of mooring lines and total occupied sea bed area. The risk of collision is assessed by considering the expected behavior in case one of the bottom moorings fails or what is considered to be the more material load demanding situations. As for performance, this parameter is at this point unfeasible to measure or predict and is suggest to be considered in further analyses.

The following diagram (Figure 6-1) summarizes the way the configurations are considered and compared.

ASSUMPTIONS
device radius [m] or scale factor []
water depth [m]
scope factor [-]
distance between devices [m]
anchor type/weight [N]
bottom mooring line type [chain/steel/fibre] and weight [N/m]
rigid connections or shared structure weight [N/m]

EVALUATION FACTORS
Number of bottom moorings [-]
Number of rigid connections [-]
Number of anchors [-]
Total bottom mooring line length [m]
Total rigid connection weight [N]

EVALUATION PARAMETERS
Total Mooring Cost [€]
Power Production ratio [-]
Total occupied sea bed area [m^2]
Survivability and risk of collision if link breaks

FIGURE 6-1 EVALUATION PROCESS

A set of initial assumptions or parameters is required to make the evaluation. These are assumed to be general enough not to restrict the applicability of the assessment. In this case the following assumptions, at full-scale, are considered:

TABLE 1 - ASSUMPTION TABLE

ASSUMPTIONS	1:1
r -device radius [m]	6
H - water depth [m]	60
Scp - scope factor [-]	2.5

D – distance between center of device and anchor [m]	(Scp -1)H
L - inter-distance factor [radii]	4
anchor type and weight [N]	dead-weight with 40t
bottom mooring line and section size [mm]	chain, 50mm studlink

Representing that five 6m radius devices are considered, 4 radii apart from each other, with rigid connections steel tubes of 5mm radius, anchored to the bottom in a 60m water depth location with 50mm link chains with 150m length.

The inter-distance factor between devices is defined as 4 radii, leaving a full diameter apart between the centers of the devices. This is in accordance to what is presented in [22], where it is suggested that for distances bigger than 4radii the hydrodynamic interference is mostly negligible.

In terms of mooring, a studded chain link with 50mm has a weight in water of around 475 N/m and a 40t deadweight anchor is assumed to be able to uphold at least a 500N load.

Some assumptions on cost and environmental impact are also necessary to perform the comparison evaluation. These were roughly assessed just to be used as indicators, but since a percentage comparison in regards to the reference case of individually moored devices is made, these assumptions should not be considered to affect the calculations much. The following values were assumed for cost ([11], [21]):

TABLE 2 - MOORING COSTS

MOORING COSTs	
Chain line [€/m]	125,88
Deadweight anchor [€/ton]	500
Rigid steel link [€/m]	50

And these for environmental impact:

TABLE 3 - ENVIRONMENTAL IMPACT FACTORS

IMPACT FACTORS	
EIlines	2
EIanchors	3
EIfootprint	1

indicating an expected higher impact coming from the number of anchors, since they represent a higher disturbance (disturbance of the sea bed ecosystem, drilling of layers, etc.) to the sea bed, followed by the number of mooring lines, given the impact in terms of their installation, impact on the seabed with lines motion and risk of collision with fauna. Finally, a smaller impact factor is given to the total occupied are

Considering this initial assumption parameters, it is possible to assess the defined evaluation factors for the specified configurations. This is summarized in following tables, where $L^* = L/\sqrt{2}$, $D^* = D/\sqrt{2}$ and $r^* = r/\sqrt{2}$:

TABLE 4 - PARAMETER TABLE

CONFIGURATION CHARACTERISTICS	0	A	B	C	D	E	F
# of bottom moorings	15	4	3	4	4	4	4
# of rigid connections	-	-	-	-	8	6	4
# of anchors	15	4	3	4	4	4	4
CONFIGURATION DIMENSIONS	**0**	**A**	**B**	**C**	**D**	**E**	**F**
lb - Bottom mooring length [m]	15 Scp H	4 Scp H	3 Scp H	4 Scp H	4 Scp H	4 Scp H	4 Scp H
lR - Rigid connection length [m]	-	-	-	-	$8\,L\,r$	$6\,L\,r$	$4\,L$ r
A - Sea bed area [m^2]	$4[2D^* + 2r]^2$	$4[D^* + 5r] \times [D^* + r]$	$2[D^* + 3r^*] \times [(1 + \sqrt{2})D^* + 4r^*]$	$4[D + 3r]^2$	$4[D^* + 3r + L^*]^2$	$4[D^* + 3r + L^*]^2$	$4[D^* + 3r + L^*]^2$
CONFIGURATION DIMENSIONS	**0**	**A**	**B**	**C**	**D**	**E**	**F**
Mooring line Cost [€]	15 Scp H Cline	4 Scp H Cline	3 Scp H Cline	4 Scp H Cline	4 Scp H Cline	4 Scp H Cline	4 Scp H Cline
Anchors Cost [€]	15 Canchor	4 Canchor	3 Canchor	4 Canchor	4 Canchor	4 Canchor	4 Canchor
Rigid link cost [€]	-	-	-	-	$8\,L\,r\,C_{link}$	$6\,L\,r\,C_{link}$	$4\,L\,r\,C_{link}$

The previous evaluation was made with generic variables to be as generic as possible. The case "0" represents the reference case of individual moored devices. Next, by applying the assumed values, these evaluation factors allow to assess the final evaluation parameters in terms of percentage comparison to the individually moored case:

Table 5 - Evaluation comparison table

EVALUATION PARAMETERS	A	B	C	D	E	F
Line Cost [%]	26,67%	20,00%	26,67%	26,67%	26,67%	26,67%
Anchor Cost [%]	26,67%	20,00%	26,67%	26,67%	26,67%	26,67%
Total Mooring Cost [%]	26,67%	20,00%	26,67%	26,69%	26,68%	26,68%
Sea bed area [%]	33,62%	35,90%	60,13%	50,13%	50,13%	50,13%
Environmental Impact [%]	33,61%	35,89%	60,10%	50,10%	50,10%	50,10%
Risk Assessment [%]	2	3	1	1	2	3

It should be noted that the total mooring cost should also reflect the installation costs, which, by reducing the number of bottom-mooring lines, is expected to be further reduce the less bottom-moorings there are.

7. EXPERIMENTAL CONSIDERATIONS

7.1. Model Scale Considerations

The experiments to be carried out are limited by the capabilities and dimension limitations of the wave tank where they are to be carried out. In this case, Plymouth wave basin dimensions are 15.5x35x3 m.

This imposes a limit on the maximum device scale factor to be considered. The wave tank dimensions have to be sufficient for the placement of the five devices together with their moorings. Given that the reference case of individually moored devices is also to beconsidered and tested, which is the one expected that occupies the maximum footprint area, the maximum scale that can be carried out is that of 1:30. This scale is considered to be sufficient for the testing of the normal operational conditions and of extreme wave events. At this scale the following input parameters are required:

TABLE 6 - ASSUMPTION TABLE

ASSUMPTIONS	1:1	1:30
r -device radius [m]	6	0.2
H - water depth [m]	60	2
Scp - scope factor [-]	2.5	2.5
D – distance between center of device and anchor [m]	(Scp -1)H	(Scp -1)H
L - inter-distance factor [radii]	4	4
anchor type and weight [N]	dead-weight with 40t	dead-weight with 1,5kg
bottom mooring line and section size [mm]	chain, 50mm link	chain, 0,3mm link

Representing that five 0.2m radius devices are considered, 4 radii or 0,8m apart from each other, with rigid connections steel tubes of 0.8mm radius, anchored to the bottom in a 2m water depth with 0,3mm link chains with 5m length. The chain is scaled in terms of weight and not directly in terms of link size.

7.2. Data Acquisition Considerations

As stated before, the proposed outcome is a report on analysis of different potential configurations rigidly inter-moored devices (compact aggregates) in what concerns loads, motions, risk of collision and performance.

Therefore, the necessary data to acquire for comparison are the mooring loads, the motion of the devices or structure, an assessment on power performance of each device and an assessment in terms of risk.

For the data acquisition of the mooring loads, loads cells are to be attached to each of the connecting bottom mooring line to assess the demands on the fairlead. These load cells need to be chosen and design such that are capable to measure the expected loads. It should be remmebered that the configurations are to be tested in extreme wave conditions survivability conditions were loads can become quite high.

For the acquisition on power, pressure gauges are to be placed on top of the opening to measure the air flow and in this way access the performance if air turbine were to be installed.

In terms of motion, it is expected that a system of video tracking is installed in order to register the motion of the devices or structure, for later analysis and evaluation in terms of motion in all six degrees-of-freedom.

Finally, in terms of risk assessment, this is to be done at a later stage, by looking at each configuration and to make an assessment of the impact of line breaking or the risk of collision given the measured device motions.

7.3. Manufacturing Limitations

The available budget for the performance of the test needs to be sufficient for the construction of the devices and rigid connection structures together with the necessary data acquisition instruments. This is considered to be the only restriction in terms of manufacturing since the device model to be used and constructed is chosen in such a way to be easily implemented.

The manufacturing will involve the construction of five equal metal structures connected to a system of rigid connections with an opening on the top to model the PTO. To these structures bottom mooring chain lines need to be attached at specific given points depending on the configuration to keep the structures in places.

Each device will be modular and attachable in it's different sides in order to possibilitate testing the different configurations. One consideration to have is since the 5 devices will be physically connected through a rigid connection, there will be a need to consider how to place them in the wave tank since once attached they will consist of a rather large structure.

7.4. Device tested

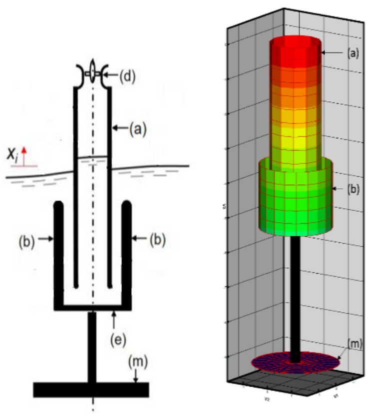


FIGURE 7-1 COAXIAL DUCTED OWC

The devices to be tested are considered to be OWC devices. The concept of the Coaxial ducted OWC is suggested to be used (Figure 7-1). This device is formed by two concentric tubes (a) and (b). Tube (a) is partially submerged below sea level and open to the atmosphere. Tube (b) is totally submerged and closed at bottom by surface (e). The tubes are connected to an anti-heave plate (m) and the PTO (d) is an air turbine.

The following dimensions at real scale and 1:30 scale are considered:

TABLE 7 - DEVICE DIMENSIONS

DEVICE DIMENSIONS	1:1	1:30
Tube (a) diameter [m]	1.75	0.06
Tube (b) diameter [m]	2.5	0.08
Anti-heave plate (m) diameter [m]	3	0.1
Total draft [m]	9.25	0.308

8. ARRAY CONFIGURATION CONSIDERED

8.1. Proposed configurations for further analysis

Given the previous evaluation of the different configurations, in terms of estimation on mooring cost, required seabed area and environmental impact an risk of collision it is proposed that the configuration which seem to present higher benefits and lower impacts or risks are further analyzed and tested, namely configurations A, C and E.

Configuration B although it represents a decrease in the number of bottom mooring lines, it does not reduce the footprint areas significantly when compared to Configuration A and C. It is also not easily scalable for a higher number of devices and is not insensitive to the wave direction. Configuration A is very easily scalable for a higher number of devices and configuration C can be interesting since it largely reduces the required footprint area. It should however be careful analyzed in terms of power performance since the devices are so closely placed together.

Between the three remaining configurations D-F, configuration D is the more robust; it does not represent a high decrease in the mooring cost. Configuration F has no redundancy in terms of inter-links and therefore was a higher risk of failure. Configuration E represents a good compromise between these two configurations.

8.2. Concluding remarks

In this deliverable, a preliminary analysis on the benefits of having rigid inter-connections between devices, in order to decrease the mooring costs and eventually also the environmental impacts associated to them, is presented.

Four main parameters associated to moorings are identified and suggested as evaluation factors for comparison between different mooring configurations. These are cost, footprint area, environmental impact and risk of collision or failure. Impact on performance is of course also a main aspect to take into consideration, but this was not possible in this initial analysis, but will be so in the upcoming work.

Six different configurations are proposed and analyzed in terms of these parameters for the case of an array of five devices. These are compared with the reference case of individually moored devices. From these six configurations, three are proposed for further analysis.

Numerical and also experimental analysis is to be carried out, which hopefully will validate each other and this initial analysis and estimation on the benefits of rigidly inter-connecting floating wave energy devices. The numerical analysis is to be performed by INNOSEA and the experimental work by Plymouth University at their wave tank.

Hopefully this will allow to identify the most promising rigidly-interconnected configurations for arrays of wave energy devices, allowing to reduce the costs associated to the installation and also maintenance operations of moorings and electrical cables, as breakthrough to make wave energy a more competitive technology, as proposed in the WETFEET project.

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