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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

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Pre-deployment and operational actions associated with marine energy arrays

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Guidance on Pre-deployment actions associated with marine energy arrays

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Summary

This report addresses key pre-deployment issues associated with wave and tidal energy arrays. There are a number of forward-looking statements herein that have been arrived at through a progressive and analytical view of how the industry might develop. Justification of how the industry might develop is given in chapter 1. Guidance on best practice is given for a range of array deployment scales, for the various elements of an array and the associated equipment and actions required for deployment and operation.

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1. INTRODUCTION

1.1 GUIDANCE APPLICABLE TO PRE-DEPLOYMENT OF ARRAYS

There are a great many issues that require comprehensive understanding in advance of deployment of any specific wave or tidal energy array. Nearly all technological issues will be expanded in terms of spatial and temporal considerations when moving from a singular prototype device to the first array (of any specific device). For example, the deployment method used at the sea-trial stage where an installation vessel was utilised for 4 weeks is highly unlikely to be repeated for an array of ten devices. The technical and economic imperatives will be changed to a large degree as arrays, by definition, are about generating meaningful amounts of energy at an increasingly competitive price.

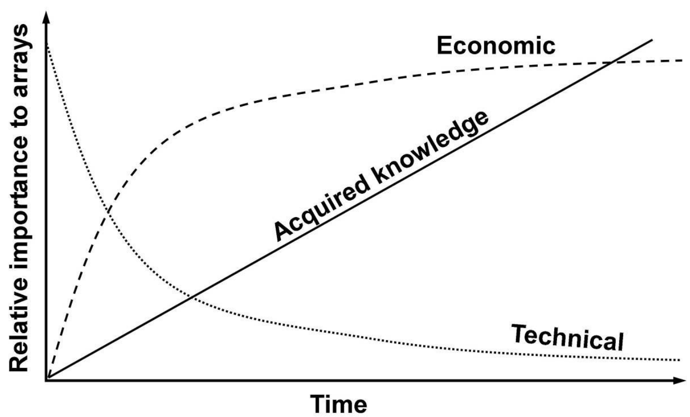


Figure 1 - Factors required over time for successful deployment and operation of marine energy arrays

At array scale the technical and economic drivers for device design, pre-deployment and operational phases are inextricably linked. Thus the reader is referred to section III of the protocol documents. IIC is technically focussed but it is acknowledged that for various pre-deployment issues that the technology will be driven by economic factors. Figure 1 illustrates the changing dynamic and importance of technical and economic issues for arrays. Early arrays will target technical success with the knowledge that mass deployment and increased learning will reduce unit costs as array sizes increase. Once arrays become very large the technology will be de-risked to a large degree and thus project economics will be the driving force much as we see presently for the offshore wind energy industry.

Guidance given in this document and the wider part of the pre-deployment aspects of IIC will aim to achieve the following:

- Draw upon existing pre-deployment and operational issues from related industries (such as offshore wind) that can benefit the marine energy sector
- Identify knowledge gaps and areas growth
- Give guidance on how the marine energy industry can best expand
- Highlight potential future issues that could slow or stop the industry from reaching large commercial array deployments in a timely and effective manner

1.2 EVOLUTION AND GROWTH OF MARINE ENERGY ARRAYS

Early arrays are likely to be composed of a small number of devices in order that:

- Total arrays costs are manageable
- Experience of multiple deployments at a single site can be achieved
- Meaningful quantities of power can be generated whilst not exceeding local electrical grid capacity

It is likely that arrays will evolve in size and complexity as the technology develops. A key driver for nearly all types of wave and tidal device will be the minimisation of negative interaction effects between devices whereby structural loading is increased and/or power production is reduced. Early arrays will almost certainly be composed of a single row of devices aligned perpendicular to the incoming wave or tidal resource (where the resource has a low degree of directionality). Arrays can be expanded by including a second row where downstream or down wave devices are positioned in the spaces left between devices in the upstream/up wave row (see Figure 1). This is the limit of what we will refer to as 1st-generation arrays. This configuration has the following benefits.

a. It will minimise device interaction
b. Maintenance and access to devices is not restricted as both rows can be approached from outside the array
c. Arrays can potentially become quite large with this configuration depending upon location

This of course is assuming that a particular site has a resource constant over a large spatial extent. It may be the case that other drivers will override the layout described above. Matching devices to sites is a topic addressed elsewhere in deliverable 5.3.

Second generation arrays would be for multiple rows of devices (greater than 2) where interaction effects do occur. The benefits of a large number of devices at the same site outweigh the potential for increased device loading and/or reduced performance and access issues to some devices within the array. Figure 2 illustrates this issue as the furthest row downstream is most likely to encounter some form of negative interactive effects from the upstream rows whilst access to the middle row could be more difficult due to the bounding effect of the two adjacent rows.

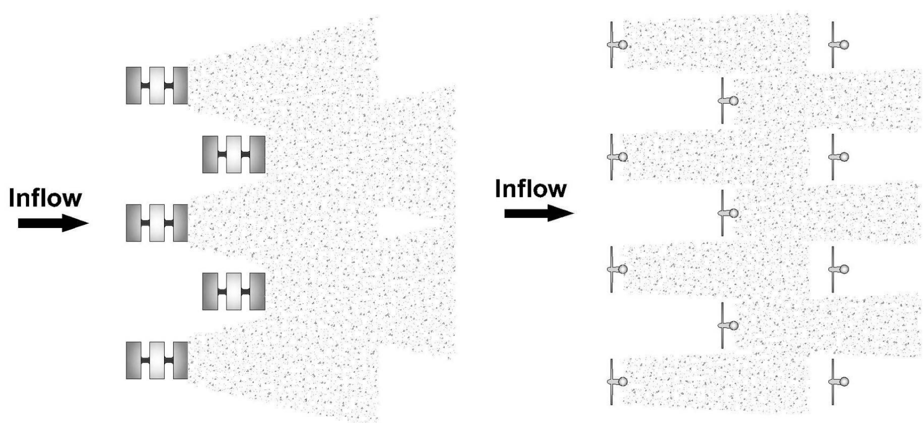


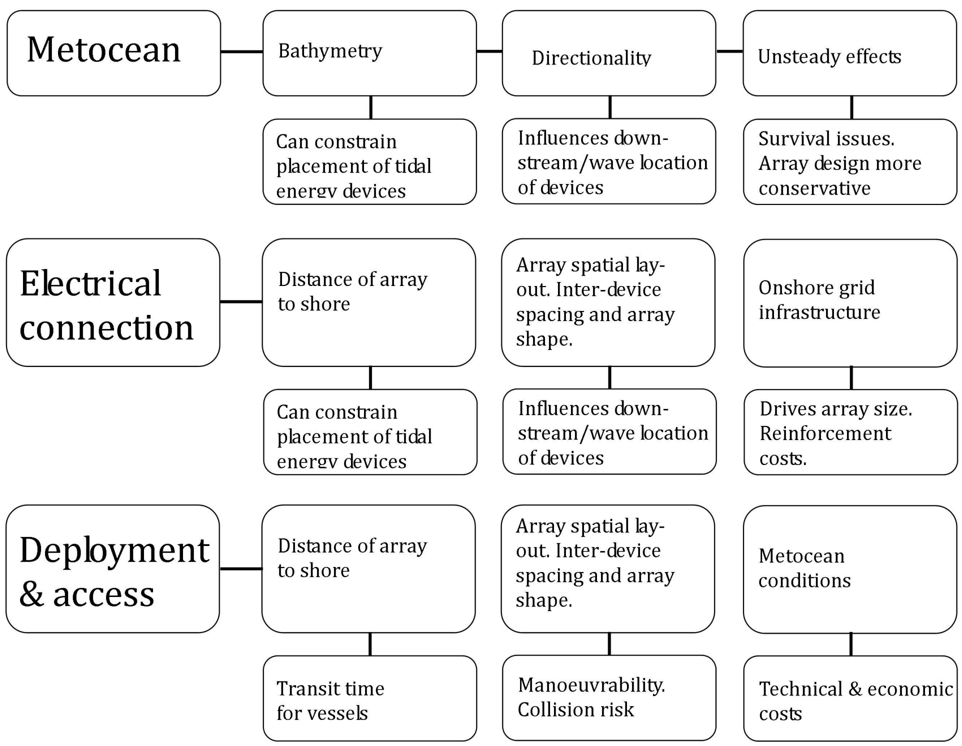
Figure 2 - Plan view of 2-Row wave energy array (left) and 3-row tidal array (right)

The definition given above means that the rated power of an array is independent of this classification. Instead it is driven by the operational complexity of the array. 2nd-generation arrays are more likely for larger-scale deployments on tens or even hundreds of devices. As tidal energy sites are often more constrained that wave energy sites (especially compared with deep-water wave) it is expected that 2nd-generation type layouts would be employed at tidal energy sites before wave energy arrays.

The classification of arrays in this manner is important as many of the device and performance metrics applied to arrays become more subjective for 2nd-generation arrays. Definition and comparisons between several 1st-generation arrays should, in theory, be easier.

Regardless of array size there are a number of key drivers that will influence the evolution of array design, especially larger arrays assuming of course that the energy available at the site is sufficient. 3 key drivers and their effects are given below.

Figure 3 – Drivers for array deployment site location



1.3 STATUS OF MULTIPLE DEVICE ARRAYS

At present arrays are at the formative stage. Many devices are in the process of sea-trials and plans are in place for small arrays; most are composed of less than 10 devices. It appears that for tidal energy bathymetry is a key constraint for array layout with some planned early arrays adopting a 2nd-generation layout (see deliverable 5.4 for definition) with devices operating downstream of each other albeit at a conservative longitudinal spacing. Bathymetry can also affect the geometry of an array moving the design away from the symmetry proposed for an ideal site in deliverable 5.4. Early plans for wave energy converter arrays appear to be single row arrangements aligned orthogonal to the flow and are as such less constrained by metocean conditions compared to tidal energy converters.

1.4 PREDEPLOYMENT ISSUES FOR ARRAYS

At the pre-deployment stage of an array there are a large number of issues that require consideration. Figure 4 illustrates some of the principal processes and parameters applicable at the pre-deployment stage. It is assumed that sections IA and IB of the Equimar protocol have been given due attention at this stage. However they are included in the following Figure for completeness.

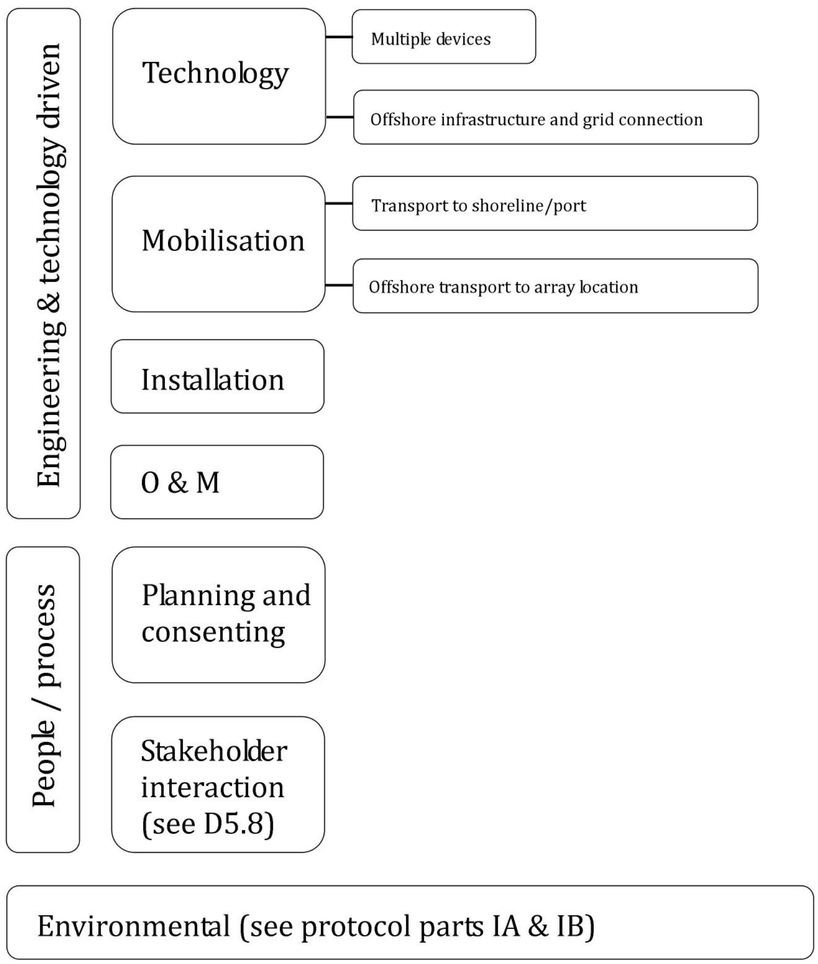


Figure 4 – Pre-deployment considerations for marine energy arrays

Planning and consenting is highly dependant upon the country of installation and is not addressed by the Equimar protocols. Marine energy stakeholders are encouraged to seek this information separately.

2. GUIDANCE RELATED TO ARRAY DEPLOYMENT SCALES

The issue of how arrays might develop in design and layout has been addressed above. However, when dealing with many of the pre-deployment actions a classification that is not dependant upon rated power and semi-independent of the number of devices does not align with economic factors. Therefore the scope of this document we must define some arbitrary limits to the evolutionary sizes of marine energy arrays. The manner and size of array evolution will be driven by a number of factors including but not inclusive to:

a) Political/ planning

Arbitrary limits may be enforced to ensure that array developers can deliver at smaller scales before progressing up to more expansive and costly arrays.

b) Technical

The industry is likely to self-regulate based upon the high technical element and lower understanding related to early array deployments. A smaller array is easier to manage and faster to deploy. The remoteness of many wave and tidal energy sites could place landfall locations where a weak electrical grid exists. The cost of grid reinforcement will be a factor to array size with early arrays likely to fall within existing capacity to avoid additional costs.

c) Financial

Financial backers or owners of arrays are unlikely to fund larger, more costly arrays until the technology has been proven on a smaller scale. As costs per unit rated power will reduce over time it is prudent to increase the scale of array deployment at a financially optimised rate.

Therefore the following scales of array deployments are considered:

Demonstrator arrays – up to 10 devices

Small - 10-50 devices

Medium arrays – 50-200 devices

Large arrays – 200+ devices

Electrical arrangements (on and offshore), array layout and deployment issues all increase in complexity with each of these 4 stages.

An argument could be put forward to define array size by rated power output as this has implications for integration with the electrical grid. However, onshore grid strength will be project and location specific. For example the grid strength in the North West of Scotland is relatively weak considering the large wave and tidal energy resource that is technically exploitable whilst Portugal has a strong grid running along the coast and project integration should be much easier. Early arrays will undoubtedly be sized to avoid grid reinforcement.

Perhaps the principal purpose of sea trials of wave and tidal energy devices conducted to date is the safe deployment and completion of an effective device testing schedule. For this reason a number of devices have taken long periods of time to install; typically in the order of several weeks. Clearly this method of installation cannot be applied to increasingly large arrays of devices if economically competitive electricity is to be produced. Therefore devices and methods for installation (deployment) must improve in terms of reduced time and cost.

Table 1 details some of the key characteristics of array devices and deployment issues that are likely to occur with increasing scale.

Table 1. Principal parameters associated with the increasing scale of marine energy arrays

Array type	Number of devices	Purpose of array	Device design	Device installation vessel required
Demonstrator	≈10	Demonstration of availability, grid connection. Trial of installation methods for multiple deployments	Utilisation of design used for sea trials (good understanding) with technical modifications depending upon sea trial success.	Existing with heavy lift capabilities. Deployment widows potentially small
Small	10-50	Up-scaling to small commercial arrays. Proof of cost reduction through scale and evolution of components	Device evolution from design used at sea trial and demonstrator array stages. Potential for improved reaction and hydrodynamic subsystems. Modifications to control and power take off.	Modified existing. To complete install more rapidly or extend installation window
Medium	50-200	Cost reduction to upper end of grid system prices, payback times comparable with existing energy generation technologies	Device approaching a more stabilised design for metocean conditions not far removed from previous array stage. Modified for more economical deployment and O&M.	Potentially custom or heavily modified existing vessels. Some devices might be modified in order to use smaller, cheaper and more numerous existing vessels.
Large	>200	Generation costs competitive with existing technologies. Use of evolved components, device designs, deployment and O&M methods.	Next generation device design. Arrays moving to more challenging and energetic sites. Potentially very different technology employed especially reaction subsystem, deployment and O&M methods.	

2.1 METOCEAN FACTORS AFFECTING DEPLOYMENT

Section III of the Equimar protocols details some analysis of deployment windows for typical wave and tidal energy sites based upon the operating limits of existing vessels. It is clear that metocean conditions will have a major bearing upon deployment actions and also with array operational and maintenance.

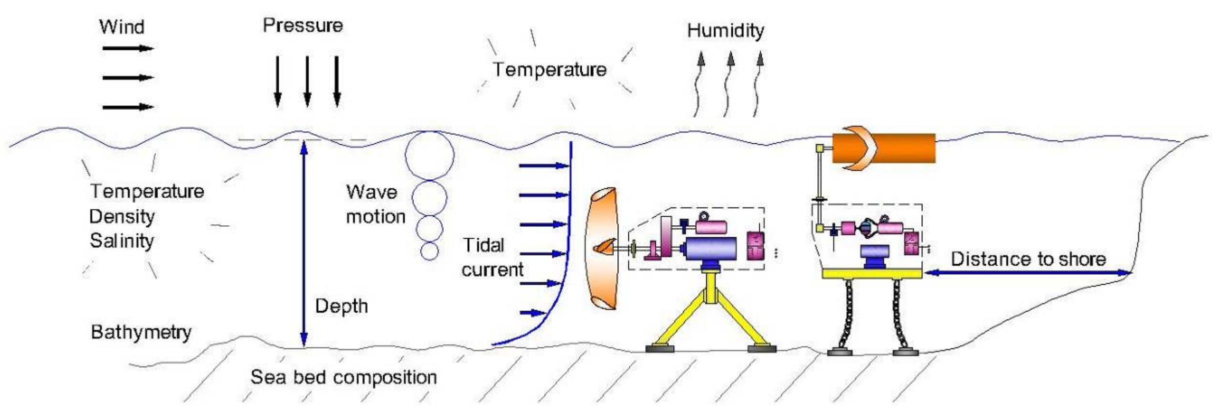


Figure 5 – Metocean parameters applicable to marine energy arrays

Figure 5 illustrates a number of metocean parameter applicable at any particular site. For array planning both the distance to shore and the strength of the resource hold common drivers for both wave and tidal energy. These are covered in table 2 below:

Table 2. Metocean evolution with array scale

Array type	Number of devices	Distance to shore	Wave/tidal energy resource
Demonstrator	≈10	Distance to shore minimised to enable short transit times to site maximising deployment windows with existing vessels.	Significant enough to produce good amounts of energy and reasonable payback periods considering likelihood of generous electricity tariffs. Peak waves/tidal currents limited to ensure survivability, increase availability and minimise access constraints.
Small	10-50	Distance to shore increasing due to the larger spatial extent of array (conflicts with maritime traffic etc. more prevalent closer to shore) but offset by the increasing cost of electrical connection over greater distances.	Resource significant enough to produce good amounts of energy and reasonable payback periods considering likelihood of generous electricity tariffs. Peak waves/tidal currents limited to ensure survivability, increase availability and minimise access constraints.
Medium	50-200	Larger areas of seabed required, changes in bathymetry more critical for tidal than deep water wave.	Increasingly energetic resource as financial support is tapered leaving reduced device cost or increasing energy generation as key cost drivers. At this stage maximal resource limits will be better understood.
Large	>200	Device design evolution coupled to resource so more energetic sites utilised. Potentially further offshore for deep water wave.	With evolved device design metocean conditions will be as energetic as possible balancing the need for maximised energy generation whilst minimising O&M, device failures etc.

Depth is a key parameter for tidal energy. In the near term depths will be limited by 2 factors:

- Maximum operating depth for installation vessels, especially those that make contact with the sea bed (jack up barges)
- Capital costs will increase with depth for any particular device design

2.2 DEVICE DESIGN FOR ARRAYS

We can also expect device design to evolve over time as the scale of deployment increases. Figure 6 illustrates the subdivision of wave and tidal energy devices into 4 principal subsystems as used in part II of the Equimar protocol:

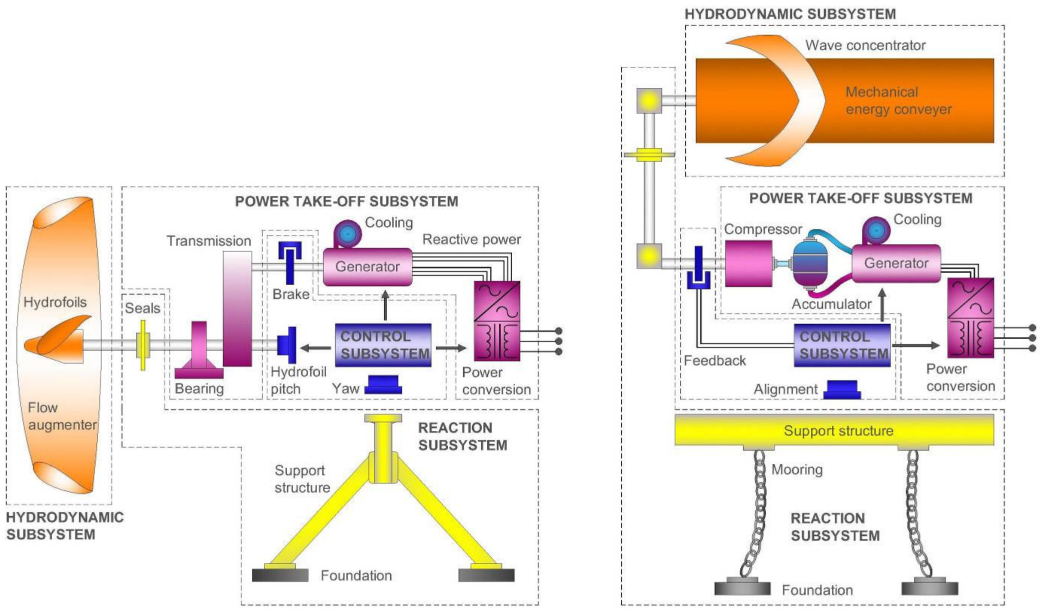


Figure 6 – Subsystems and example components for wave and tidal energy converters

Due to the wide variety of wave and tidal energy device designs guidance is given herein by subsystem.

2.2.1 Hydrodynamic subsystem - issues for deployment

Hydrodynamic subsystems are expected to be at the forefront of device evolution. Figure 7 illustrates 2 paths that could proliferate for both wave and tidal in a combined or discrete manner. A key are of capital expenditure, deployment and operation & maintenance is the reaction subsystem (principally the mooring or anchor). As site selection progresses as per table 1 mooring systems will become more costly and therefore it will be prudent to increase device energy capture per unit metric of the reaction subsystem. We may well see the size of hydrodynamic subsystems increasing and/or the number increasing (per discrete device).

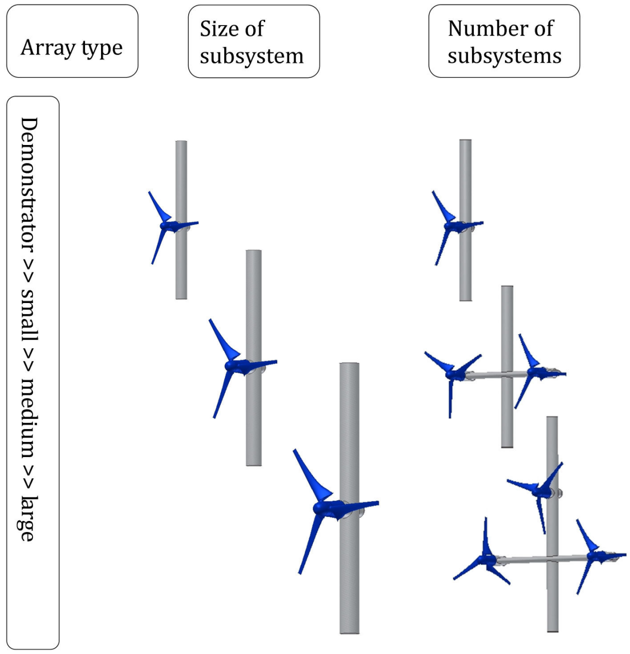


Figure 7 – Evolution paths of the Hydrodynamic Subsystem

2.2.2 Reaction subsystem - issues for deployment

The evolution of the reaction subsystem will be more device-specific. For wave energy whilst the type of mooring system may not change appreciably for any particular device and that many are designed for discrete depths; generally near shore and deeper water. For the latter case arrays will undoubtedly increase in size and distance offshore may increase but water depths will be constrained to less than 100m in nearly all cases; typical of shallow continental shelf seas. Therefore changes in moorings are likely to be less fundamental than is expected for tidal energy. Most tidal energy devices to date have conducted sea trials in water depths less than 40m as these are suitable for both jack-up and crane barges. This allows deployment with piled foundations the design and installation of which is well understood. However, the majority of tidal energy is located in water depths greater than 40m where piled foundations become less economic and practical. Therefore the evolution of the tidal energy reaction subsystems may well be predominantly driven by increasing water depth as per Figure 8.

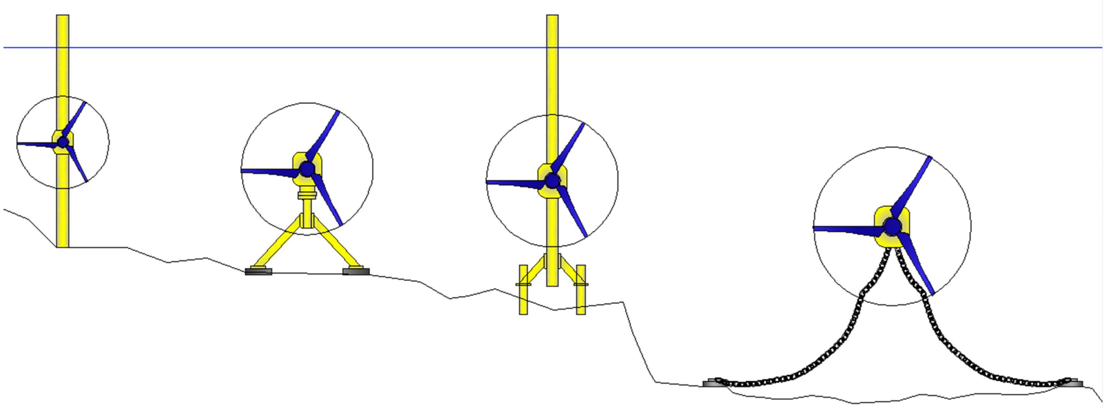


Figure 8 –Example of varying reaction subsystem design with increasing depth for tidal energy converters

Deliverable 7.3.2 discusses some of the technical and economic issues associated with different anchoring systems that are part of the reaction subsystem. It is clear that there are advantages/disadvantages with each and that mooring systems and devices are likely to be modified as each specific marine energy device evolves over time.

There are a large number of mooring/foundation types that can be employed for wave and tidal energy converters. The relative merits of each are not covered here as they are often specific to either a specific device or a family of similar devices. A further issue is that moorings/foundation are often grouped into similar types or can be expanded to incorporate small changes in specification or design. To address all the slight variations in mooring/anchor/foundation systems would involve repetition of guidance. Therefore the basic form of anchors (defined as the interface with a solid structure Seabed, shoreline etc.) are:

Gravity foundation - uses mass as a resisting force.

Pile - long member embedded into sea bed or ground. Uses resistive force of material surrounding the pile and friction between pile surface and embedded material to resist overturning and pulling forces.

Embedment anchor - anchor is dragged along seabed and due to its shape is forced downwards into the seabed. Anchors can also be embedded via excavating a hole and backfilling to burry the anchor. This method is much less practical for marine energy converters.

Table 3. Deployment actions for different mooring/foundation systems

Basic Mooring/foundation type	Gravity base	Pile	Embedment anchor
Variants	Material and shape of foundation.	Deployment method - Driven Suction, drilled Shape - generally tubular but other shapes/profiles available	Drag embedment or buried/ dug?
Specific design issues affecting deployment	Deployment weight, transport method - towed or carried. Is the foundation incrementally ballasted (injected at site) or complete? Ballast material. How does it contact the seabed (grouted?)	Length, diameter, embedment depth	How many anchors per device? Configuration of multiple anchors at site (interference).
Deployment actions at site	1. Lower foundation in controlled manner to sea bed. 2. Influence of metocean conditions. 3. Is the alignment of foundation significant? How can this be achieved?	Driven piles action from vessels or pile top driver left on site?	
Generic issues for deployment	Is seabed material appropriate? Continuous over array deployment area? Can anchors/foundations etc. be installed incrementally ahead of remainder of device? If so how will the remainder of the device make contact with the foundation?		

From these mooring types there are a number of methods of attaching a device:

1. Chain, rope or wired to marine energy converter (usually floating wave or floating/semi-submerged tidal energy coverter). These can be a catenery-type mooring line or a taut mooring.
2. Direct to other device subsystems (such as piled foundation)

Methods of increasing deployment efficiency (hence cost of energy):

- Consider alternative foundation anchoring design (may impact on MEC design)
- Increasing installation rates (novel deployment methodologies, increasing deployment windows)
- Optimised foundation design for different sites or throughout an array

2.2.3 Power Take off and control subsystems - issues for deployment

The power take-off and control subsystems in general are likely to have less impact upon deployment and O&M actions. Key characteristics that might have an influence include:

- Shared subsystems
- Modified control strategies to ease deployment (ability to leave devices at site in an inoperative or semi-operative state)

2.2.4 Inter-device spacing - issues for deployment

Inter-device spacing has been addressed in deliverable 5.4 of part IIC of the protocol. Many of the technical issues applicable to device spacing were addressed there however some additional information regarding deployment and access are covered here.

Demonstrator arrays are likely to be deployed by non-specialist vessels and therefore it reasonable to assume that they might require more space for manoeuvring. Vessels equipped with manoeuvring thrusters are best suited to tight device spacing although the loss of control should be taken into account; an uncontrolled vessel can easily drift into a field of devices. Therefore the device developer and array owner should collaborate to ensure that the device spacing required for optimised energy extraction does not conflict with any vessel actions.

Care must also be taken at the design stage that inter-device cabling, hubs etc. can be installed appropriately but vessels available at the tie of deployment. For demonstrator and small arrays vessel availability might be problematic hence consideration should be made for installation by different types of vessels.

2.3 VESSEL DESIGN FOR ARRAYS

For an array it is pertinent to use vessels specialised to a particular task. This is already in practice for large offshore wind farms where turbine installation vessels differ from those installing electrical cables.

Part III of the Equimar protocol covers deployment windows for typical wave and tidal energy sites. With the present state of the art vessels and installation requirements it is clear that either device or vessel capabilities much be improved to reduce deployment costs and technical success. Evolution of vessels and devices could follow a number of scenarios. Table 4 details one such development path:

Table 4. Evolution of Marine energy converters and vessels with increasing array scale

Array type	**Number of devices**	**Vessels**
Demonstrator	≈10	Existing vessels used. Constraint and conflicts with other industries tolerated
Small	10-50	Device and vessel modifications as industry expands. Potential conflict of use with other industries such as offshore wind/ oil & gas unless new vessels are constructed.
Medium	50-200	Increase in conventional craft as industry grows. Emergence of dedicated vessels for marine energy industry or even particular devices
Large	>200	Dedicate service industry and/or array operators with specialist deployment vessels

In part IIC of the protocol the issues of existing and modified craft will be considered. The operational issues surrounding specialist vessels will not be considered.

2.3.1 Barges/pontoons

Typically these are towed into position with the option of using them as working platforms. Anchored to an existing structure or to the sea bed. With the nature of the resource at wave and tidal energy sites it is unlikely that such structures hold any advantage for use.

2.3.2 Self-elevating (jack-up) barge

A powered barge with legs that can be lowered to make contact with the seabed such that the barge platform can be raised above the water surface. This gives a stable working platform at site. Many vessels are equipped with deck cranes and can handle drilling/driving actions for pile foundations and have been used for installation of tidal energy devices at the sea trial stage of development. Key performance parameters of such vessels are:

- Lifting water depth - typically 40m although some vessels can operate in deeper water
- Maximum payload - dependant upon size, smaller barges may not be able to lift heavy 1st-generation devices
- Maximum wave height and tidal current - 2-3m wave height and 1.5-1.75m/s tidal current are typical maximum values
- Maximum wind speed - 15-20m/s (54-72 kph)

The largest jack-up barges can operate in water depths up to 70m but costs may well be prohibitive. With longer legs max working tidal currents are likely to be lower due to larger effect of vortex induced vibrations on the circular legs. Section III of the protocol addresses the time that conventional jack-up barges can sped at a typical tidal energy site. It is clear that without modification of vessel design and/device deployment actions the present technology status is not efficient enough to promote growth in the sector. Jack-up barges may be used for near-shore wave energy devices. In a similar manner the limiting significant wave height of 3m may impact upon deployment windows.

Installation action for jack-up barges might entail:

- Smaller lifting actions
- Driving of pile foundations (from vessel or pile-top rig)
- Sea bed drilling (various bores, angles)
- Other actions where a stable platform is required at site

A clear evolution route for jack-up barges is to increase the deployment windows at a particular site. Section III of the protocol addresses vessel deployment windows at a tidal energy site where the vessel is limited to tidal currents less than 1.5m/s. One route to increasing this is to investigate the use of non-circular jacking legs in order to reduce the drag force acting upon the vessel. Table 5 gives some example drag values for a jack-up barge with 4 legs each at 40m length, 1.5m diameter and with various cross sectional shapes.

Table 5. Estimates of leg drag forces for different shaped jack up barge legs

Velocity (m/s)	Leg shape	Drag coefficient	Total drag force (kN)
1.5	Circular	0.9	841
1.5	Oval	0.2	187
2.025	Oval	0.2	838
3.21	Symmetrical aerofoil	0.02	838

The increases in operational flow speeds with changing leg shape are clear although other factors such as resonance and vortex-induced-vibrations might reduce these values. I should be noted that installation of the 'Seaflow' tidal device in the UK in 2003 employed additional streamlining to the legs in order to increase time on-site.

Tidal energy sites between islands and in straits are often less susceptible to wave action compared to open-sea sites. However, even in the winter months significant wave heights may exceed limiting values for such vessels. Measures to increase the working value of H_s would benefit deployment of marine energy converters, both tidal and shallow water wave.

2.3.3 Crane barge

Crane barges as the name implies are barge vessels with the ability to lift heavy loads from deck. Mooring is usually through multi-point anchors (up to 8) and the barge deck areas are often large (up to 100m * 100m) in order to accommodate heavy-lift cranes. Lift capacity generally decreases with height; upper limit values range around 8000t lift capacity and lift heights up to 80m above deck level. The largest vessels are used for offshore oil and gas platform installation and O&M and their specifications easily accommodate the present wave and tidal energy devices on the market.

Crane barges are nearly always equipped with manoeuvring thrusters but are rarely self-propelled. In this case a tug or similar towing vessels will need to be utilised to travel to site. Transit times should be adjusted for the towed load in question. As with jack-up vessels measures to increase the operational metocean conditions of crane barges would benefit the marine energy sector.

2.3.4 Tugs

Tugs are principally used for towing such as crane barges and pontoons. They can also be equipped to perform additional functions such as installation of sea bed anchors and moorings. Tugs can be employed to tow devices directly to site if they are buoyant and have appropriately designed harness systems. Examples would include floating wave energy converters and potentially 2nd-generation tidal devices designed to be ballasted down at site to their appropriate position in the water column.

2.4 DEPLOYMENT METHODOLOGIES

The lifecycle of an array can be summarised by the process described in Figure 9.

1. Location/site research
2. Site metocean measurements
3. Development plan
4. Deployment protocol
5. Planning and licensing
6. Deployment of electrical infrastructure
7. Deployment of reaction subsystems
8. Deployment of remainder of devices
9. Grid connection and commissioning
10. Operation and maintenance phase

Figure 9 –Array planning and deployment process

The key issue here is that deployment planning and the development of a methodology or protocol should be considered at an early stage. This is heavily dependant upon the site, local infrastructure, device design and vessel capability/availability.

2.4.1 Barriers to successful and timely installation

There are a number of actions and events that have the potential to disrupt the deployment of an array. Some examples are listed below.

Disruptive elements

- Planning/consenting/ regulation delays
- Supply chain delays (elements of array not ready for mobilisation)
- Availability of installation vessels (conflict with other industries)
- Capability and appropriateness of vessel for device and site
- Weather (extremes)
- Access issues to array site (conflicts)
- Vessels malfunction/ fault
- Damage to array elements during installation
- Devices not installed on appropriate station
- Site conditions not as expected
- Site location and transit times from port to site
- Linked disruptive elements (e.g. weather delay causes deployment vessel to leave for another job)

It should be noted that the list above is not exhaustive and array stakeholders are advised to compile all disruptive elements for their particular array deployment.

Many of these elements are device and/or site specific and therefore they cannot be assigned levels of significance in a generic or equitable manner. Instead it is advised that the array stakeholders construct a matrix of Consequence (severity) and Probability (occurrence) to be able to rank and levels of disruptiveness. The person(s) compiling this should be risk neutral (independent). Probabilities and consequences should be defined as accurately as possible wherever possible. An example would be to use weather hind casts to assess the probability of disruption. Such an approach will maximise the resolution and accuracy of any analysis.

Remediating measures to minimise any deployment disruption are also dependant upon a number of factors including the array site, device type and also the country of deployment (infrastructure, consenting etc.). Developers must plan remediating measures at an early stage to ensure arrays are installed in a timely and effective manner.

The reader is referred to section 3 (deliverable 5.6) for information concerning the assessment of risk.

2.4.2 Deployment actions

As the size of arrays increase with time it is almost certain that the number stages required for the complete installation of the array will increase. Planning for storage of array elements should be made such that mobilisation and deployment can be achieved most effectively. For example construction time for 50 reaction subsystems might be in the order of several months (depending upon the MEC device) whilst installation might be planned for a short summer weather window. Locating all the necessary array elements at a convenient location to expedite deployment might require storage on land, dry dock or even in harbour waters.

Once deployment has commenced the following actions must have been planned for:

At each installation stage:

Ensure that access to site is not compromised. Examples include maritime transport, dredging etc.

Inter-stage state of the array

Due to the nature of the marine energy resource it is essential that for staged deployment devices or other elements of the array can be left in a safe state between deployment actions.

On completion of the deployment

Deployment planning must ensure that none of the interim stages obstruct later stages or increase difficultly of O&M operations. If this is unavoidable then O&M actions must be modified.

2.5 OPERATION AND MAINTAINANCE METHODOLOGIES

Early arrays by definition will be composed of devices not too dissimilar to the full-scale prototype units. Whilst sea trials might have informed the device developer of some of the likely device failure paths and their potential solutions a key aim of the sea trials is performance verification and thus steady operation over long periods will not always be executed. We can therefore deduce that demonstrator arrays might have relatively high O&M requirements per device or per installed capacity compared to large arrays composed of second or even third-generation technology.

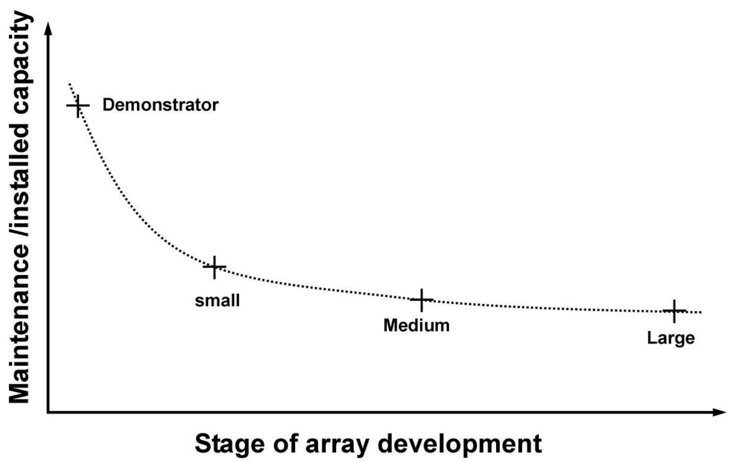


Figure 7 – Maintenance load with up-scaling of marine energy arrays

2.5.1Location of Operation and Maintenance actions

Whole Operation and Maintenance characterisation can eventually come down to cost, providing all aspects are included (cost of vessels, equipment, lost production due to inaccessibility, lost production due to reduced capacity, etc.). Frequency and levels of maintenance can then be attributed to an array. Despite a lack of data for the most closely related application of offshore wind energy Monte Carlo simulations are being utilised in order to plan effective maintenance strategies for various wind farms.

Locations for maintenance can be summarised as:

a. In situ: Generally only viable with small components. With issues surrounding weather windows and access to devices this maintenance location is best-suited to fast removal and replacement of components. 25kg is a practical working weight for handled components in air. Underwater, much larger parts can be made neutral buoyant and can be moved through the water before a vessel takes it on board.

b. Taking the device to a harbour, dry dock on onboard another vessel. Rapid de-installation of the device is recommended for such an action. A strategy for the re-deployment should also be considered at the device design stage, especially if initial deployment involves permanent structures or actions that are not compatible with re-deployment.

c. Remotely. Examples could be to switch alternative components in the case of redundancy or to re-route power/processes through a device to maintain performance.

2.5.2 Frequency and types of maintenance actions

Fault detection is essential for determining the type and frequency of maintenance actions. This may also reduce the severity of maintenance required that should lead to more technically and economically efficient maintenance actions. The frequency of maintenance action could be subdivided into the following types:

a. Scheduled/regular/periodic maintenance: These are planned actions identified as being necessary based upon simulations or Failure Mode and Effect Analysis (see Deliverable D5.6)
b. Corrective/reactive: For faults that occur unexpectedly.
c. Opportunistic/preventative: Actions performed simultaneously with other types of action particularly when a fault has not occurred. In this manner maintenance actions can be combined and potential future actions can be reduced.

In all cases the necessity of maintenance actions will be based upon a cost/benefit/risk matrix.

2.5.3 Technical ease of operation and maintenance

Assuming that maintenance is performed in-situ the technical ease will be mostly governed by the device type. Other factors are likely to include:

- Device type
- Metocean conditions during maintenance action
- Nature of replacing component/system (weight, shape, connections, length of time required)
- Local location (on device (above water line, underwater, on vessel)
- Vessel type (influences flexibility and actions available)
- Array size, location and layout

2.5.4 Cost of operation an maintenance

Cost of maintenance is one of the key drivers alongside safety. For example any maintenance action will be based upon a cost/benefit justification and there are many variables that will inform such a decision. Safety falls outside this but could be described as a driver based upon cost, moral obligation and risk. For example, if one device is failing and risks damaging further devices in the array this would be based upon cost. If a device risks breaking loose and drifting into a shipping lane there is a moral obligation to repair or extract the device before an incident occurs.

As part of this document the following array deployment scales were defined:

- Demonstrator arrays – up to 10 devices
- Small - 10-50 devices
- Medium arrays – 50-200 devices
- Large arrays – 200+ devices

The cost of maintenance for each scale is likely to be different alongside the types of maintenance actions due to technical specification and understanding associated with each scale.

For demonstrator arrays devices are likely to be close in specification to those employed at sea trials. Faults occurring at sea trial stage might be remedied but access and availability might be more difficult especially if a test centre or sheltered location was used during sea trial operations.

The following stage of deployment of small arrays (10-50 devices) implies that a reasonable number of offshore marine energy arrays might be in operation. Thus it could be expected that vessel availability might be higher and that device design is improved above previous levels. Scheduled maintenance actions could be more prevalent.

Medium arrays (50-200 devices) will involve another step-change in maintenance actions and hence cost. Electrical connection of the array will be larger and more complex and increasing maintenance load might be attributed to this. At this stage devices are expected to be highly evolved from the demonstrator array units with a view of maximising energy capture and reducing costs through fewer and more effective maintenance actions. Specialist vessels with enhanced capabilities should be readily available. Therefore the cost per device for maintenance should reduce.

Once large arrays (>200 devices) are installed the industry should be reaching maturity. Maintenance actions will be refined but increasing distances offshore will undoubtedly lead to metocean conditions being a greater driver for maintenance. If the array is densely packed then vessel manoeuvrability might be a key factor in performing any in-situ actions.

With data only recently being make available for offshore wind operational expenditure it is difficult to draw any comparisons in terms of costs. Marine energy arrays will be installed in more aggressive environments and the large number of device types that might be deployed in small arrays will lead to a wide band of costs for operational expenditure of marine energy arrays. Development of Monte Carlo simulations or stochastic models is most important for the industry moving forwards.

2.5.5 Array availability

The availability of an array for maintenance is defined as the proportion of time that operational actions could be conducted if required. Availability of an array for maintenance action will be governed by a number of factors:

- Type of action (remote or in-situ)
- Metocean constraints (see WP7 D7.1/2)
- Type of craft/vessel used for intervention
- Distance of array from vessel home (transit time to array)
- Nature of maintenance action (repair, replacement, size/weight of component etc.)

It is clear that availability is dependant upon a number of factors but the over riding issue is likely to be metocean conditions. Offshore wind farms can have availability for 80% of the time although this can drop below 50% during winter months (data from Vindby offshore wind farm). With the more severe metocean conditions at marine energy array locations it is clear that:

- Specialist vessels are required with enhanced sea-keeping capabilities
- Maintenance actions should be reduced wherever possible. Scheduled maintenance is clearly preferred above other forms

- If required, in-situ maintenance actions should be fast and effective

2.6 RELIABILITY AND REDUNDANCY

Device reliability will undoubted increase over time with scales of deployment in a similar manner as offshore wind energy. Low reliability can cause uncertainty which subsequently leads to unscheduled maintenance actions; the least desirable scenario. Offshore wind energy has seen increased levels of sealing to keep components sheltered from the more corrosive offshore environment (compared to onshore turbines). Atmospheric conditions within the interior of the turbines are also controlled. Reliability and redundancy of components and systems have been increased reflecting the lower availability of offshore wind farms for maintenance actions and the increased costs. Finally direct drive transmissions are proving to be a lower maintenance option as gearboxes are generally regarded as most likely to fail (over other components) or require regular maintenance.

Hydrodynamic subsystem:

Physical forces on the energy capture components are likely to be high. Stress over millions of cycles or peak loading arising from storm surges or breaking wave impacts should be designed and tested to maximise reliability. Bio-fouling might be an issue in terms of reducing energy capture performance or causing sensors/actuators etc. to have a reduced performance or fail. Redundancy is difficult to design into this subsystem especially with generic guidance. It might be possible with particular wave or tidal devices.

Power take-off subsystem:

Issues here can be understood from the wind energy industry although the magnitude and likelihood of any reliability/maintenance actions will be significantly different. Reliability issues for the power take-off subsystem will be prevalent for seals, pressures (of hydraulics) gearboxes, generators and other moving parts. Assuming the environment for a specific component is kept within design conditions then reliability should be quantifiable. Reliability will be more important for device-specific component or conventional parts perhaps modified and operating under different design conditions. Reliability can be achieved by having multiple components such as parallel generator sets such that modular replacement is more manageable and "graceful degradation" can be employed for devices to ensure performance does not drop off in a binary manner (see deliverable 5.3 for further detail).

Control subsystem:

Electrical failures are a key concern in the marine environment. Electrical systems should be well-sealed and robust as poor electrical connections and corrosion are likely failure mechanisms. Passive device control might reduce the need for complex electronics. Potting of electrical components (filling with non-conductive compounds to reduce damage through shock, impact, water ingress etc.) should be conducted wherever practical. Electrical systems can most benefit from redundancy as the form factor of many components is very small and costs are generally low. Switching to backup systems clearly demands additional components so a cost/benefit approach should be taken.

Reaction subsystem:

Similarly with the hydrodynamic subsystem physical loading and corrosion and bio-fouling are the principal mechanisms for reduced performance or failure. Sealing of the device is incorporated here and robust seals should be used. Pressurised units and/or multiple seals will address reliability and redundancy respectively.

2.7 SHARED SUBSYSTEMS

Key areas where shared subsystems can be employed to reduce operational actions are power take-off and electrical connections.

A power take-off subsystem might be shared between a number of hydrodynamic subsystems on one device or could be shared by a number of different devices. Power density will obviously be greater but it is expected that CAPEX and OPEX per unit power is reduced if such shared subsystems are employed.

Offshore wind farms now commonly have shared substations on a separate platform, which houses transformers and other power conditioning equipment to enable high voltage transmission to shore. These are generally more accessible than wind turbines themselves, which may require more capital expenditure, but spread over several turbines the benefit outweighs the cost. This is likely to be even more beneficial for wave and tidal energy arrays, which are generally even less accessible than wind turbines due to more extreme metocean conditions. Even for smaller arrays shared electrical connection equipment can be employed. Access is a key issue as a failure at such a nodal point may affect the power production from significant fraction or the entire array.