**Operation and Maintenance procedures**

**D5.2**

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## Executive summary

This report provides a high level but qualitive description on the required activities for operating and maintaining a floating island such as the *Space@Sea* island. Operations and maintenance of offshore structures contributes with a substantial part of the total operational expenditures (OPEX) over a life time of minimum 25 years. Experience from current offshore wind industry shows us that floating wind structures have higher operational expenditures, due to O&M activities, than bottom fixed foundations. The reason of this additional cost is due to the fact that floating structures suffer more due their dynamic behavior imposed by (harsh) offshore weather conditions. Although the development of offshore floating islands is rather new, the Oil & Gas market has extensive experience in operating & maintaining floating production, storage and off-loading structures (FPSO).

It is observed that developers of foundations and mooring systems strive to design their products maintenance free. But even though a maintenance free design might be possible, such solutions are more expensive and may not be economically feasible. Hence O&M or Operation and Maintenance procedures are common practice to operate structures inside safe margins and schedule preventive maintenance. O&M will be essential for future floating structures such as the *Space@Sea* floating island that are complex, have many high loaded parts, and that are required to ensure reliable operation throughout their lifetime. The use of remote monitoring infrastructure (*Task5.4 – remote monitoring*) is expected to be essential for long term condition monitoring, and allowing for acceptable in situ inspection frequencies and its associated cost, and reliable scheduled maintenance activities.

One of the most important factors for choosing a floating structure over a bottom fixed solution, is its flexibility and modularity during the installation, operation and also during O&M. Stakeholders could decide to build up the island gradually over time in order to justify the investment and mitigate the overall risks. Same accounts for adapting the island during operation and even during maintenance activities. The latter is required if floating to floating operations are too risky which means that it's more appropriate to tow the floating module to shore to perform the maintenance activities. This is also done in the offshore floating wind sector.

This report describes the activities for operating & maintaining the floating island whereas these activities can be distinguished in corrective maintenance and preventive maintenance activities. Corrective maintenance relates to unscheduled maintenance which means that something has gone wrong and the O&M contractor has to intervene. Preventive maintenance relates to scheduled maintenance which is fixed and pre-determined in order to keep the island operational and in structural health. This type of fixed maintenance can be executed by scheduled inspection campaigns (ref. chapter 3) or by means of condition-based maintenance which is described in *Task5.4 – remote monitoring.* It should be noted that condition monitoring equipment allows the contractor to reduce, but not fully replace visual in situ inspections as the retrieved data will be focused around a priori identified failure modes.

A high-level cost estimation based on experience with bottom fixed and floating wind farms is linked to the O&M activities as outlined in chapter 3. An additional cost estimate is provided for adjusting the configuration or replacing modules in the island configuration. This is based on financial figures mentioned in *Task5.2 – Transport & installation* as this requires the same type of procedures installation & marine equipment.

The paper ends with an outlook of performing O&M activities in a future period of 10 or more years away. One of the items which is expected to take an important role in the scheduled visual inspection campaigns is the use of Unmanned Aerial Vehicles (UAV's) and autonomous vessels.

# 1 Introduction

## 1.1 Motivation

One of the most important factors for choosing the *Space@Sea* modular floating island concept over a vessel or bottom fixed foundation is the differences in operation and maintenance. The flexibility of modular floating island concepts provides wide opportunities for operational usage, extensions or modifications of that usage along the life of the structure. The operational costs that come with this flexibility however, might have a larger financial impact than more classic concepts.

Due to innovative origin of *Space@Sea*, no pre-defined list of operations or maintenance is present per application. Replacing one of the modules due to an essential repair, decommissioning or any other operation, requires a certain protocol with financial consequences. Therefore, stakeholders within *Space@Sea* need to know before their investing, what the level of probability and consequence are. If it turns out that there are too many levels of probability with large consequences, stakeholders will not take the risk for financial investments.

The concept and scale of floating islands as considered in Space@Sea is new and to previous experience is available to outline O&M procedures. This approach outlined in this report provides a list of prioritized operations and maintenance procedures for the Space@Sea island that is based on knowledge and data coming from the Space@Sea partners in this workpackage. That includes wide operational experience with offshore bottom fixed, and floating wind farms, and design involvement with offshore oil and gas plants. The result is a high level, qualitive estimation on the operational expenditures required during the lifetime of "a" Space@Sea island. Below table provides the expertise and experience of each partner which has been brought together in this report.

| Partner | (Core) Business related to Space@Sea | Expertise in the report |
|---|---|---|
| GOC | GOC (GeoSea) which is the former name of DEME Offshore is an offshore marine contractor with an unrivalled track record in the transport and installation (T&I) of offshore windfarms (foundations, turbines, cables, rock dumping etc.). We have worked on some of the largest wind farms in the industry and those that are furthest from the shore, and in the deepest waters.<br>DEME Offshore is a pioneer in the "floating wind" sector and is already involved in two floating projects, which use different technologies. For Equinor ASA we have performed the front-end engineering and design (FEED) study on the Hywind Tampen project in Norway. The scope of the contract was to develop and optimise the design and construction methodology for the foundations, including the secondary steel outfitting, mooring arrangement and project execution strategy.<br>In Belgium, we are part of the MPVAQUA consortium, developing a cost-competitive concept for the floater structure to support large, offshore floating PV solutions | DEME Offshore has put its expertise on the operation and maintenance of bottom-fixed windfarms and its developments in the use of offshore drones for visual inspections.<br>DEME Offshore has technical and financial expertise to estimate the O&M activities for the Space@Sea floating island based on its experience and expertise on offshore bottom-fixed windfarm. |
| MARIN | MARIN is a leading Maritime Research Institute and is involved in hydro structural design concepts since 1932. Specific experience includes industry driven hull optimisations for propulsion efficiency, optimized motion response, mooring design and optimised bottom moorings, structural hull monitoring systems for fatigue and ultimate loads and multi body dynamics in floating arrangements and cargo configurations. | The experience of MARIN with technical challenges across the wide range of maritime industry was combined with the operational experience of the other partners to work out functional requirements as the starting point for the O&M procedures. |

| | | |
|---|---|---|
| | Background R&D aimed at innovations in maritime technology solutions has always been a part of MARIN's strategic mission in order to be able to provide support to the expected industry needs in the short term future.<br><br>MARIN relies on a staff of around 350 dedicated people. The nature of the provided assistance includes model scale investigations, on board measurements and troubleshooting campaigns in service condition, numerical studies and training in full sized simulators. | |
| MOCEAN | MOCEAN is an independent Marine Engineering consultancy company focussed on marine innovations, offshore installation and offshore designs.<br><br>Being physically accurate and embracing research topics within projects enables MOCEAN to bring innovation projects to life. Projects where no precedence is available benefit from accurate numerical modelling capabilities combined with a long-standing experience of the practicalities of offshore operations. This unique combination has led to our significant contribution to a range of industry first developments or studies, such as Space@Sea. | The offshore experience and the responsibility w.r.t. the Space@Sea Business WP1 resulted in being the Deliverable Leader for the WP5. Mocean was responsible for combining the knowledge of the two additional partners and providing a general O&M Lifecycle Scenario assessment for Space@Sea. |

## 1.2 Scope of Work

Task 5.4 O&M will evaluate and document operational procedures, major maintenance scenarios, and their impact on the "payload" modules on top of the floaters. The results should enable the comparison of floating island solutions with classic concept as needed to evaluate cost-benefits for the cradle to the grave lifecycle of a floating island concept.

This deliverable is developed to provide O&M information into WP1, as a pre-determined task being *Milestone (MS)-08*, where the business case for a floating island is worked out for a specific case. The MS-08 has been completed on 05/06/2020.

The challenge to a review of operation and maintenance considerations for large scale floating islands as covered by the *Space@Sea* project is the fact that they do not yet exist. A floating island design iteration is evaluated in the project, but details are missing for major part as the development is an iterative process. Full blown and detailed evaluation of O&M considerations will be a part of later design iterations. At this stage however a first evaluation is done with respect to the specific things that are particular for floating islands.

## 1.3 Approach

The flowchart represented in Figure 1-1 reflects the strategy used for the research discussed in this report. This final strategy was constructed after multiple iterations and trials during writing.

Floating island structures of the type considered in space at sea are not in operation or even designed yet. A list of required Operations and Maintenance procedures for floating islands is thus unavailable at present. It was the principal goal of this research to define or propose such an O&M activity list. This was based on "fundamental functions" of the *Space@Sea* floating island and the notion that O&M activities should follow from their purpose to ensure prolonged and reliable performance of these fundamental functions. The identification of fundamental functions of the floating island that need to be ensured by O&M is thus the starting point of this report.

After defining the fundamental functions, the O&M activities are determined. Experience with bottom-fixed and floating offshore windfarms is used as the basis to determine/estimate the O&M activities and related cost of the *Space@Sea* floating island. It is noted that the operational expenditures of a bottom-fixed windfarm equal the total investment cost after a lifetime of 25 years. It is expected that the operational expenditures for floating structures will be higher.

Once the functional requirements are defined and compared with the current offshore wind market, this paper will consider a specific case where the functional requirements and its list of prioritized O&M activities, together with its associated operational expenditures will be applied on and will provide the input for WP1 business case.

A future outlook chapter is added to focus on the innovations which can bring opportunities and benefits to Space@Sea.

This report concludes with essential O&M activities and its associated financial assessment and will show high level the outlook of operations & maintenance activities in the future with target 2030.

Defining these components on a basic level and determining their level of risk, will show a list of prioritized operations & maintenance procedures and their financial consequences. In the end this list allows a comparison to the already mentioned solutions and aids in justifying the decision when choosing a concept which satisfies the Space@Sea purpose.

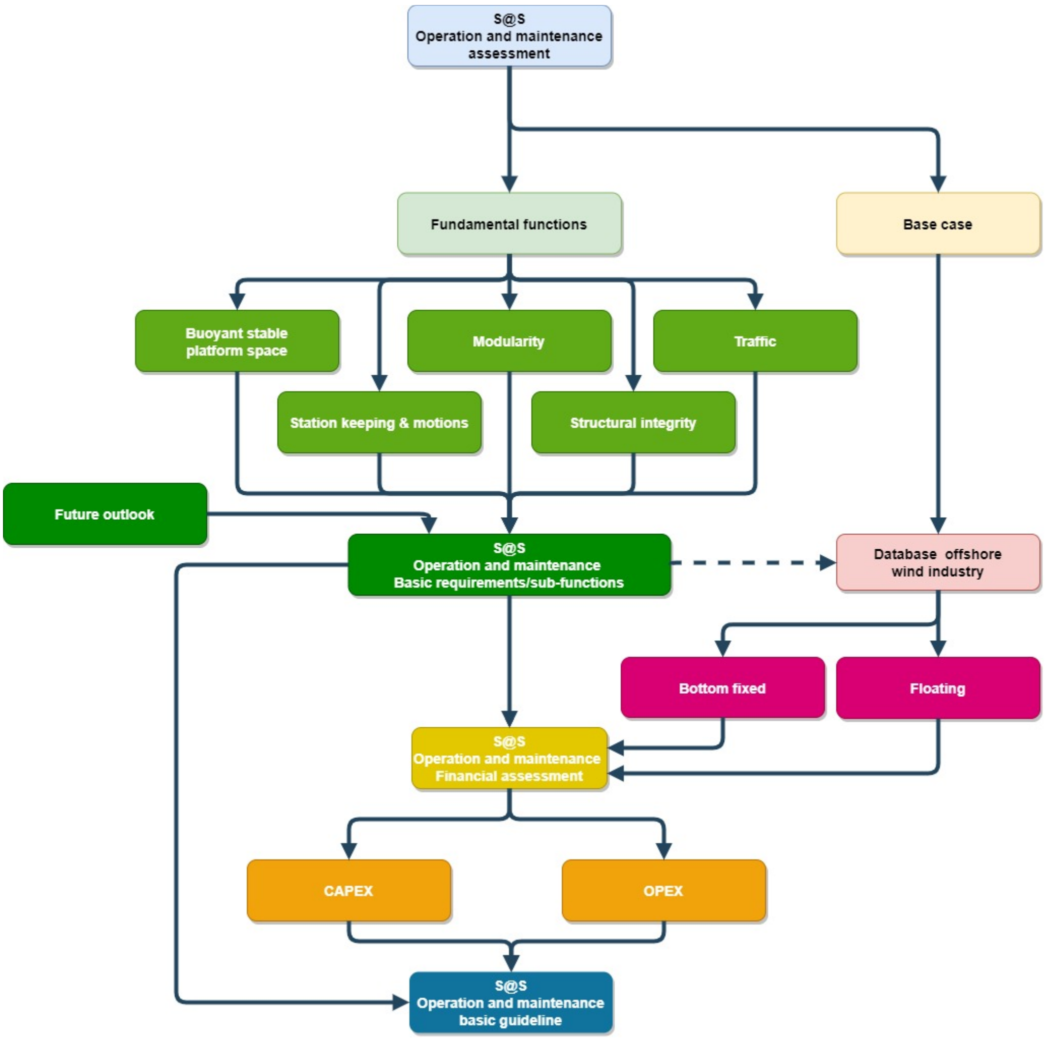



Figure 1-1 Strategy flowchart for O&M assessment

# 2 Fundamental functions

O&M procedures aim to ensure the functionality of the underlying structure. That functionality can be broken down in a part related to the floating base, and a second part related to the installed payload on top. This present review is focused on the functionality of the floating base structure. It should be noted that O&M for the top structure will be part of the detailed design for the business application and is not further discussed in this paper. This topic is subject for further assessments beyond the Space@Sea project.

The minimal functionality of the floating *Space@Sea* island that has to be ensured by an O&M regime is broken down in following aspects for present scope;

| | |
|---|---|
| Buoyancy | The primary function of the floating island is to provide effective floating space at sea |
| Station keeping | The assembly has to maintain its intended position |
| Modularity | The configuration of the island comprises of many individual floaters. The strength of the *Space@Sea* concept lies in the fact that it is possible to remove or add modules, and change the configuration of the island based on the location and weather conditions |
| Traffic | Movement of personnel, goods, spare parts, energy, fluids and utility flows should move to, from and across modules in an efficient and simple matter |
| Structural Integrity | The single floaters, as well as the assembled island, should stay intact during any kind of (harsh) weather conditions |
| Extreme events | The floating island should be capable to prevent any extreme events on its own (fire, collision, water ingress etc.) |

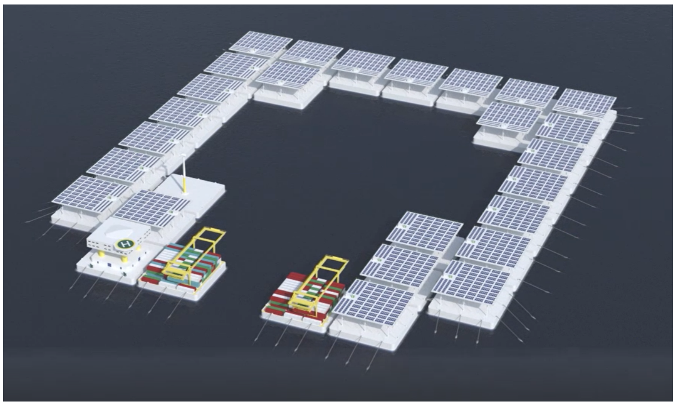


Figure 2-1 Indicative figure of an assembly in construction (Energyhub@Sea & Logistics@Sea)

## 2.1 Buoyant stable platform space

The primary function of a floating island is to provide space or working area for the application that is installed onto it. The principal functions of that space are listed as:

- Buoyant, useable space / working area. It should be resistant against foundering in both damaged and intact conditions.
- Level controlled (via ballasting). As dependent on operational use, the loading condition may change continuously by loading/unloading or by (quasi) permanent installation of heavy large structures.
- Sufficiently stability in local environmental conditions. Wind and wave induced motions should remain under specified limits for various modes of unrestricted or weather restricted operations on the platform.

Relevant parameters are:

- Draught and inclination
- Ballast system status & tank alarms

## 2.2 Station keeping & motions

Functional requirements for station keeping are broken down in a part that addresses the entire island and a part that addressed individual modules. The functional requirement for the entire island is that it has to maintain its intended position, and that individual modules have to stay properly connected to the island.

### 2.2.1 Full island station keeping

The floating island requires an arrangement to maintain a given installed position, or (in case of a self-propelled or controlled drifting concept) to maintain a designated track. Physical arrangements and operating procedures are required for either of these approaches. The basic function to be fulfilled is

- The instantaneous position (latitude; longitude) and orientation (heading) of the island configuration should not deviate from the reference point (fixed) or track (dynamic over time) and heading more than a given tolerance.

Different solutions can be considered to meet this functional requirement. Typically, mooring arrangements but potentially also less obvious options as tug and push boats, auto propulsion systems by thrusters, sails, under water kites, etc.

Relevant principal parameters are:

- Position reference location and heading
- Actual and to be expected external loads from wind, current, waves, ice, traffic
- Acceptable deviation from target position and alignment

### 2.2.2 Motions

The floating island will exhibit a level of dynamic response depending on sea state and the island configuration. These motions are an innate part of floating structures. Dealing with these dynamics should be an integrated part of the islands designed functionality.

Following aspects are considered to be relevant:

- Floater motions
- Relative motions between floaters
- Loads in the connection joints

Relations between these aspects, the environment and the operating degrees of freedom have to be known and monitored for a well-considered operations and maintenance regime.

Hot spots in terms of loading will most likely be the connection joints and their direct vicinity. The joints convey and absorb the loads and forces induced by external loads, mooring forces and relative motions. They should be sufficiently rigid to minimize local secondary motions while at the same time be flexible enough to deal with the global deformations that will occur in more severe weather conditions. Forces will be induced in and transferred by the joints. A part of these loads will be dissipative and cause surface friction, heating, structural damping, and possibly wear and tear. Principal functions for the module joints are:

- Constrain relative motions between modules (axial, transverse, vertical, bending, torsion, yawing)
- Transfer internal loads and absorb less constrained relative motions between individual floaters without excessive abrasion, wear and tear.

Relevant principal parameters are:

- Floater rigid body motions

- Relative motions between joint interfaces expressed in local system of coordinates with respect to maximum safe levels
- Induced reaction forces in joints with respect to maximum working loads

Secondary effects that may be used to evaluate progressive wear

- Abrasion and wear
- Temperature, and noise signatures

#### 2.2.3 Module joints

Each module has to be joined to other modules in order to make up the full island assembly. The joints used for that, needs to be strong enough to absorb and convey the internal forces as induced by external loads and mooring forces. They should be sufficiently rigid to minimize local secondary motions while at the same time be flexible enough to deal with the global deformations that will occur in more severe weather conditions. Forces will be conveyed via the joints. A part will be related to friction and cause structural damping, heating up, possible wear and tear. The joints will have to be able to deal with that. Proposed principal functions for the module joints are:

- Constrain relative motions between modules (axial, transverse, vertical, bending, torsion, yawing)
- Transfer internal loads and absorb resulting relative motions between forces

Relevant principal parameters are:

- Relative motions between joint interfaces expressed in local system of coordinates
- Induced reaction forces in the joint

### 2.3 Modularity

Modularity sets the *Space@Sea* floating island concept apart from other offshore floating structures. A configuration of multiple modules can be either (dis)assembled and configured on site or at the quay side. Such modifications can be called in case of changes to the operational requirements to the business application on the island as increased or decreasing scale or can be called for (un)scheduled maintenance or replacements of existing individual modules. That ability calls for specific operations and the ability to perform these operations has to be designed into the structure.

#### 2.3.1 Extend / adjust the island configuration in place

The *Space@Sea* concept enables the ability to extend the floating island assembly with additional modules if needed, making the concept flexible and retrofittable. It can be decided by the stakeholders to gradually build up the island to mitigate the investment risk or choosing the right application (Energyhub@Sea, Living@Sea, Farming@Sea, Transport&Logistics@Sea or others) at the right time.

The minimal functionality and operations required to enable this are expected to be:

- Temporary disengagement of the mooring system at the to be extended area
- Apply redundant or additional (mooring) capacity to ensure station keeping
- Disengage / engage module joints and remove / add and handle old and new modules
- Re-engage mooring configuration to comply with new configuration

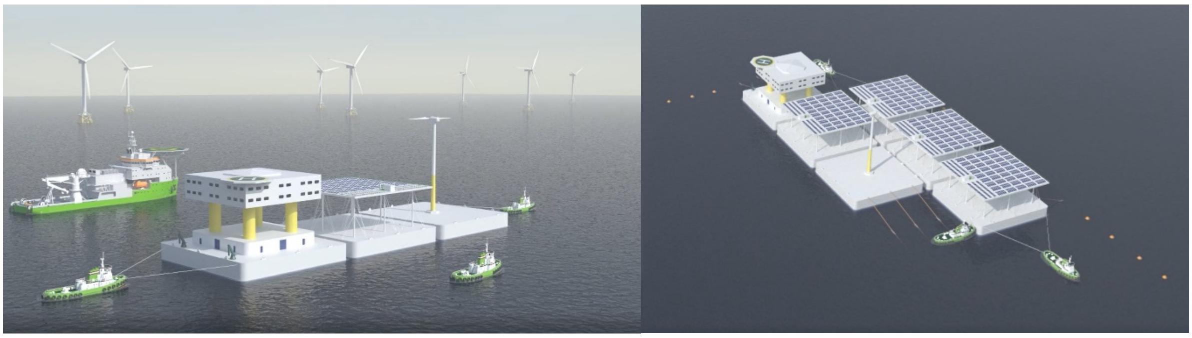


Figure 2-2 Towage and offshore installation floating modules (WP5.2)

#### 2.3.2 Adjust configuration / shape for (severe) weather

Vessels are prepared and sea fastened for anticipated bad weather conditions. Similar approaches may be needed for floating island configurations for the following reasons.

- Adjust / minimize windage to reduce wind induced drift loads onto the mooring system.
- Change alignment to waves to minimize drift forces by diffracted waves
- Change global island configuration to maximize structural capacity of intermodular joints. In particular choose proper balance between rigidity/flexibility and damping.

#### 2.3.3 Extracting single modules

Extracting decommissioning individual modules calls for similar operations as these configured to extend the assembly. The additional aspect however is how to deal with the extracted module. Following functionality/operations are considered relevant specifically for extracted modules.

- Should be individually towable
- Procedure for decommissioning, cyclic re-use of components and / or materials

### 2.4 Structural integrity

Structural integrity is the requirement that a structure can continue to fulfill its functional requirements for a much longer time after it is commissioned without breaking down. Engineering practice is to dimension structures to expected working conditions over a target life time. Prudent O&M implies that the exposure to loads, the structure response and condition of the structure itself is monitored and compared against design expectations. Scheduled preventive maintenance is needed to avoid unexpected break down by wear and tear. Breakdowns can be expensive because of unfavorable downtime and require unscheduled reactive repairs. The ability to monitor response and condition, perform preventive maintenance, and where needed repair and replace failing parts well before expected time of failure is an essential function of the O&M process. This runs from the individual module to the entire assembly. Specific considerations on measurements and monitoring solutions for floating islands are addressed in Space@Sea report D5.3 Remote Monitoring and are not further repeater here.

High capital value offshore structures are already being equipped with hull monitoring systems to track true hull condition against the designed condition. These are used to schedule timely maintenance, and avoid costly unexpected breakdowns by worn gear. Preventive maintenance will be essential as well for floating island structures to ensure performance of essential parts at times when they are needed most, and avoid expensive breakdowns, consequential damages and high unscheduled repair costs.

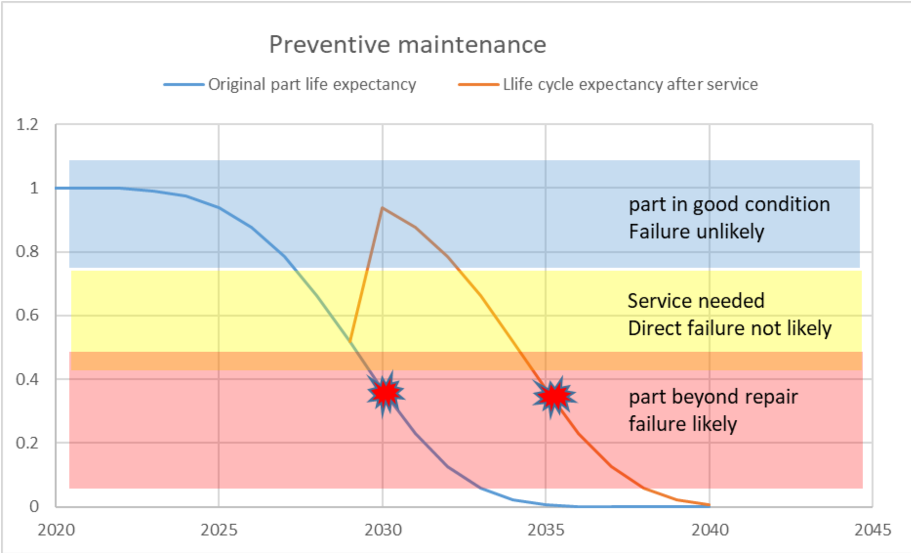



Figure 2-3 Lifecycle preventive maintenance

Monitoring structure condition perform preventive maintenance, and where needed repair and replace failing parts are thus essential functions. This applies to individual modules as well as to the entire island assembly. Essential aspects that are required for this are:

- A model that describes the condition of structural parts as function of time and environmental loads
- A means to monitor the status of actual structural parts with respect to the design assumptions
- Means to capture the actual environmental loads as compared to design assumptions
- Ability to perform preventive / reactive maintenance to restore condition to a level where likelihood of unexpected breakdown is low

### 2.4.1 Individual module

The functions of individual modules that are related to structural integrity are listed as follows:

**Buoyancy & space, continued ability to carry payload.**

- integrity of principal structure,
- wall thickness
- water tightness
- marine growth at exterior and in piping system

**Ballasting capacity, continued ability to maintain required draught and inclination.**

- Ballasting infrastructure
- pumps, piping
- draught and sounding system and alarms

**Strength, continued ability to absorb and transfer external loads from moorings, joints, and other interfaces.**

- Wall thickness
- Corrosion & corrosion protection
- fatigue at member joints and welds
- cracking and plastic deformations

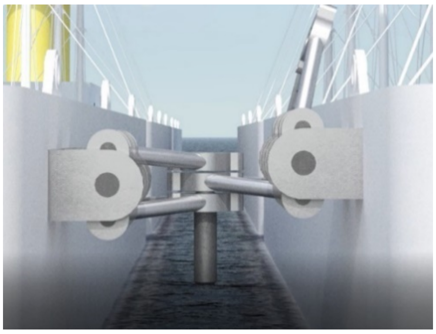


Figure 2-4 Smart flexible connectors designed by ICE [ref. D4.4]

#### 2.4.2 Full Island

Structural integrity of the full island is the sum of the integrity of the individual modules added with the overall performance of the inter module joints, and the global mooring system. The functions in that aspect are:

- Continued performance of the intermodular joints to maintain the shape and structural rigidity of the full island assembly.
- Continued performance of the mooring system to maintain position and alignment of the island assembly.

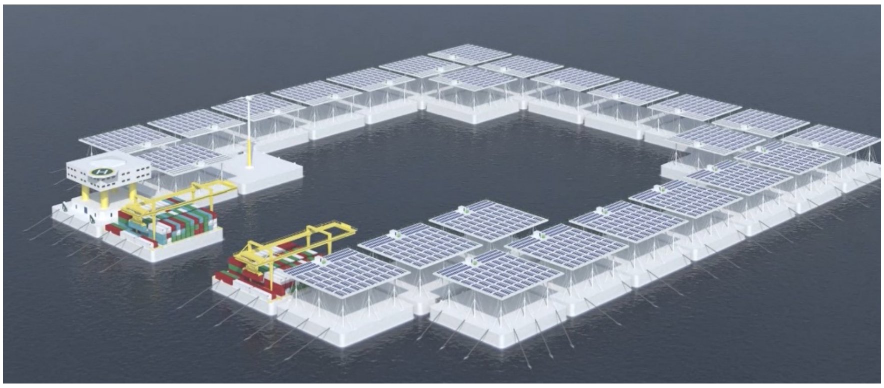


Figure 2-5 Island configuration in construction

Status of connection joints to maintain the shape and structural rigidity of the full island assembly.

- Wear pattern
- Condition of abrasion pads
- Temperature images
- Noise signature

Performance of the mooring system to maintain position and alignment of the island assembly.

- Chain pretension
- Thickness of chain links at high load locations
- Condition at anchor points
- Performance at chain stopper locations

#### 2.4.3 Monitoring

Structural integrity ensures continued performance of specific functions in accordance with their design expectations and is called preventive maintenance and consists of pre-determined maintenance and condition-based maintenance and is shown in below figure. Reference is made to *WP5 – deliverable 5.3 remote monitoring* for more information.

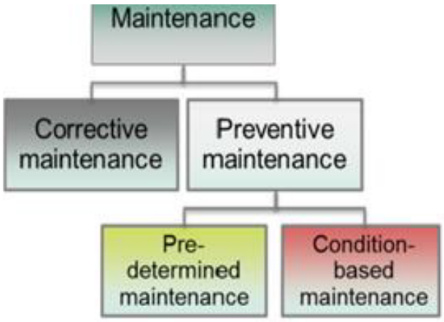



Figure 2-6 Corrective and preventive maintenance infrastructure

#### 2.4.4 Extreme events & Alarms

Part of operational practice is minimizing risk for extraordinary and extreme events. For the floating island these are listed to be at this moment:

- Fire hazards
- Ship collisions
- Inert / explosive gas in enclosed spaces

## 2.5 Traffic & logistics

The operation of a floating island will involve various flows between the exterior and the interior of the island, and also across the boundaries of individual floaters that make up the island. These aspects are basic requirements to accommodate operation of the island and as such they are expected to be part of the basic functional requirements.

Following flows are identified:

#### 2.5.1 Personnel traffic

Technicians / passengers / inhabitants should be able to enter onto, move across and leave the island configuration. Functionality should include boat landings, port area, helicopter decks, motion compensated bridges, pavements, underdeck passageways and many more. Requirements for solutions should include operations and maintenance to ensure solid foothold, lighting, weather and fall protection along the full island.

#### 2.5.2 Goods and spare parts

Transfer of goods and spare parts is an essential part of operation of a large facility. On a floating island this will include large flow of goods from the exterior onto the island via port or helicopter deck, but also an internal flow across floaters. The floater decks will not have unlimited load carrying ability. Requirements and limitations for transfer of heavy goods and/or spare parts in bulk or specific CTU across the floater decks, or moving and operation of heavy machinery (cranes) for operation and maintenance purposes have to be further worked out in a next phase of the *Space@Sea* project. A dedicated floater for O&M purposes only should be taken into account during the design phase.

#### 2.5.3 Exchanging utilities - Energy, water, waste and data

The individual floaters on the island will be hooked up to share joint utility resources. Typically energy, water, waste, and data. A means to exchange these will have to be defined and operated. The implementations will have impact on the ease of installation and modification of the configuration as listed under modularity. Standardized approaches for the hookups may be needed if floaters from different contractors have to be suited to couple together. This applies to the mechanical implementation of transfer of energy, water and gas. It may apply to software infrastructure where it comes to data hookups.

- Energy flow (gaseous, fluid, electric)
- Fresh water
- Waste treatment (grey water, sewage)

- Operational data network

# 3 Operations & Maintenance activities

This chapter will focus on specifying O&M activities. The experience of the workgroup partners with O&M in offshore wind is used as a starting point. An overview of O&M activities is developed starting with "simple" bottom fixed offshore wind fields (a), from there to more complex moored and floating offshore wind (b), and finally to the multi modular floating and moored floating island concept (c). The activity list for the floating island is checked against the functional requirements specifications of previous chapter.

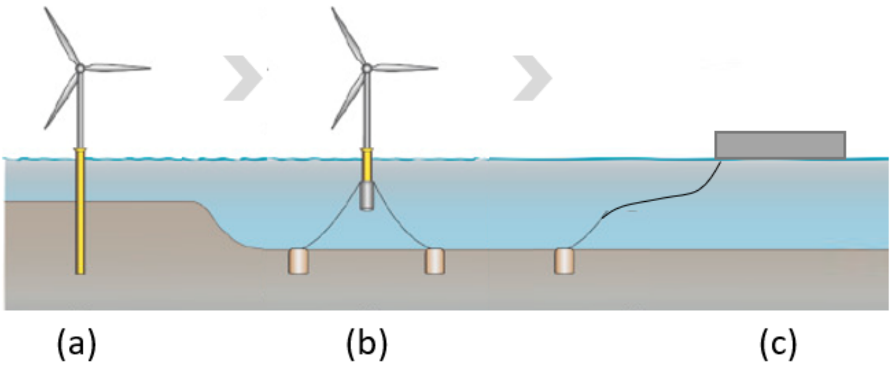



Figure 3-1 Chapter 4 description reflecting the chronological order of origin of data.

It is noted that operations and maintenance of offshore windfarms contributes with a substantial part of the total levelized cost of energy (LCOE). The total operational expenditures (OPEX) after a lifetime of 25 years equals the total investment cost of an offshore windfarm. This shows the importance of keeping the windfarm operational by maintaining the assets in order to extend their lifetime and avoid failures and damages which could harm the production of green electricity.

In order to maintain the offshore windfarm, visual inspections are required to monitor the structural health of the components and structures. Offshore windfarm operators have long-term service contracts with offshore contractors to perform these visual inspections and repair/replace if required. Their job is to keep the turbines spinning to generate electricity and in case of damage, to repair and/or replace as fast as possible.

The objective of this chapter, together with chapter **Fout! Verwijzingsbron niet gevonden.**, is to provide a high level but qualitative overview of the offshore Operations & Maintenance (O&M) activities that are required to keep an offshore windfarm operational. As described in section 2, this report is only focusing on the assets that are below water or afloat. All structures and/or components above the structure is not subject of this report. This means that this section will not describe the O&M activities of the transition piece, turbine tower, nacelle, blades etc. but only the foundation and cables.-

*It is noted that the floating wind industry is a complete new and emerging market resulting in limited available data on the O&M activities. However, the oil & gas sector is using floating structures for decades (e.g. Floating Production Storage and Offloading FPSO) and has built up many data on how to operate and maintain floating objects in open sea. This latter explains why large oil & gas companies are leading the floating wind market due to their large experience and extensive knowledge.*

## 3.1 O&M reference cases

This section shares the existing knowledge on the O&M for offshore bottom fixed and floating windfarms, used as reference cases to aid the creation of the Space@Sea O&M program evaluated in 3.2.

### 3.1.1 Offshore 'bottom fixed' windfarm

An offshore windfarm consists of wind turbine foundations, with on top a tower and nacelle. Each turbine is connected with an inter array high voltage cable in a string setup. All strings are collected in an offshore high voltage substation (OHVS) where the electricity will be transformed (and if required converted) to an allowable voltage to export the electricity to shore through the export cable. Each wind turbine foundation requires scour protection (rocks) to prevent scour effect around the foundation and on top of the cables embedded in the seabed. Below figure shows the infrastructure of an offshore 'bottom fixed' windfarm.

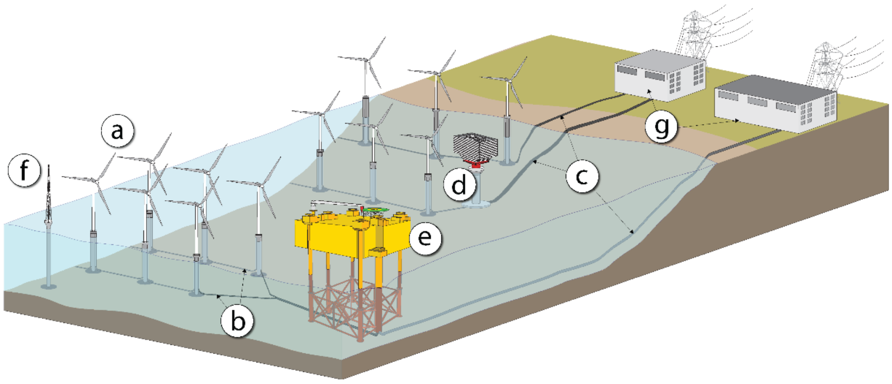



Figure 3-2 (a) wind turbines and foundation, (b) inter array cables, (c) export cables, (d) transformer station, (e) converter station

All the above-mentioned assets require frequently inspections and preventive maintenance. The frequency of these inspections is mostly described in an O&M program schedule. Depending on the contractor, an O&M program schedule is divided in above water and under water inspections. Considering the above figure, above water inspections implies the tower, nacelles and the top structure of the transformer and/or converter station. Below water inspections implies the turbine foundations, inter and export cables and also the scour protection around the foundation and on top of the cables.

*Note: This chapter is using a fictive offshore windfarm with 50 turbines as reference to explain the frequency of operations & maintenance activities and its associated cost.*

The following chapters will be further described:

- Below water inspections
  - Foundations
  - Cables and scour protection

#### *3.1.1.1 Below water inspections - foundations*

On a yearly basis, underwater inspections of foundations shall be performed by means of a remotely operated vehicle (ROV) and supporting vessel on an average of 20% of all wind turbine foundations including the transformer/converter station. This percentage is highly depending on the requirements of the offshore windfarm operator but is generally taken as rule of thumb. The appointed foundations per year are mainly spread over the offshore windfarm where water depths are varying, resulting in different wave conditions and different impact on the below water structures. When applying 20%, this means that all foundations of the offshore wind farm have been inspected after 5 years.

The inspection campaign of the foundation is mainly executed during good weather seasons as this period allows the O&M contractor to deploy its vessels and ROV's, limits the risk of weather delays. The time lapse between two consecutive yearly underwater inspections shall not exceed 14 months. Apart from purely visual inspections and recording, the ROV setup shall allow for basis marine growth thickness measurements on the foundations which can be executed during the inspection campaign. These measurements should provide a rough estimate of the marine growth thickness on the foundations and will be further analyzed onshore. When the marine growth exceeds a certain pre-defined thickness, an additional campaign should be setup in order to remove the marine growth. Monitoring marine growth on the foundation can also be done with tailor made sensor devices and is described in WP5.4 – remote monitoring.

In general, marine growth build-up in splash zones on oil & gas platforms and offshore wind farm foundation has direct consequences. It adds static weight to the foundation, and it increases the diameter and surface roughness resulting in increasing dynamic and hydrodynamic loadings associated with wave and tidal actions on the structure. Until now, controlling marine growth has been an expensive and time-consuming process. Expensive because this extra weight and roughness has been taken into account for the design and time consuming to monitor and clean the foundations.

Below table shows an indicative example on the most stringent O&M activities that should be performed during the inspection of the wind turbine generator (WTG) foundations.

Table 3-1 Below water inspections offshore wind

| **Description of activity** | **WTG** |
|---|---|
| Inspection of submerged foundation surface incl. marine growth, coating and possible external collision damage | X |
| Inspection of tidal replenishment holes in the foundation surface incl. coating and marine growth | X |
| Inspection of status and check of consumption of sacrificial anodes on the anode cage around WTG foundation (monopile) / J-tube cage on OSS foundation (monopile) | X |
| Inspection of anode cage (AC) including its supports on the foundation | X |
| Inspection of J-tube cage including its supports on the foundation | |
| Inspection of anode cable connection of the anode / J-tube cage to the MP surface | X |
| Inspection of submerged part of the boat landing(s) and access arrangement(s) as well as their connection to the TP (this might require a certain degree of marine growth removal, for purpose of enabling inspection), incl. marine growth, coating and possible external collision damage | X |
| Inspection of cable protection systems (CPS), starting at the cable entry holes up to where they enter in burial | X |
| Inspection of scour protection in the first meters around the foundation, including the position where the CPS enters in burial | X |
| Spot checks of marine growth thickness on the foundation (enabling to map the marine growth thickness related to depth under still water level and orientation) and/or anode surface | X |

The above inspections require a capable vessel with sufficient deck space and certified personnel to operate the ROV. The observation or inspection class ROV should be suitable for the envisaged environmental conditions and equipped with ultra-high definition camera and a marine growth removal tool to enable inspections, and not for cleaning purposes. Optionally, the ROV can be equipped with additional sensor devices to measure the water quality during its inspections, allowing the O&M contractor to provide offshore wind farm operators additional useful data on the water quality without obstructing the anticipated inspection activities.


Figure 3-3 Inspection ROV inside offshore windfarm (indicative)

Generally, the O&M contractor is free to plan his work in these yearly periods in close consultations with the client, as long as the time lapse between the inspections does not exceed. Contractor should deliver for each activity an inspection report describing the methodology, the processing and results. All visual data will be delivered to the client for review. In the case that the underwater inspections would give an indication of damage, defect or any other irregularity, cleaning and/or repair by means of a working class ROV might be needed. The client can, in such case, request the contractor to prepare and execute the works with generally a notification period of at least 4 weeks prior to execution.

#### *3.1.1.2 Below water inspections – cables and scour protection*

On a yearly basis, underwater inspections of cables shall be performed by means of ROV on all cables. The yearly inspection campaign will most of the time be executed during good weather seasons as this period allows the contractor to deploy vessels with multi beam echo sounders (MBES) for both bathymetric and topographic surveys and limits the risk of weather delays. The time lapse between two consecutive yearly underwater inspections shall not exceed 14 months. Below figure shows an example of a MBES system.

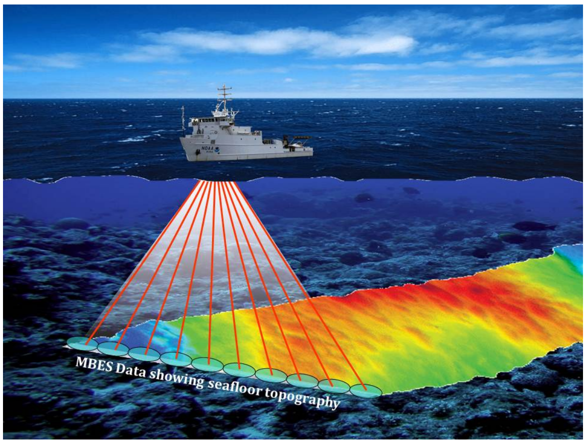



Figure 3-4 Subsea topography survey/inspections

Multibeam bathymetry over the cable routes will be executed over a width of 50 m for the cables and the scour protection and surrounding seabed will be inspected in an area of 125 m diameter around the turbine foundation and around 200m diameter around the transformer/converter station.

Bathymetric multibeam survey is a discrete beam formed, vessel-mounted multibeam system and includes full quality control and data processing facilities capable of providing data binning statistics, final sounding density, geo-referenced XYZ data in digital format, contour maps and profiles. The sounding system has a real time bathymetric display to provide confirmation of data acquisition and preliminary assessment of gross bottom features. The survey is conducted at a constant speed to achieve the same density of data (5-15 knots). This speed will be adjusted such that the quality of the data gathered is not affected.

#### 3.1.2 Offshore 'floating' windfarm

Floating wind turbines does not have a bottom fixed foundation but are replaced by a floating platform, mooring lines and anchor points. The inter array and export cables are still existing, however these cables are more flexible to withstand more dynamical loads. This is shown in the below concept drawing.

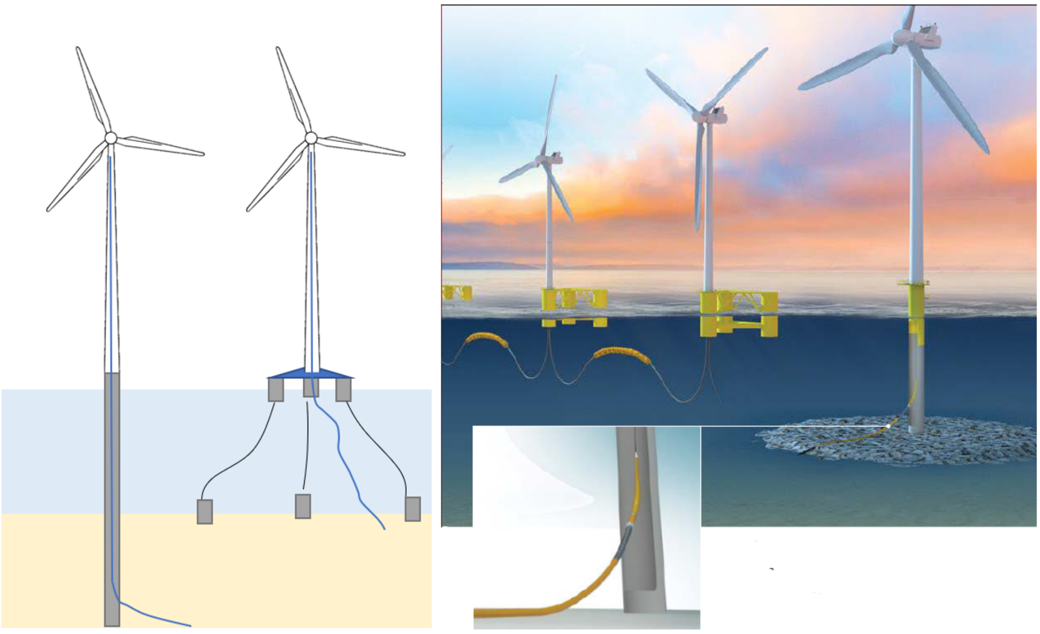


Figure 3-5 Infrastructure of cables for from fixed monopile to floating wind turbines

Based on the above provided O&M activities, it is assumed that for floating wind farms the following inspections are required.

- Below water inspections
  - Foundation inspection (floating structure)
  - Pile anchor inspection
  - Mooring line inspection
  - Cable inspection
  - Chain stopper inspection
  - Scour protection inspection

The above list shows that an extra asset (mooring system) has been added to the list which requires frequently inspections due to its dynamical behavior. Mooring lines are constantly under heavy load conditions and are a very critical asset in the balance of plant. Additionally, mooring lines are very attractive and sensitive to marine growth which could have a major impact on the lifetime of the mooring lines and the floating foundation on its turn. Therefore, special attention has been made in this paper for the inspection and maintenance of the mooring lines and its connection to the foundation and floating module.

##### *3.1.2.1 Below water inspections – floating module*

Same as for bottom fixed, on a yearly basis, underwater inspections of the floating foundations should be performed by means of ROV to monitoring the structural integrity and the appearance of marine growth. Because these floating foundations suffers more than bottom fixed foundation, this paper assumes that on a yearly basis all foundation should be inspected. Same as for bottom fixed, a yearly inspection campaign will most of the time be executed during good weather seasons as this period allows the contractor to deploy ROV's and limits the risk of weather delays. Because it is assumed that this type of foundations requires an inspection of all units, it might be that some foundations can't be inspected during the good weather period and depends on the total amount of floating structures.

For this type of foundations, apart from purely visual inspections and recording, the ROV setup shall allow for basis marine growth thickness measurements on the foundations. These measurements shall provide a rough estimate of the marine growth thickness.

#### *3.1.2.2 Below water inspections – mooring system, cables and scour protection*

A mooring line can be damaged or in worst case brake due to several reasons listed below. This section provides a high level but qualitive understanding on the inspection of mooring lines with a ROV.

Marine growth is a term that is used to specifically refer to species that attach to or grow on the mooring lines, which often causing problems in the functionality. The process of plant and animals growing on underwater structures are subject to more rapid corrosion. The total weight of the mooring line will increase drastically resulting in more loads and quicker degradation effects which are more described below. Additionally, marine growth covers the mooring line such that the effects of damages and breakage are not visible during ROV inspections. For this reason, it is highly recommended to consider a high marine growth inspection frequency with an associated cleaning operation based on a certain thickness level.

***ROV inspection and cleaning of marine growth on mooring lines***

Reference is made to D5.3 'remote monitoring' which is focusing on structural health monitoring, data collection and data interpretation. Sensor devices are being installed on several allocated mooring lines to monitor not only the loads but also the weight of a mooring line. If the weight increases linearly over a certain period, this could mean that marine organism has grown on the mooring lines. There are two (2) thresholds that should trigger the O&M contractor to visit the offshore site;

- When the total weight of the mooring lines exceeds a certain limit (unplanned O&M schedule). This task is part of D5.3
- Before inspection of the structural integrity of the mooring lines (planned O&M schedule) and this task is part of D5.4

By using a purpose made ROV, it can both inspect and remove marine growth if required. The ROV makes use of specific nylon bristles or high-pressure water jets to remove the marine growth without damaging the mooring line.

The quantity and duration of marine growth is site specific and should be further assessed when more details are available on the offshore location. In this report, it has been assumed that every two (2) years a planned inspection and potential cleaning operation should take place prior to the inspection of the structural integrity of the mooring lines which has a frequency of each two (2) years.

The Figure 3-6 shown the revolutionary marine growth control solution from the company *Foundocean* offers wind farm operators a continuous sweeping tool made of rubber rollers. Due to its buoyancy, it moves along the waves and cleans the foundations eliminating the need for periodic cleaning and substantially reducing the O&M cost.

Figure 3-6 Offshore Marine growth

***ROV inspection of structural integrity of mooring lines***

The ROV inspection of the structural integrity of the mooring lines includes many different aspects. This section provides a high level but qualitive description on the different aspects that should be inspected.

- Inspection of corrosion and corrosion protection
- Inspection of wear and damage
- Inspection of straightness of the mooring lines
- Inspection of the relative pre-tensioning of the mooring lines
- Inspection of trenching

*Inspection of corrosion and corrosion protection*

Cathodic Potential (CP) readings of a mooring system are not only important in determining whether individual components are cathodically protected against corrosion or are freely corroding, but also in showing whether the Cathodic Protection System (CPS) is working as designed. CPS systems are mainly used in the offshore wind industry and on vessel designs for protecting the primary steel structure from corrosion. This can be either sacrificial anodes (blocks) or with impressed current cathodic protection systems. Both options are commonly used.

Based on the input from work package 3 (Bluewater) there is no CPS foreseen in the design of the mooring line. The design of the mooring lines foresees an extra steel thickness (so called Corrosion Allowance) designed for exposure of 50 years in corrosive conditions. This results in extra steel weight of the mooring line and associated extra cost.

Regardless of whether a chain allowance is included on the chain bar diameter or not, the chain should be periodically checked to ensure that the bar diameter is above the minimum strength requirements. This can be accomplished by either a go/no go gauge, a mechanical or an optical calliper device.

Corrosion patterns can be very useful in determining both the performance of the CPS and in identifying specific degradation mechanisms in certain mooring system components.


Figure 3-7 Corrosion inspection of catenary lines

*Inspection of wear*

Chains, unless held in significant tension, will naturally fall into a smooth catenary, assuming that there are no kinks, twist or dog legs in the chain, and as such the shape of the catenary will change as the load comes on and off the chain. In order for the catenary to change shape, each link has to move in relation to the links on either side of it, thus causing wear at the interface between the individual links, which is known as the inter-grip area. In a well-balanced mooring system, the wear should generally be in line with the axial load on the line as shown in the example below.

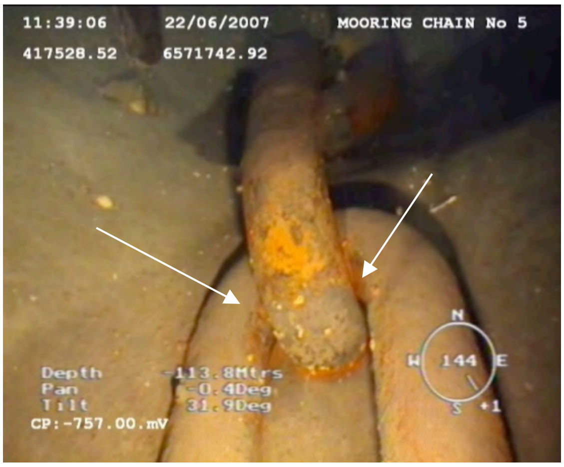



Figure 3-8 Wear inspection of mooring chain

If the system is not well balanced, or any of the lines are undergoing whipping action, the area of wear will be more spread out. It is important to monitor the wear rate on the chain links so that action can be planned in case the inter-grip bar diameter falls below a certain minimum strength level. This can be monitored with an ROV.

Not only the friction between two (2) chains gives damage, but also the friction between the mooring line and boulders and/or debris on the seabed could damage the mooring lines. When the damage exceeds the limit, one should take the boulders and/or debris away from the mooring line area.

*Inspection of straightness and relative pre-tensioning*

Fundamentally, for a mooring line to work as designed and analysed, all of its components need to be in good alignment. The alignment of each interface within the mooring system should therefore be checked at each survey by looking along the mooring line, as far as this is achievable, as illustrated in below figure left. Several images from slightly different angles should always be taken as perspective.

An ROV survey gives the opportunity to check the relative angles between the lines in a group to ensure that they are all sharing an equal load, as illustrated in the pictures below right.


Figure 3-9 Inspection of mooring line tension and straightness

*Inspection of trenching*

Unless the seabed is hard at the offshore site then it is likely that the mooring lines will have created some sort of trench due to movement both up and down on the seabed, and side to side, as the floating structure moves with the prevailing weather.

In some cases, the trenching can become very pronounced and affect the integrity of the mooring system. Also, if the trench or width of the marks on the seabed are wide this can indicate that the floating structure is moving extensively. Consequently, the size and shape of the trenches should be noted at each survey, particularly as a change in the size or shape of the trench can in some instances indicate that the behaviour of the system has changed. The following example pictures show the sort of images that are useful to look into this sort of behaviour. It is worth noting that the marks from the mooring components give an indication of how the mooring line has been moving.

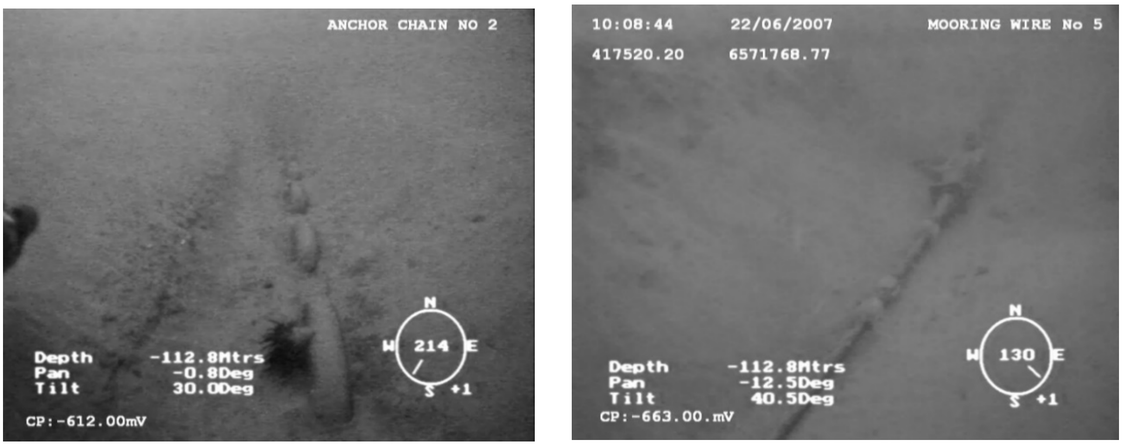



Figure 3-10 Inspection of trenching due to dynamics of mooring lines

#### *3.1.2.3 Below water inspections – Chain stoppers*

Most of the time, the chain stoppers for floating wind structures are located below water surface and requires an ROV to inspect the structural health. Nowadays, the chain stoppers have sensors to measure both the loads in the mooring line but also the structural integrity of the chain stopper. When the retrieved data shows anomalies, a visual inspection with an ROV is required to analyze the issue.

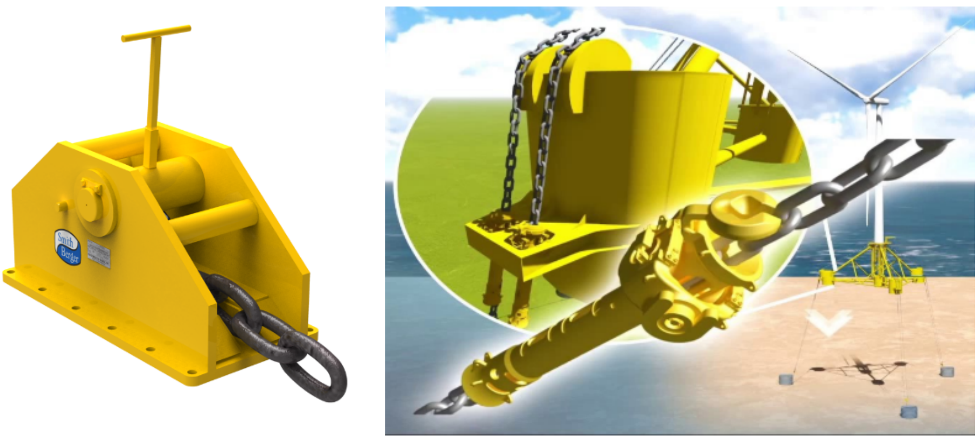


Figure 3-11 Examples of chainstoppers

## 3.2 O&M program – Space@Sea floating island

The space@Sea flaoting island configuration is more complex than a floating offshore wind unit. There are multiple dozens of units floating at the same location. Each has its own mooring and ballasting arrangments plus the additonal complications of very large driftforces, relative motions, linking forces and a very broad spectrum of activities taking place on the superstructure. The extra O&M considerations on top of the previously mentioned for fixed and floating offshore wind are reviewed using the functional requirements.

As indicated in section 1.1, DEME has the technical and financial expertise on the O&M of offshore bottom-fixed windfarms. Using this financial expertise together with the above described technical information allows us to provide a good understanding of the O&M activities of the Space@Sea floating island and its associated cost.

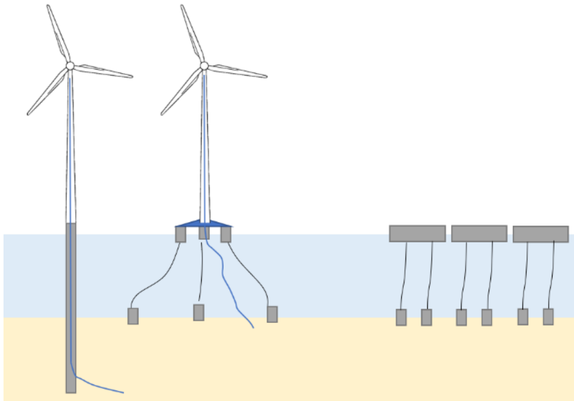
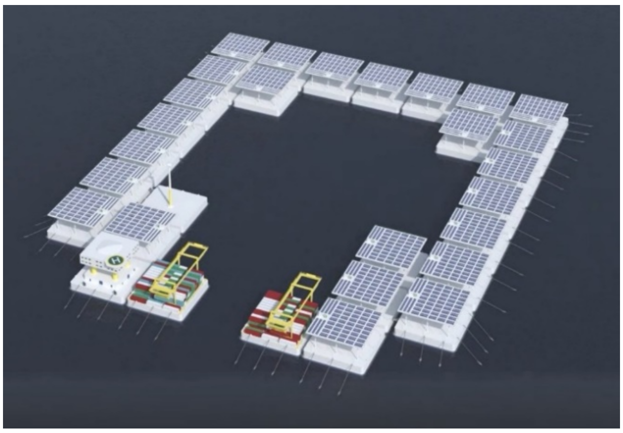


Figure 3-12 Transition from fixed to floating to S@S

This report considers the Mediterranean Sea case as, according to WP3, this turned out to become more feasible than the North Sea configuration, with respect to the design of the mooring system.

The island consists of 78 floating modules which are stowed into a square shape. The module is divided into different setups and each setup has its own application. Below table shows the different setups with on the left an indicative figure on a configuration with *Energyhub@Sea* and *Logistics@Sea* modules.



| | |
|---|---|
| *Energyhub@Sea* | **27 modules** |
| *Living@Sea* | 7 modules |
| *Farming@Sea* | 15 modules |
| *Logistics@Sea* | **2 modules** |
| *Wave Energy Converters (WEC)* | 27 modules |
| **TOTAL** | **78 modules** |

Figure 3-13 Island configuration Mediteranean Sea - Energyhub@Sea and Logistics@Sea

As shown in above figure, the Energyhub@Sea consists of floating modules with either wind turbines, solar panels or an O&M hub for offshore technicians. The Energyhub@Sea modules are connected with the mooring lines. The *Living@Sea*, *Farming@Sea* and *Logistics@Sea* floating modules are positioned inside the *Energyhub@Sea* and *Logistics@Sea* modules.

The wave energy converters will be installed on the outer side of the *Energyhub@Sea* modules which means that the mooring lines will be located below these modules. It also means that the *Energyhub@Sea* modules require specific chain stoppers which are located inside the modules to ensure that the WEC are not damaging the income mooring line.

The above island configuration, located in the Mediterranean Sea close to Marseille, consists of 78 floating modules which are connected with in total 71 catenary lines. Each mooring line is connected to a driven pile which is located approx. 750 meters away from the island and is mainly resting on the seabed as indicated in below figure.

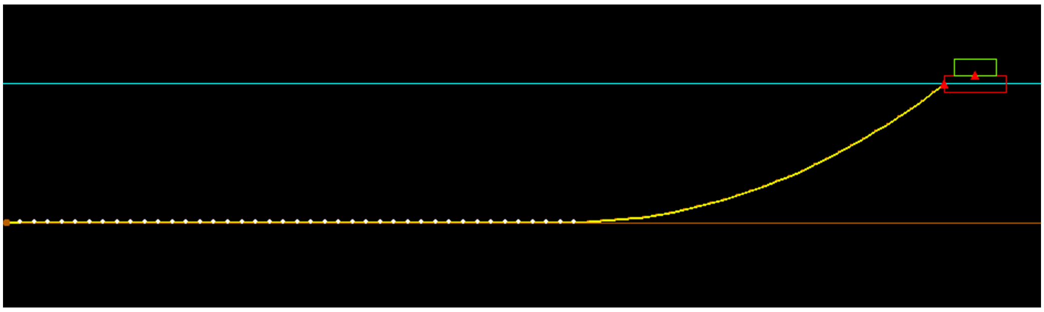


Figure 3-14 Anchoring in Orcaflex

One (1) catenary line weights approx. 370 ton, based on the provided design iterations from WP3 (*bluewater*). More technical data is provided in below table.

| Parameter | Unit | Value |
|---|---|---|
| Outside Diameter | [m] | 1.8288 |
| Pile Wall Thickness | [mm] | 30-50 |
| Overall Pile Length | [m] | 45 |
| Distance pad-eye to pile top | [m] | ± 15 |
| Pile Top Elevation | [m] | Level with Seabed |
| Embedded Pile Section | [m] | 45 |
| Estimated Pile Weight (Including pad-eye structure) | [tonnes] | 90 |
| Estimated weight mooring line | [tonnes] | 493 kg/m |
| Length mooring line | [m] | ± 750 |


Figure 3-15 Bluewater technical data

Taking into account the most predominately encountered soil types in the Mediterranean Sea being clay, sand or inter layered an anchor pile provides the most viable and cost-effective anchor point solution. More information on the anchor pile design can be found in WP3 and on the transport and installation in WP5.

### 3.2.1 Results from reference cases

#### *3.2.1.1 Outer shell and below water water inspections for corrosion & marine growth*

As stated in section 3.1.1.1, it is assumed that 20% of all foundations should be inspected on a yearly basis on the occurrence of marine growth. Applying this on the considered case results in the inspection of approx. 15 floating Space@Sea modules including the Wave Energy Converters.

Considering above table from Figure 3-13, it means that each 5 years, all floating modules have been inspected. Inspecting the foundations of 'bottom fixed' is relatively easy due to its static behavior. On floating foundations, it makes the job more difficult due to the movement of the floating foundations.

For the *Space@Sea* floating island, the inspection by ROV requires extra attention to not lose the ROV out of sight as the operator should operate the ROV constantly below the platforms. This project did not assess the ability to let a vessel sail between floating modules (below the connectors). This should be further assessed in a next phase of the Space@Sea project.

#### *3.2.1.2 Mooring system, cables and scour protection*

The *Space@Sea* floating modules consists of 71 mooring lines and are located relatively close to each other around the island. Based on the below drawing, the max. distance between two (2) mooring lines is approx. 10m. This setup is different with floating wind farms where each foundation has only 2 or 3 mooring lines which should hold the foundation at place. The impact when a single line breaks is much more significant on the remaining mooring lines compared to the *Space@Sea* floating island. However, the breakdown of a single mooring line is always critical and direct actions are required.

Same as for bottom fixed and floating windfarms, marine growth might occur on the mooring lines of the Space@Sea modules and should be monitored, inspected and cleaned if needed. Reference is made to section 0.

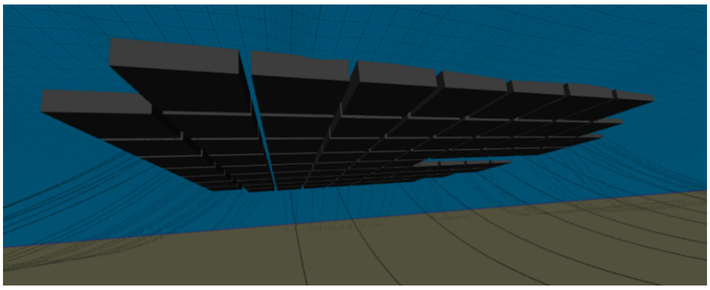
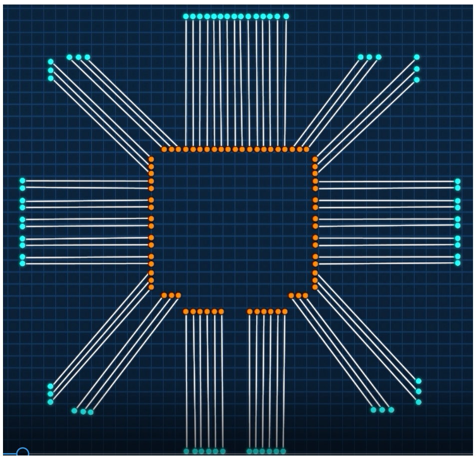



Figure 3-16 Space@Sea mooring system configuration

***ROV inspection of structural integrity of mooring lines***

Same as floating wind, ROV inspections are required to monitor the structural integrity of the mooring lines. This implies the inspection of corrosion and corrosion protection, wear and damage, straightness, relative pre-tensioning and potential trenching which has been discussed in section 3.1.2.2.

It should be noted that in the case of *Space@Sea*, the design of the catenary lines (reference WP3 – Bluewater) foresees corrosion allowance which means that no corrosion protection such as coating and/or cathodic protection is required. This means that the mooring line implies extra steel to overcome corrosion while keeping it structural health.

The *Space@Sea* floating modules makes use of a fixed pile anchor which is fully embedded in the seabed. This means that the connection of the catenary line with the anchor pile is embedded as well. Reference is made to *D5.3 remote monitoring* which describes the structural health monitoring of this connections. Critical trenching might occur at the location where the catenary line reaches the seabed level.

#### *3.2.1.3 Chain stoppers and module link connectors*

Above water inspections for the *Space@Sea* floating island consists of the inspection of the chain stoppers and connectors between the floating modules.

Inspection of the chain stoppers is required to analyse if the floating island has experienced any heavy loads during operation. As this is a critical asset in the mooring system, this should be frequently inspected and maintained if required. As stated in the conclusion above, for inspecting and maintaining these chain stoppers, there should be a service platform available for O&M technicians. This recommendation will be communicated to the designers of the platform.

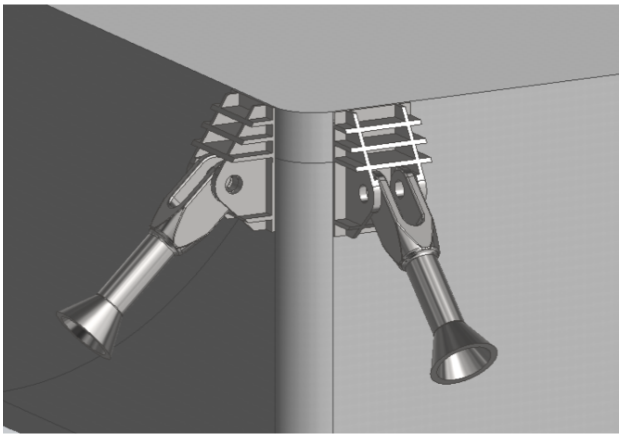


Figure 3-17 Chain stopper 3D-model

Calculating the various external forces on the anchor system such as wind, current and wave, with their combinations is difficult. A remote monitoring system could provide a great benefit here, such as the use of a load monitoring device comprising "load cells" in chain stopper for the real time measurement of mooring load on the chain. The system also includes wireless, intrinsically safe, portable monitors that can alarm at high loadings. This recommendation will be given to task 5.4 – Remote monitoring.

It should be noted that the Space@Sea project has not assessed the design of the chain stoppers and is subject for a next phase of the Space@Sea project. It is important to remark that the chain stoppers should be integrated in the floating module design on the bottom side as the wave energy converters are located around the modules which are connected to the mooring lines.

Inspection of chain stoppers is not new and is already done of floating wind foundations, but connectors between floating modules is something unique for Space@Sea and never done before. Due to the fact that supporting vessels cannot reach out to the connectors visualized in Figure 3-18, a special purpose made supporting crane is required to provide support during the (dis)connection and repair of the connectors. Visual inspections of the connectors can be easily executed by UAV's (ref. section 4.1).

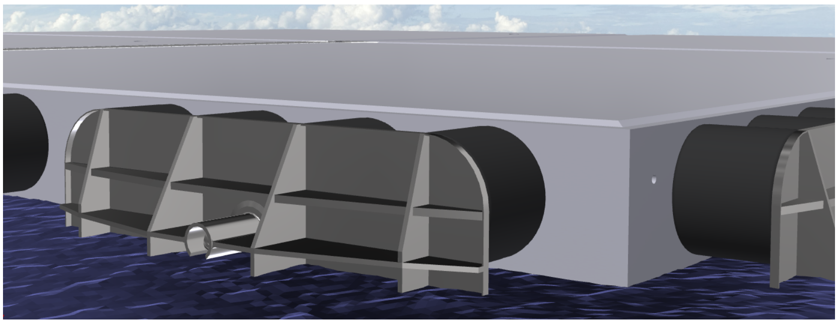


Figure 3-18 Flexible connector from D4.4

### 3.2.2 O&M to ensuring stabile and safe floating space

Each individual floater module should have an autonomous monitoring infrastructure to track that the actual state of the module does not deviate from the expected condition outside acceptable criteria.

#### *3.2.2.1 Floatability*

Water ingress is a primary hazard for any floating structure. Water ingress can affect the draught of the floater and may affect stability in case of not envisaged free fluid surfaces. Typically, all individual compartments should be outfitted with bilge alarms and pump capacity to deal with leaks. If larger breaches of shell integrity are likely then specific mitigating actions have to be developed to deal with it. These may vary from:

- Sealing the breach from inside/outside either temporary or permanent. Plugging the breach or overlaying it from outside with structurally suited material.

- Extract/eject the module from the island assembly to minimize collateral damage in case of foundering.

#### 3.2.2.2 Ballast condition

It is essential for the full island configuration that individual floaters are operated at proper draughts and inclining angles in order to minimized relative motions and loads in the inter connections. For that purpose it is essential that each floater is outfitted with a ballast management system. That system includes tank level gauging, platform draught and inclination, and a ballast water transfer system with pipes, valves and pumps.

It will be unpractical to manually sound individual ballast tanks because of the multitude of floaters in a full island configuration.

- Individual floaters should have draught, heel and trim sensors.
- Each ballast tanks should have a tank gauging system
- The floater should have a ballast water pump and piping arrangement

#### 3.2.2.3 Temperature / Fire

Fire is a primary hazard to the confined location that a floating island is. A fire alarm and firefighting subsystem has to be installed in place to mitigate this. Different alarm and firefighting requirements may well be considered at various locations depending on accessibility and sensitivity.

#### 3.2.2.4 Gas levels

The floating island assembly will be comprised of large numbers of floaters that each have their own above and below decks areas. In particular the below decks spaces are anticipated to be confined and may be expected to be sensitive to buildup concentrations of non-breathable, and possibly toxic or explosive gases. A gas detection system is required at all locations that are confined yet normally accessible.

Normal safety measures to access to confined spaces should be followed when entering not normally accessible or non-ventilated spaces.

#### 3.2.2.5 Motion levels

Motion levels will be part of limiting factors for internal loads, mooring performance, forces in the module joints, and for operations on the payload deck. Motion capture technology is presently not expensive anymore. It is thus noted that motions should be monitored on each individual module.

### 3.2.3 Modularity - Operations & Maintenance procedures and schedule

One of the major benefits of the *Space@Sea* floating island configuration is its modularity. By disconnecting the connectors and mooring lines it can be easily removed or replaced by another module. It should be noted that removing modules from the inside of the island configurations is more challenging and time consuming than on the outside. Additionally, removing a module has most likely an impact on the structural integrity of the remaining modules but this is not part of this work package.

Removal or replacement activities of floating modules is categorized in three (3) levels

| | |
|---|---|
| Level 1 removal | Consists of the removal of the outside floating WEC modules (red) |
| Level 2 removal | Consists of the removal of the outside floating modules (yellow) which are connected to the mooring lines |
| Level 3 removal | Consists of the removal of the inside floating modules (other colors) |

It should be noted that a level 3 removal consists of a level 1 and level 2 removal as the outside should always be removed before removing the inside. In some cases, this could be avoided by providing an entrance area inside the configuration (see later).

#### *3.2.3.1 Level 1 removal*

Level 1, visualized in Figure 3-19, removal consists of the removal of the wave energy converters (red shapes) by disconnecting the connectors on one, two or maximum three sides of the module. This requires both manual handling and one tugboat for maneuvering and removing the module out of the configuration. It should be noted that the design of the connectors is essential for an easy and efficient disconnection and removal of the floating modules. It is highly recommended to provide supporting cranes on the floating modules to provide support during the disconnection of the connectors and/or let the connector disconnect themselves without any human interaction. Crane support from an offshore construction vessel is not possible as this can't reach all sides of the modules.

Additionally, for removal of the WEC modules it is essential that the mooring lines are not blocking the movements. This should be assessed in a next phase of the *Space@Sea* project.

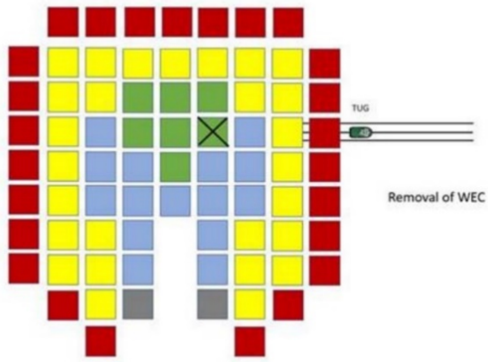



Figure 3-19 level 1 removal: WEC

#### *3.2.3.2 Level 2 removal*

Level 2, visualized in Figure 3-20, removal consists of the removal of the outside floating modules (yellow shapes) by disconnecting the connectors on one, two or maximum three sides of the module and the disconnection of the mooring lines. Same as above, this requires manual handling, in support of cranes, to disconnect the connectors. For this removal, an offshore construction vessel can be used to disconnect the floating module with the mooring lines as this can be reached on the outside of the island configuration. The OCV should also move the mooring lines away from the island and connect them temporarily to a buoy in order to provide sufficient space to remove other inner modules.

This requires both manual handling and one (1) tugboat for manoeuvring and removing the module out of the configuration. It should be noted that the design of the connectors is essential for an easy and efficient disconnection and removal of the floating modules. It is highly recommended to provide supporting cranes on the floating modules to provide support during the disconnection of the connectors and/or let the connector disconnect themselves without any human interaction. Crane support from an offshore construction vessel is not possible as this can't reach all sides of the modules.

Additionally, for removal of the WEC modules it is essential that the mooring lines are not blocking the movements. This should be assessed in a next phase of the *Space@Sea* project.

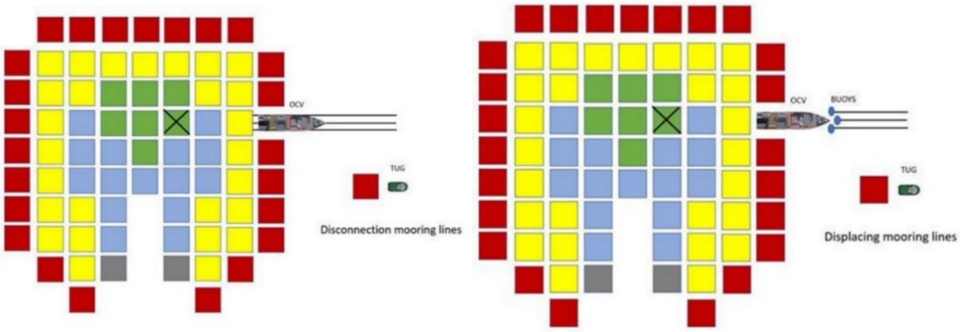



Figure 3-20 level 2 removal concept sketch

#### 3.2.3.3 *Level 3 removal*

Level 3, visualized in Figure 3-21, removal consists of the removal of all inner floating modules (green/blue shapes) by disconnecting the connectors on one, two, three or four sides of the module. For reaching level 3, it is of course required to first complete level 1 and 2.

Reference is made to task 5.2 where it was proposed to perform a triple towage, meaning that three floating modules can be towed to site. Also, for removal, this triple towage can be executed. All offshore equipment used for level 1 and level 2 is required for level 3 removals.

Same as above, this requires manual handling, in support of cranes, to disconnect the connectors and the mooring lines. For this removal, an offshore construction vessel can be used to disconnect the floating module with the mooring lines as this can be reached on the outside of the island configuration. The OCV should also move the mooring lines away from the island and connect them temporarily to a buoy in order to provide sufficient space to remove other inner modules.

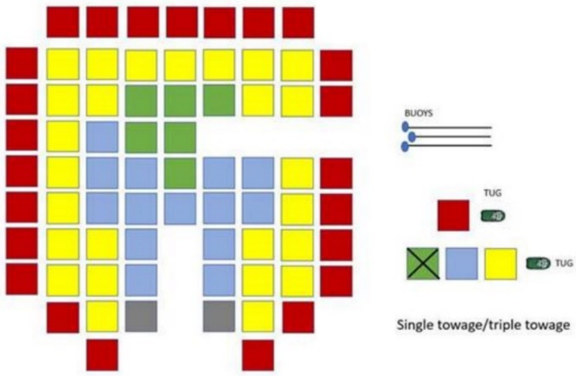



Figure 3-21 Level 3 removal concept sketch

#### 3.2.3.4 *Operational expenditures*

Since a level 3 removal consists of all previous levels, this report only focusses on the operational expenditures of that level. Below table shows the day rates of the offshore equipment and the removal durations.

Table 3-2 Duration estimate for removal activity

| NR | Removal Activity | Required marine equipment | duration |
|---|---|---|---|
| 0 | Sailing to offshore site | | 1 hour |
| 1 | Removal WEC floating modules | Tug A and Tug B | 2 hours |
| 2 | Disconnection mooring lines, replacing mooring lines | OCV | +4 hours |

| | | | |
|---|---|---|---|
| 3 | Disconnection inner floating modules | N.A. | +2 hours per module |
| 4 | Single / Triple removal towage<br>Offshore disconnection | Tug C & D / Tug C, D & E<br>OCV | +1 hours / single module<br>+2 hours / duo module<br>+3 hours / triple module |
| 5 | Sailing to assembly port | | 1 hour |

Assuming a day rate of 5000 €/day (all in) for one (1) tugboat and 120 000 €/day for an offshore construction vessel, the following table has estimated the cost per removal level.

Table 3-3 Cost estimate per level of removal

| **Level** | **Total cost per level** |
|---|---|
| Level 1 | 2 x 5000 €/day x 0.5 day = **5000 €** |
| Level 2 | 4 x 5000 €/day x 1 day = 20 000 €<br>1 x 120 000 €/day = 120 000 €<br>TOTAL: **140 000 €** |
| Level 3 | 5 x 5000 €/day x 1.5 day = 37 500 €<br>1 x 120 000 €/day x 1.5 day = 180 000 €<br>TOTAL: **217 500 €** |

### 3.2.4 Structural Integrity - Operations & Maintenance procedures and schedule

#### *3.2.4.1 Operations & Maintenance schedule Space@Sea floating island*

Below table shows all the assets applicable on the floating island which should be inspected and maintained but ordered in function of occurrence and impact level. For instance, the inspection of the pile anchor foundation is not possible due to the fact that it is completely embedded in the seabed. Additionally, the occurrence of any damage on the pile anchor is very low but the impact is very high, as this means that the full pile should be retrieved out of the seabed with is a very complex and cost-effective activity.

| O&M Asset and actions list – Occurrence and impact of Mooring system | | | | | |
|---|---|---|---|---|---|
| **Asset** | **Action inspection** | **Action Maintenance** | **Recommendations/integration with other work packages** | **occurrence** | **Impact** |
| Anchor pile foundation | Check the inclination of the anchor pile in the seabed with a pile inclination tool | Retrieve pile out the seabed and install pile back within tolerances | N. A | LOW | HIGH |
| Marine growth on pile stick up (above seabed) | Survey with ROV | Waterjet cleaning inside and outside pile | N. A | HIGH | LOW |
| Scour around the pile (cavitation) | Survey with ROV | Add painting 5m from top pile and install scour protection around the pile (rock dumping) | | HIGH | LOW |
| Pad eye failure – disconnection anchor foundation with mooring line | Survey the shape of mooring line | Retrieve pile from seabed and install new pile and mooring line | Can the design change to have a pile stick up with pad eyes above seabed? (WP3)<br>Structural health monitoring (WP5) | LOW | HIGH |
| Marine growth on mooring line | Survey with ROV | Clean the mooring lines if marine growth has reached a certain thickness | Structural health monitoring (WP5) | HIGH | HIGH |
| Mooring line failure | Survey with ROV on the shape/inclination of the mooring line | On-site repair with ROV/divers or onshore repair | Warehouse for spare parts onshore/offshore (WP1)<br>Structural health monitoring | MEDIUM | HIGH |
| Chain stopper failure (above water) | Survey with ROV | On-site repair with technicians | Foresee a service platform on the floaters<br>Structural health monitoring (WP5) | MEDIUM | LOW |
| Marine growth on floating modules | Survey with ROV | Clean the mooring lines if marine growth has reached a certain thickness | | HIGH | HIGH |

Table 3-4 Risk assessment of S@S O&M

It is concluded that only the O&M assets that result in a medium to high occurrence in combination with a medium impact on techno-economics will be further elaborated in this report. All assets will be further discussed in below sections while only a few will be described in detail.

***Below water inspections – anchor pile foundation inspection***

Due to the fact that the anchor foundation is completely embedded in the seabed makes it very difficult to inspect the structural integrity of the pile anchor. Reference is made to Task 5.4 remote monitoring for more information on structural health monitoring of the pile anchor. The occurrence of pile anchor damage is in this case very low as we consider steel piles which are 40m embedded in the seabed. When a damage occurs, this could have a high impact on the cost as this pile should be retrieved out of the seabed which is a very complex operation. Conclusion, the anchor pile will not be monitored with equipment nor inspected for damage as the occurrence is very low. Very low operational expenditures.

***Below water inspections – marine growth on pile stick up***

As stated above, the pile anchor is completely embedded in the seabed which means that the pile stick- up is limited. Marine growth on the top of the pile will occur but this should not create any risk. Conclusion, the occurrence is high, but the impact is very low which means that it should not be frequently inspected by an ROV. Very low operational expenditures.

***Below water inspections – scour around piles***

As stated above, the pile anchor is completely embedded in the seabed which means that the pile stick- up is limited. This means that the effect of scour around the pile is very limited, so occurrence is very low. In case of occurrence, the impact is very high as this has an impact on the structural integrity of the pile anchor and the mooring lines on its turn. Conclusion, the scour around the pile will be part of the frequent inspection campaign but it is not expected to spend budget for rock dumping in order to avoid scour. Low operational expenditures.

***Below water inspections – pad eye failure – disconnection mooring line***

Same as the anchor pile foundation inspection discussed in section **Fout! Verwijzingsbron niet gevonden.**, the inspection of potential pad eye failure is not possible as it is approx. 15m embedded in the seabed. Reference is made to WP5.4 remote monitoring for more information on structural health monitoring of the pad eye, connection between pile anchor and mooring lines. The occurrence of pad eye failure is very low due to embedment in the seabed, but it could have a major impact on the floating island configuration and the structural integrity of the other mooring line which should take over these loads, with the risk of further damage of other assets. Conclusion, the pad eye will not be monitored with equipment nor inspected for damage as the occurrence is very low. Very low operational expenditures.

***Below water inspections – marine growth on mooring lines and floating modules***

Any structure submerged in the sea will eventually host a community of marine organisms growing on and associated with its surface. This marine growth, or biofouling, is comprised of a variety of species depending on the location, depth and configuration of the structure. Marine growth on offshore structures can have consequences for structural integrity, hydrodynamic efficiency, and survivability, and may also encourage the establishment and growth of non-native or invasive species.

The industry consultation indicated that key concerns associated with the development of marine growth were biofouling mass, thickness, surface roughness, heat transfer properties, corrosion, and impacts on wet connectors. Marine growth can alter the weight of structures considerably. The weight of biofouling acting on a structure depends on the volume of biofouling and the relative proportions of hard, dense species and soft, less dense species.

A remote operated vehicle (ROV) can be used to visually inspect the marine growth on a submerged asset and/or to measure its thickness. When the thickness reaches a pre-defined limit, the ROV can be used to clean the marine growth with the use of brushers or water jets. Both the occurrence of marine growth on the mooring lines and floating modules is very high with an associated high impact level as these extra weight causes extra loads and drag. During an ROV visual inspection campaign, the contractor will measure the thickness the marine growth and if required clean the surface.

The inspection campaign starts early in the morning with the transfer from the port to the offshore site. It is assumed that the offshore site is approx. 1 hour away from the port. An O&M contractor works maximum 12 hours per day which means that it has only 10 hours per day to execute the inspections consisting of the activities listed in ***Fout! Verwijzingsbron niet gevonden.***

This table concludes that it takes around **14 working days**, excluding weather down time, to inspect 10 floating modules of the *Space@Sea* floating island. In below table, it is not considered that the O&M contractor stays offshore. In case they have the possibility to stay offshore, the price will go down due to no sailing time resulting in less fuel consumption and more working hours per day.

Table 3-5 high level cost calculation foundation inspection

| **O&M Activity** | **Unit rate [€]** | **Comments** |
|---|---|---|
| Mobilization and demobilization of the spread | 20 K € | Lump sum |
| Inspection of 10 floaters (incl. reporting) | 70 K € | 5000 €/day x 14 days |
| Provision of weather delay | 35 K € | Depends on the O&M contractor. This paper assumes 50% of inspection cost |
| Provision for fuel costs per year | 3.75 K € | Depends on the O&M contractor. This paper assumes 3% of total cost per year |
| TOTAL COST PER YEAR – below water inspections foundations | **128.75 K €/year** | - |
| TOTAL LIFETIME COST – below water inspections foundations | **3.2 mio €*** | 25 years lifetime |

*the total cost increases when client requests to repair when there is damage or irregularity. This paper assumes that during the full lifetime of a windfarm, it takes an additional 20% of the cost.

***Below water inspections – mooring line – chain stopper failure***

During extreme load conditions, for instance imposed by extreme weather conditions, the mooring lines and chain stoppers of the floating *Space@Sea* island might lead to failure, such as a single mooring line breakage or even a cascade of mooring line breakages with potential catastrophic collision consequences. Although the occurrence of mooring line failure is rather low, the impact level is very high. It should be noted that the occurrence of a single mooring line failure is higher than a cascade of mooring lines. The *Space@Sea* floating modules consists of approx. 71 mooring lines resulting in a redundant system which should be able to withstand extreme loads even when it should take over the loads during a single failure.

Mooring line failures are very difficult to inspect visually and especially when marine growth is covering it. It is very important that marine growth cleaning is performed before the mooring line inspections.

Considering the below lay out of the mooring lines on the *Space@Sea* floating island, it is required that all 71 mooring lines are being checked each year. Below table shows high level an estimation on the total duration and associated cost for inspecting the mooring line on both marine growth and structurally and clean them if required. In parallel, marine growth and scour around the pile can be checked optionally.

Table 3-6 high level cost calculation cable and scour protection inspection

| **O&M Activity** | **Unit rate [€]** | **Comments** |
|---|---|---|
| Mobilization and demobilization of the spread | 20 K € | Lump sum |
| Inspection of all mooring lines with a multi beam echo sounder (MBES) | 120 K € | Cost based on a length of approx. 1 km |

| | | |
|---|---|---|
| | | 5000 €/day x 3 mooring lines per day= 24 days |
| Provision of weather delay | 60 K € | Depends on the O&M contractor. This paper assumes 50% of inspection cost |
| Provision for fuel costs per year | 6 K € | Depends on the O&M contractor. This paper assumes 3% of total cost per year |
| TOTAL COST PER YEAR – below water cable inspections | **206 K €/ year** | - |
| TOTAL LIFETIME COST – below water cable inspections | **5.2 mio €** | -25 years lifetime |

It can be concluded that O&M contractors should foresee every year a period of time to execute the yearly inspections. O&M contractors are free to plan the works but are generally executing this during the good weather seasons which starts in May and ends in September. When a damage or irregularity has to be inspected, the O&M contractor should be flexible to execute the cleaning and/or repair works. It takes around 2 weeks to inspect 10 floating modules per year. The total cost during the lifetime of 25 years for a below water inspection of floating modules is 3.2 mio €. Additionally, it takes again 2 weeks to inspect all mooring lines with a total cost of 5.2 mio during its lifetime.

#### 3.2.5 Traffic - Operations & Maintenance procedures and schedule

The floating island assembly will rely on traffic of personnel, goods, energy, fuels and fluids etc from module to module. O&M procedures will have to be in place to ensure safety and fit for purpose of boat landings, helicopter landings, module 2 module cross-overs, energy, water and waste grids, and last but not least the underlying data interface network that is in place for the (remote) monitoring system to support previously listed O&M maintenance schedules.

It is noted that O&M traffic of service engineers to offshore wind parks poses a significant challenge to their operation. Workability is limited by access challenges and motion induced sickness in small boats while in transit from shore to the park, or awaiting opportunity to transfer onto the turbine structure.

Floating islands may well be more suitable to setup more permanent infrastructure for traffic maintenance in the general sense since there is room to house a permanent support and maintenance on the island for longer time. This could be an improvement compared to the access complications on existing single bottom fixed or floating turbine setups. Options to consider are:

- Utility service staff to assist with personnel access
- Manned data centres controlling the data infrastructure, power grid, and water and waste infrastructure

This could be similar to public services in small on shore cities. These aspects are not elaborated in further detail in this report since they will rely very strong on the nature of the payload superstructure.

# 4 Operation and Maintenance future outlook

## 4.1 Above water inspections - Offshore use of drones

The global wind turbine inspection drone market is expected to be around 6 billion dollars in the next 5 years and many companies around the globe are experimenting already on onshore turbines. In June 2018, Skyspecs successfully completed an automated inspection of the world's largest offshore wind turbine in the Irish Sea and in February 2019, DEME and SABCA (tier 1 aerospace industry supplier) have entered into a partnership for the development and deployment of UAV's to perform surveillance and inspection works in the offshore industry;

This fast growing market will soon be mature enough to be used for offshore conditions and will form the basis for offshore visual inspections. This section described the potential of using drones on the *Space@Sea* island.

The UAV, unmanned aerial vehicles or 'drones' will become the standard for offshore inspection campaigns. This state-of-the-art technology reduces the cost, time and risk compared to manual handling by O&M technicians. By the time that *Space@Sea* has been installed, this technology will be mature enough to apply at large scale and will be fully autonomous. The latter means that a drone will be stationed in a docking station or 'drone box' on the floating island, and it will fulfill its task every day and night. Most likely, one (1) drone will not be sufficient to surveillance the full island and therefore it is assumed that at least four (4) drones will be responsible to cover a specific part of the floating island configuration. Considering the above provided configuration it means that one (1) drone will cover an area of 175m x 175 or 5 by 5 island setups.

The following tasks can be executed with UAV's:

- Surveillance trip around the island area during day and night. Provide real time video footage to marine coordination center
- Be stand by for any interaction
  - Search and rescue
- Monitor incoming and outgoing vessels and send data to marine coordination center
- Perform visual inspections on floating modules (splash zone)
- Perform visual inspections on assets above floating module (on demand)
  - Visual inspection wind turbines
  - Visual inspection buildings
  - Visual inspection damage solar panels
- IR inspections during night
- Parcel delivery on demand (e.g. spare parts)
- Mammal observation
- And many more

### 4.1.1 UAV inspection campaigns on Space@Sea

The UAV wakes up fully charged at a preset time, the drone box will open and the drone lifts off to a preset altitude.

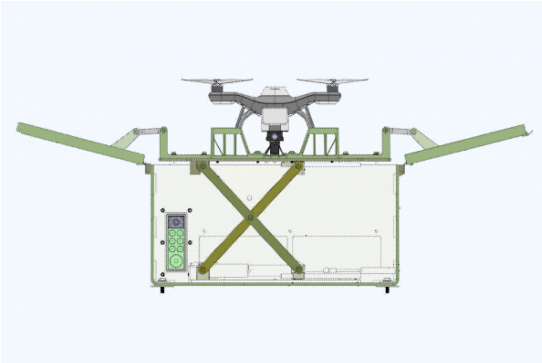


Figure 4-1 Drone usage for inspection

The drone will start with a few round trips around its preset area (e.g. 175m x 175m) and delivers real time video footage during its flight. The marine coordination center monitors the video screen and if an emergency occurs, they can easily take over the control of the drone. The drone is equipped with artificial intelligence which enables to scan certain objects and provide more information on that object. For instance, when a vessel is entering the floating island, the drone will capture the vessel's name and will automatically generate data of that object. When this data does not match the database, the drone will stop its daily round trip activity and it will fly and follow this specific object.


Figure 4-2 Modern example of drone inspection

It should be noted that drones can intervene and track the vessel, but they have not the ability to intercept. This means that a vessel should be 24/7 stand by if interception of vessels is required.

The drone will continue its round trip and is waiting for new orders. One of these orders could be to perform more detailed visual inspections on demand. Large assets such as but not limited to buildings, wind turbines, PV panels, cranes etc. requires frequently a visual inspection for any damage such as breakage, corrosion etc. On demand, the drone can be flown to the specific location to perform this structural inspection service.

The drone will fly around the asset, following a pre-defined path, and captures hundreds of images with a very high definition. All data will be gathered into a database where a tailor-made 3D mapping software programme combines all images into a 3D model. This model will be used as comparison from previous visual inspection campaigns which enables the software to recognizes any anomality's in the structure. This means that before the installation of the *Space@Sea* floating modules, all assets should have been monitored and 3D mapped. In the offshore wind business, they tend to start with this as well. Before load out of the foundations, a visual inspection will be performed with a drone resulting in a 3D model. When the foundations arrive at offshore location, the same visual inspection will be performed in order to monitor if the foundations have been damaged during transport. When the foundations have been installed, a 3rd and last visual inspection will be applied to ensure that the structure has not been damaged during the offshore installation. This data will be shown to the client and results in an open and efficient hand over service.

Drones are also capable to perform task during the night. Thanks to advanced technology such as infrared light, it enables the drone to recognize certain assets during night which are often difficult to recognize during day time. During the night, a drone can monitor any temperature differences by using it infrared camera. When fire occurs at one of the area's, the drone can easily recognize this and inform the marine coordination center with an alarm. Same accounts for water ingress, a vessel entering or leaving the area, man over board, mammal observation and many more.

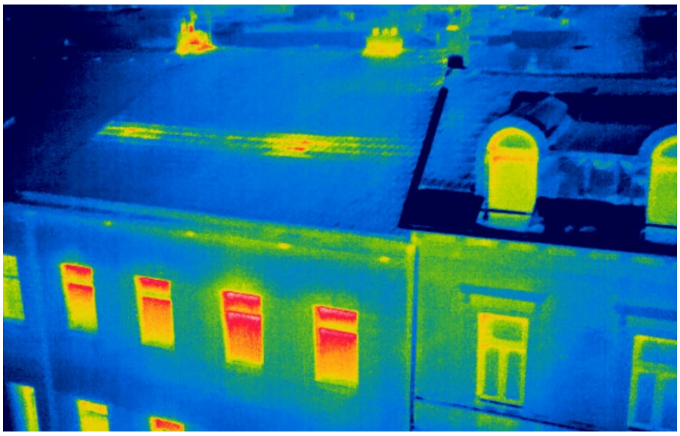


Figure 4-3 Infrared inspection using drones

A last, but not least, important asset of using drones is parcel delivery. Drones are able, to a certain extent, to deliver parcels from shore to offshore. Currently, this technology is under development, but many maritime companies sees this as an add on to speed up the process and reduce the cost. The Danish company Maersk is testing drones for urgent parcel deliveries to a vessel at sea. They state that drones are a good alternative instead of sending barges to the vessel when they are not in the port. With the current pay load of drones, on average a vessel has three (3) cases per year in which the barge transport could be substituted by a drone. Taking into account an average barge day rate of 1000 USD means a potential avoidance of 3000 USD – 9000 USD per vessel per year and if you consider that Maersk has 100 tankers in its fleet, the savings potential could be substantial.

Above water inspections on the floating modules can be easily done by O&M technicians. However, the inspections of the chain stoppers, located at the side of a floating module or the connectors between the modules requires extra supporting equipment such as a support vessel with lifting crane. It should be noted that not all modules can be reached with a crane type of vessel and requires other solutions. One of these potential solutions is the use of offshore drones to visually inspect the integrity of the connectors and chain stoppers and analyze the data with artificial intelligence. Below table shows high level the total CAPEX and OPEX (2020 price) of operating a drone for O&M purposes.

Table 4-1 Summary of CAPEX and OPEX for drone equipment

| CAPEX | | | | |
|---|---|---|---|---|
| **Asset** | **Cost [€]** | **# pcs** | **Total Cost [€]** | **Comments** |
| Drone hardware | 100 000 €/pcs | 5 pcs | **500.000 €** | *4 drones and 1 spare* |
| Drone station box | 250 000 €/pcs | 5 pcs | **1.250.000 €** | *4 drone stations and 1 spare* |
| Surveillance equipment | 100 000 €/pcs<br>50 000 €/pcs<br>150 000 €/pcs | 5 pcs | **1.500.000 €** | *HD camera for visual inspections*<br>*Tools for parcel delivery*<br>*IR camera* |
| Data collection, acquisition and visualization | Lump sum | | **500.000 €** | |

| | | | | |
|---|---|---|---|---|
| Project management and engineering | | | **500.000 €** | |
| **TOTAL** | | | **4.500.000 €** | *Incl. contingency* |

| **OPEX per 25 years lifetime** | | | | |
|---|---|---|---|---|
| **Asset** | **Cost [€] per year** | **# years** | **Total Cost [€]** | **Comments** |
| Drone O&M | 50 000 € | 25 | **1.250.000 €** | |
| Drone station box O&M | 100 000 € | 25 | **2.500.000 €** | |
| Surveillance equipment O&M | 25 000 € | 25 | **625.000 €** | |
| Data collection, acquisition and visualization service | 100.000 € | 25 | **2.500.000 €** | |
| Project management and engineering | LS | | **500.000 €** | |
| **TOTAL** | | | **7.375.000 €** | *Incl. contingency* |

# 5 Conclusion

This report concluded on a high level but qualitive description of the basic required activities for operating and maintain a floating island such as the Space@Sea concept. Although Space@Sea is still in an early phase of concept or design evaluation and therefore being very difficult to narrow down the scope of maintenance, the navigation through this deliverable shows chronological steps that were taken to generate a generic methodology to derive a basic O&M description of a floating modular island.

Starting by dividing the Space@Sea into 5 distinct functions as roots to establish the basic O&M activities:

1. Buoyant stable of the platform space
2. Station keeping and motions of the platform
3. Modularity of the platform
4. Structural integrity
5. Traffic & logistics

For the development of the Space@Sea O&M activities, the bottom fixed offshore wind and floating offshore wind experience has been used as an example and copy industry standard O&M activities as evaluated in section 3.2.

Current innovations towards UAV shows great impact on reducing the lifetime cost for O&M as originally multiple maintenance procedures can be combined into one inspection procedure.

Finally, it is to be concluded that the early stage of a concept phase like S@S, does come with limitations due to the majority of unknowns. Establishing a baseline for maintenance has been achieved, but future expansion/engineering on the Space@Sea concept will bring the possibility of developing the O&M lifecycle scenario booklet from a basic one to an advanced one.