Deliverable 5.2: Characterization of logistic requirements

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ABSTRACT

This report presents the Deliverable 5.2. This document extensively reviews the key offshore logistics operations driving the development of an array of wave or tidal energy devices. A large amount of information with relevance for the development of the DTOcean lifecycle logistics module was compiled in a systematic approach. The methodology applied was designed for characterizing the logistic requirements associated with the execution of the marine operations.

Deliverables 5.2 focuses primarily on the assembly and installation, on one hand, and the operation and maintenance activities, on the other hand. However, procurement, manufacturing and decommissioning are also addressed in a simplified approach. The present document is formulated around three main array sub-component: the electrical infrastructure, the moorings and foundations and the wave and tidal devices.

Through the detailed description of the logistic activities involved during the development of an ocean energy array, both well-established methods and innovative solutions are outlined. Ultimately, this report also tends to reflect the state-of-the art in terms of maritime infrastructure available to carry out the necessary offshore operations. Illustrations, references, indicative quantitative measures and key summary tables strew the content of this deliverable supporting the identification and classification of the most relevant information.

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1 INTRODUCTION

1.1 OBJECTIVES

This report presents Deliverable 5.2 – ‘Characterization of logistic requirements’ which describes the main logistic operations necessary to execute a wave or tidal energy project from the manufacturing phase to the decommissioning phase.

The objectives of D5.2 can be summarized as follows:

- Review the key logistic operations to be considered in the DTOcean design tool following the recommendations of D5.1;
- Describe and illustrate the procedure of the logistic operations of each major array sub-component type along the project lifetime;
- Identify the critical parameters that influence the selection of the suitable maritime infrastructure to perform the logistic operations.

1.2 SCOPE OF THE REPORT

In D5.1, the methodology of the lifecycle logistics module that will be developed within the frame of DTOcean design tool was depicted. Based on the results of a consultation of potential end-users of the tool, the most critical operations to consider in the lifecycle logistics module have been pointed out. Therefore, D5.2 also concentrates on the most relevant logistic phases[1], as identified in D5.1[1], i.e: the assembly, the installation and the operation and maintenance (O&M). Furthermore, the procurement and manufacturing of the components is discussed in this report in order to understand how the location of the factories may affect the schedule of a project. Finally, the decommissioning stage is only briefly described in D5.2 since its impact on the Levelized Cost of Energy (LCOE) at the end of the arrays lifetime (expected to be 20 years) is considered to be low and there is large uncertainty on how infrastructure and techniques will evolve until that period.

Following the lifecycle progression along this document, it should be noted that three main array subcomponents represent the core of the content of D5.2, respectively: the electrical infrastructure, the moorings and foundations and, eventually, the wave and tidal devices. Since the DTOcean project is firmly centralized around the design of arrays of devices rather than single unit, this report also considers the implications of multi-unit layout on the logistic requirements.

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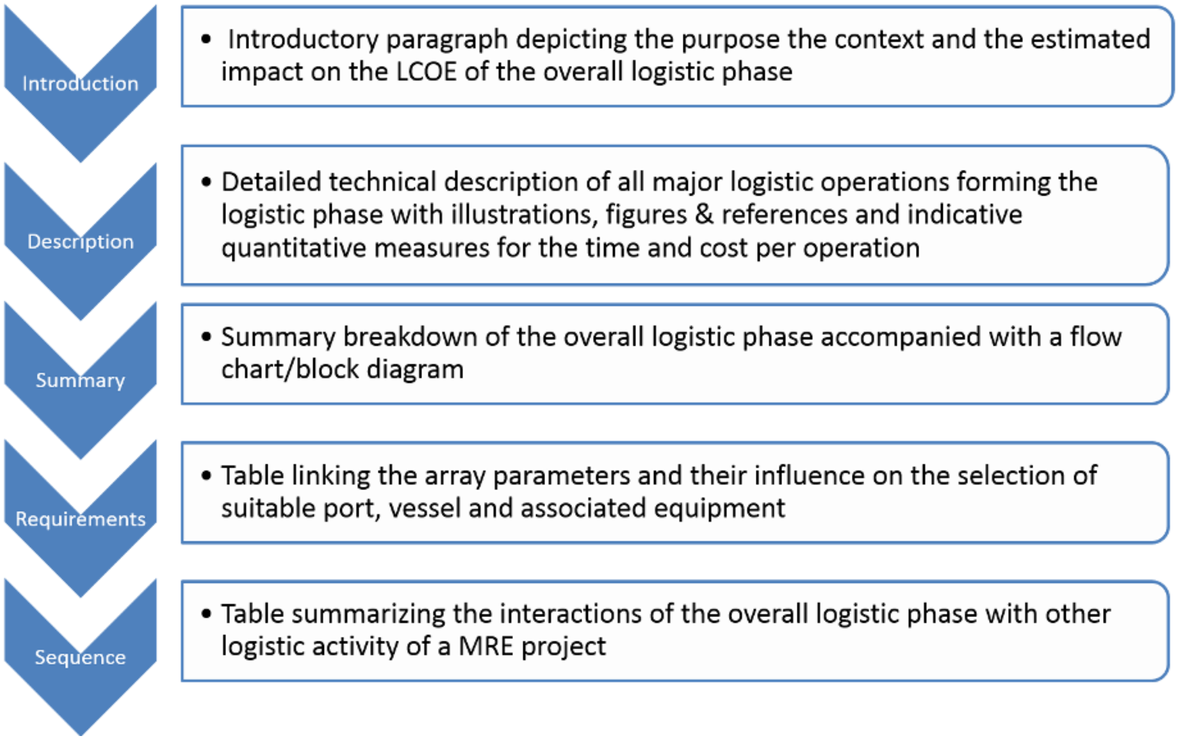
[1] a logistic phase, as considered in D5.2, is a milestone in the project development of a MRE farm such as the installation of the foundations or the manufacturing of the steel structure components and, hence, one logistic phase is typically formed by a series of individual logistic operations such as for example transporting, lifting and drilling.

1.3 METHODOLOGY

To achieve the objectives previously listed, four main subtasks included in the DTOcean description of work were carried out. The first three subtasks correspond to the characterization of the assembly and installation requirements for the three main array sub-components, i.e. the electrical infrastructure, the moorings and foundations and the wave and tidal devices. The assessment of one particular operation encompasses a detailed description of the procedure including illustrations such as schematic representation and/or real images.

The last subtask was dedicated to the O&M considerations. This section compiles the foreseen maintenance requirements that occur during the service life of a marine renewable energy (MRE) project using the information provided by the previous three subtasks as well as the monitoring requirements. Also, as previously mentioned a short description on the components procurement and manufacturing logistic requirements as well as for decommissioning was included.

In order to facilitate the overall understanding of the flow of resource associated with all the logistic activities, the key interactions between some of the operations are explained. Summing up, a systematic approach for thoroughly evaluating one logistic phase is adopted in this report. This procedure can be enumerated in five points, as shown in Figure 1.3-1.



- Introductory paragraph depicting the purpose the context and the estimated impact on the LCOE of the overall logistic phase
- Detailed technical description of all major logistic operations forming the logistic phase with illustrations, figures & references and indicative quantitative measures for the time and cost per operation
- Summary breakdown of the overall logistic phase accompanied with a flow chart/block diagram
- Table linking the array parameters and their influence on the selection of suitable port, vessel and associated equipment
- Table summarizing the interactions of the overall logistic phase with other logistic activity of a MRE project

Figure 1.3-1: Five steps methodology for the assessment of the logistic requirements associated with each logistic phase

As illustrated in Figure 1.3-1 , the third step of the methodology consists of providing a flow-chart which summarizes the key logistic steps to complete one particular logistic phase. Two colors have been used to differentiate the following (see Figure 1.3-2 for an example):

- Red color: this logistic step will be assessed with details in the DTOcean WP5 tool
- Blue color: this logistic step will be subject to either a simplified assessment or will not be considered for evaluation in the DTOcean WP5 tool
-

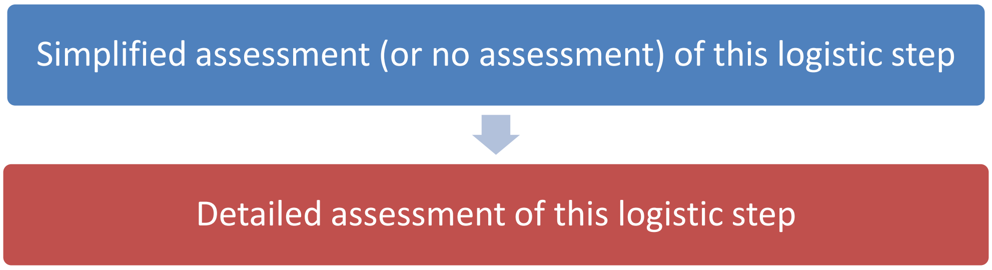


Figure 1.3-2: Code colour for the assessment of the logistic steps in the third step of the methodology within the WP5 DTOcean tool

1.4 OUTLINE

This report is articulated around four content-oriented chapters following this introduction:

- Chapter 2 describes logistic considerations of activities within MRE projects before its final assembly and installation;
- Chapter 3 details the logistic requirements associated with the deployment phase (i.e the assembly and installation of the whole farm);
- Chapter 4 characterizes these logistic requirements during the service life of a MRE project
- Finally, the report briefly tackles the decommissioning requirements before concluding in Chapter 5 & 6.

One should note that sections 3 & 4 encompass the core outcome of this deliverable in which the methodology previously introduced is strictly applied.

It is important to underline that this report assembles information on a large list of operations for MRE arrays including descriptions of methods, requirements, equipment, schedules, etc. Yet, the present document is by no means representative of all MRE projects. Different logistic approaches are envisaged depending mostly on the technology and the site selected. Besides, innovations are expected in the equipment and techniques employed. However, this report provides an extensive description of the actual state-of-the-art based on previous experience with the first full-scale prototypes as well as in related sectors such as offshore wind and Oil & Gas.

2 PROCUREMENT AND MANUFACTURING REQUIREMENTS

In Chapter 2, the key activities occurring before the installation of a MRE project are discussed. Firstly, section 2.1 covers the description of the work pertaining to the administrative, financial and engineering preparation before the industrial execution of a MRE array is initiated. Section 2.2 considers the manufacturing requirements associated with the production of the main array sub-component.

2.1 PLANNING, DESIGN AND PROCUREMENT

Like any offshore industrial project, significant effort is required upstream to kick-off of the construction and installation activities. During this pre-installation phase, rigorous planning is essential in order to meet the specific requirements associated with the project. In the context of planning a MRE project, one can list the following most relevant considerations:

- Administrative work and authorization procedure;
- Design and engineering work;
- Planning and procurement.

The administrative work related to the implementation of an industrial offshore project is often tedious due to the vast number of entities that must be properly contacted and informed. Moreover, the nascent nature of the wave and tidal energy sector signifies that the policy and regulatory framework is frequently being revised. In [2], the consenting processes and licenses procedure for different countries have been reviewed.

To obtain the consent to deploy a wave or tidal energy plant, a thorough consultation with the public and all parties that may be affected by the project at the planned offshore location is indispensable. These discussions are generally accompanied by an exhaustive environmental impact assessment built upon offshore surveying of the prospective area. The survey can include the following:

- Desktop study: this will evaluate the environmental constraints of the area. The task consists of analyzing the activities that occur in the area of interest. For instance, the shipping activity in the area is monitored to understand how the traffic can be regulated. An example of an environmental constraint is the presence of a protected fish farm.

- Marine survey: this step consists of thoroughly measuring the characteristics of the area of interest from a physical and environmental point of view. Survey vessels and a wide variety of measuring equipment and instrumentation systems exist to carry out these operations. Ultimately, the morphology of the seafloor, the geophysical and geotechnical properties of the soil and other environmental resource data (e.g. water depth, wave, wind, current, tidal range and temperature) are characterized.

The design and engineering pre-deployment process of an MRE farm involves an initial site selection followed by an assessment of external conditions, selection of device type and size, subsurface investigations, assessment of geo-hazards, selection of mooring and foundation structures, configuration of the electrical infrastructure, optimization of the farm layout, developing design load cases, and performing geotechnical and structural analyses. Ultimately, the chief goal of DTOcean is to deliver a suite of design tools capable of supporting the decision making process occurring at the planning stage.

Lessons from the offshore wind sector demonstrate the importance of conducting a strategic planning of the procurement process in order to drive down the costs and mitigate the risks, mostly in terms of schedule, safety and quality of the expected services/goods. As the industry continues to gather relatively new types of operational experience, integrated planning approaches are being refined. Planning and procurement issues for the wave and tidal sector are expected to be very similar to those in the offshore wind sector, and hence, one MRE project developer would be well-advised to take advantage of the invaluable information available in this “parent industry”.

With the objective to minimize the LCOE, a buyer’s network should be carefully constructed. Given the growing complexity of offshore renewable energy parks and the subsequent ever changing business needs, the procurement team should ensure to deliver consistent quality while continually concentrating on cost efficiency, business integrity and sustainability [3]. The best trade-off between local and global procurement solutions can only be achieved by means of a comprehensive supply chain analysis.

In the context of a MRE project, the buyer’s network should concentrate on the Original Equipment Manufacturers (OEM) as well as on the marine contractors. DTOcean suite of design tools shall be able to reflect the most common contractual terms found when dealing with the OEMs (including the associated warrantees that apply for the maintenance) on the one hand, and with the marine contractors (including aspects such as mobilization, safety, availability and vessel rates under different conditions).

For achieving economies of scale, mass production factories may be justified for the components that can be readily produced in series. As larger arrays of wave and tidal energy devices may be deployed in the medium to long term future, proximity of the manufacturing facilities to the deployment sites along with series production techniques will become assets increasingly advantageous.

2.2 MANUFACTURING OFFSHORE STRUCTRURES AND COMPONENTS

Historically, the construction of offshore structures has been largely entailed by the Oil & Gas industry. Although the designs for the main array subcomponents of a MRE farm are partly different than what can be found in the Oil & Gas sector, it is obvious that the fabrication of the structures and components for an array of MRE devices will heavily rely upon the experience gathered in this closely related industry.

The principal materials for offshore structures are steel and concrete. Composites are a recent addition. The fabrication and/or construction contractor is generally responsible for their procurement and quality control, although in some cases the basic material may be separately purchased by the operator and made available to the constructor [4].

Materials for offshore structures must perform in a harsh environment, subject to the many corrosive and erosive actions of the sea, under dynamic cyclic and impact conditions over a wide range of temperatures. Thus, special criteria and requirements are imposed on the material qualities and their control.

This section covers other major components than the traditional concrete and steel structures pertaining to the deployment of an array of wave and tidal energy devices. For instance, the manufacturing of the principal components for a grid connection of a MRE array is discussed. The most critical requirements impacting the characteristics of the port where offshore structures or components may have to be fabricated/assembled will be outlined in the following four subsections.

2.2.1 CONCRETE STRUCTURE

Structural concrete itself is a composite material consisting of aggregate with a cement mortar matrix, reinforcing and pre-stressing steel. Structural concrete should conform to the best practices of concrete construction and numerous codes applicable to offshore environment. The selected material properties, the structural design and fabrication procedure will set the level of performance of the concrete structure which can fall under one of the three categories below [4]:

- High Performance Concrete (HPC) or “Flowing concrete”;
- Structural Low Density Concrete (SLDC);
- Ultra High Performance Concrete (UHPC).

Concrete offshore structures are designed to remain permanently or semi-fixed to the seabed either by gravity or piling or moorings. As a consequence, concrete offshore structures are usually and readily classified into two major types and can be further broken down as depicted in Table 2.2.1-1 [5]:

Table 2.2.1-1: Different types of offshore concrete structures

Gravity base structures(GBS)	**Floating concrete structure**
• Cylindircal tanks type • Condeep type (and later evolution) • Barge type (ballasted)	• Semi-submersible • Tension Leg Platform (TLP) • Barge type

In Figure 2.2.1-1 an example photo for each of the above 2 categories of offshore concrete structures is concatenated.

Figure 2.2.1-1: Gravity based concrete structure for the Oil & Gas (left) floating concrete barge (right)

While afloat, GBS must be water tight and have stability and free board at all stages of construction. One should note that the loading conditions and combinations acting on the structure are significantly different from one stage to the next. Structural integrity must be assured at each stage. Ballasting and compressed-air systems (if these latter are employed) must be carefully and positively controlled at all stages.

One can identify the following construction and installation stages [4] (this reference details each stage but this report only enumerate them):

- Stage 1— Construction Basin;
- Stage 2— Construction of Base Raft;
- Stage 3— Float-Out;
- Stage 4— Mooring at Deep-Water Construction Site;
- Stage 5— Construction at Deep-Water Site;
- Stage 6— Shaft Construction;
- Stage 7— Towing to Deep-Water Mating Site;
- Stage 8— Construction of Deck Structure;
- Stage 9— Deck Transport;
- Stage 10— Submergence of Substructure for Deck Mating;
- Stage 11— Deck Mating;
- Stage 12— Hookup;
- Stage 13— Towing to Installation Site;
- Stage 14— Installation at Site;
- Stage 15— Installation of Conductors.

Unlike GBS, floating concrete structures are not meant to be fully submerged. Historically, the inherent weight of large floating concrete structures has been an obstacle and, therefore, only sporadic development has been observed. Floating bridges of concrete, floating piers, ferry slip docks, floating guide walls for navigation locks, and large floating storage and production vessels have been constructed in recent years and, utilizing the improved technologies of pre-stressing and high-performance lightweight concrete, appear increasingly attractive.

Maximum utilization should be made of prefabrication using precast slabs and shells. Typically, joints are cast “in-place” to ensure full continuity of reinforcing steel and to permit splicing of ducts. Precasting permits the attainment of dimensional accuracy while dispersing construction activities and increasing production. Segmental construction methods, similar to bridges, can be utilized [4].

Concrete offshore structures are expected to play a role in the manufacturing portfolio of the wave and tidal sector. One can anticipate GBS being the preferred choice at sites where the physical and environmental conditions will be favourable. Most recently, Pelamis Ltd. looked at the feasibility to change the main material of their wave energy converters’(WEC) tubular sections from steel to concrete [6].

2.2.2 STEEL STRUCTURE

In the offshore steel manufacturing industry, there exist standards from classification entities regulating the material selection and methods for fabrication [7]. Modern facilities manufacturing offshore steel structures feature highly controlled environments including semi-automatic welding, profiling, sawing, drilling and milling machines.

The most sensitive task in the fabrication of offshore steel structures is the welding. Welding procedures should be prepared, detailing steel grade, joint/groove design, thickness range, welding process, welding consumables, welding parameters, principal welding position, preheating/working temperature and post-weld heat treatment [4]. The qualification of welding procedures is based on nondestructive testing (NDT) and mechanical testing. Nondestructive testing may include x-ray (radiographic) testing, ultrasonic testing, and magnetic particle testing.

Figure 2.2.2-1: Roll-up of jacket framing [4]

Over the past few decades, several categories of offshore steel structures were classified. In Table 2.2.2-1 below, the main types of offshore steel structures are considered as fixed or floating [8]:

Table 2.2.2-1: Different types of offshore steel structures

Fixed steel structure	**Floating steel structure**
• Jacket; • Tower; • Jack-up; • Compliant tower; • Gravity structure; • Monotower;	• Monohull; • Semi-submersible; • TLP; • Spar;

The wave and tidal prototypes and pre-commercial devices that have been assembled to date were mostly made out of steel. For instance, the Pelamis P2 machine deployed in Orkney consists of four tubular sections of steel, each of them about 40 m long. Another example of a steel structure is the hull of the Alstom Oceade tidal turbine [9] that was manufactured by CMN in Cherbourg for deployment at the European Marine Energy Centre (EMEC). Figure 2.2.2-2 shows one tubular section of the P2 machine and the hull of the Hammerfest tidal turbine, another example of tidal turbine with a steel hull.

Figure 2.2.2-2: A technician attending one tubular section of the Pelamis machine (left) [10], steel hull structure of the Hammerfest tidal turbine being transported at port (right) [11]

The first wave and tidal devices deployed at sea can often be considered over-dimensioned due to the risk associated with the demonstration of such machines in offshore environments largely unexploited (highly energetic sites). As the industry matures, design and structural optimisation of the steel components along with the implementation of mass production techniques will modify the logistical requirements for the manufacturing and assembly of MRE projects. For large arrays it is advisable to set the factory at the assembly port as close as possible to the deployment site.

2.2.3 COMPOSITE STRUCTURE

Increasingly, plastic and similar synthetic materials are being utilized in marine environments. Glass, carbon and aramid fibers are embedded in a resinous synthetic polymer forming a material with customized mechanical and electrical properties. Uses range from glass fiber-reinforced plastic for pipelines to neoprene and natural rubber fenders and bearings, to polyethylene bags for slope protection and polyurethane foams for buoyancy [4].

Kevlar, nylon and carbon fiber mooring lines are commonly used in floating offshore operations. Fiberglass and carbon tendons have been employed as pre-stressing tendons on an experimental basis. Ductility of concrete piles and columns have been increased by encasement in aramid fibers. Carbon fiber sheets, affixed to the bottom of beams, increase the bending capacity while carbon fiber sheets, affixed to the sides, increase the shear capacity. Aramid fibers (Kevlar) are increasingly utilized in deep-water mooring systems [4]. Two examples of composite components that apply to the wave and tidal energy sector are presented in Figure 2.2.3-1.

Figure 2.2.3-1: Synthetic mooring line (left) and composite cast for tidal energy blades (right).

Due to their intrinsic low mass, flexibility and resilience, as well as their capacitive nature and high voltage operation, dielectric elastomer technologies have raised attention in the wave energy sector. The EU project PolyWEC is currently investigating the implementation of electro-active polymers as a mean to substitute conventional PTO systems for WECs [12]. To illustrate this work, Figure 2.2.3-2 power take-off shows the deformation test of an inflatable circular diaphragm dielectric elastomer generator.

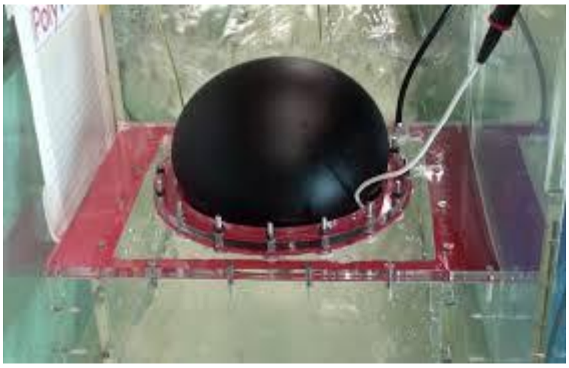


Figure 2.2.3-2: An inflatable circular diaphragm dielectric elastomer generator being tested at the University of Edinburgh within the framework of the PolyWEC project [13]

Although composites and advanced materials appear to be already considered for some components of wave and tidal machines, the large scale manufacturing of such structures remains uncertain. Further research and engineering work is needed to bring composites and advanced materials to a similar technology readiness level as those of concrete and steel structures. Besides, one should raise awareness towards the recycling issue with composite blades as it is being witnessed in the wind industry [14].

2.2.4 *OTHER MAJOR COMPONENTS*

Other components for the wave and tidal sector do not strictly fall in the above categories of three materials. This is especially the case for the electrical equipment, required for both MRE devices (e.g. PTO systems) and balance of plant (e.g. subsea cables and substations).

A clear example of the challenges associated with the fabrication of electrical equipment is the manufacturing of subsea power cables. The manufacturing of subsea power cables is a highly specialized industry with several experienced players. The subsea cables used in MRE projects are produced in large scale facilities with precision cabling extrusion and assembly equipment, and expertise in the production of electrical and thermal insulation materials for the cables.

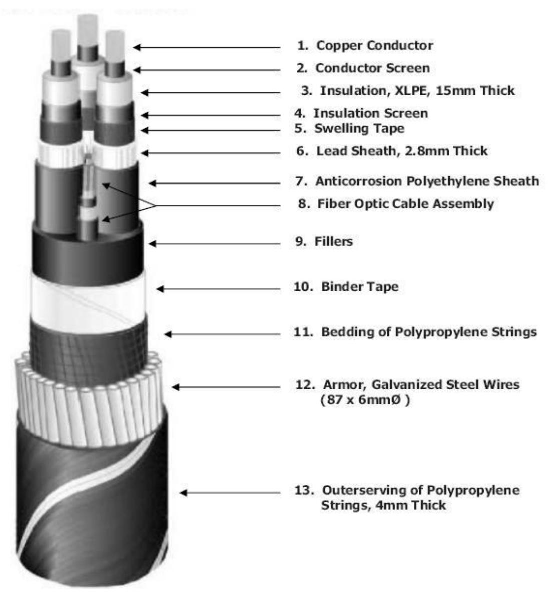


Figure 2.2.4-1: Typical three-core subsea power cable arrangement

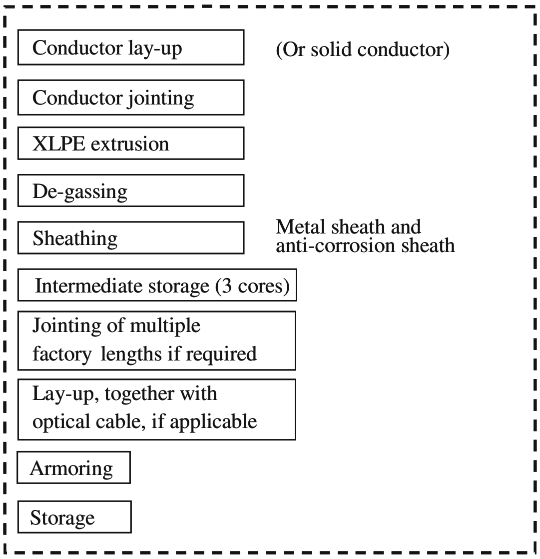


Figure 2.2.4-2: Flow chart of the manufacturing sequence of three-core submarine cables with extruded insulation [16]

From the inner to the outer section, a subsea power cable fundamentally consists of electrical conductors, an electric insulation system, protecting sheathes and armouring. The manufacturing process is consists of consecutively adding rows layer by layer to the conductor. Figure 2.2.4-2 contains a flow chart with the typical sequences of manufacturing a three-phase cable. A generic description of the main steps is done in the following paragraphs.

The process starts with the manufacturing of the conductors of which several design types of are available, however most of the submarine power cables are made up of stranded round wires. The wires are laid together in stranding machines that add layers up to the desired cross-section. This process is followed by a compression stage with the action of dies or roller sets, which helps reducing the interstices between strands. Few kilometers of conductors are produced continuously and joint together afterwards.

Figure 2.2.4-5: Power Cable stranding equipment

The next step is the application of insulation, currently most submarine power cables use cross-linked polyethylene (XLPE) as electrical and thermal insulation material. The application of the insulation on to the conductors is achieved by cable extrusion lines that apply the raw material to the conductors by an extrusion process lengths over 20km can be extruded in a single run.

Figure 2.2.4-6: Example of subsea cabling storage structures: cable drums (on the left) and a turntable (on the right) [15]

Typically, subsea power cables have extremely large lengths. In order to avoid cable joints that can compromise the reliability of the cable, long lengths are produced continuously, and stored in drums (that can carry up to 2km of cable and weight of up to 50T) or turntables (that can carry up to 120km and weigh of up to 7000T). This fact makes onshore transportation difficult and sometimes impossible to be attained. Consequently, most of the submarine power cable manufacturing facilities are located at ports or locations with connection to the sea, making use of transport vessels (such as barges) to ease the transportation of the cables to other locations or directly load the turntables to the cable laying vessels. Two examples of subsea cable manufacturing facilities are shown in Figure 2.2.4-7.

Figure 2.2.4-7: Prysmian cable factory in Kirkkonummi, Finland (left) Nexans cable factory in Halden, Norway (right)

For the offshore wind industry, the cable transportation strategy from the factory usually depends on the type of cables [16]:

1. <u>Array cables</u> (in the range of 400-800m) – Pre-cut lengths of cable are coiled around several drums in the factory and either loaded on the installation vessels or delivered to the installation port. Another option is to load the total length of array cabling on one large turntable, and on-site, cut the lengths as needed during cable laying although this requires more complicated equipment on-site, there's I less scrap cable and no drums need to be disposed of or returned.

2. <u>Export cables</u> (up to 100km and more) – For long lengths of cable, a large turntable is usually required. The normal procedure is to moor a specialized Cable Laying Vessel (CLV) to the factory where after the cable is transferred directly from the factory to the vessel turntable with the help of cable rollers and laying arms. Depending on the size of the cable, this operation can take days or even weeks to complete (the loading speed can range from 3-20m/min). Due to the relatively slow speed of the CLVs, the transportation from factory to site can take a significant amount of time and should be taken into account.

Although the scale of the projects is currently different, these strategies can also be considered for the wave and tidal scenarios being studied in the DTOcean project.

Other core electrical equipment necessary to build a MRE array include the following categories presented in Table 2.2.4-1.

Table 2.2.4-1: Core electrical components for the power-take-off system and the substation.

Power-Take-Off (PTO) system	**Onshore/offshore substation**
• Electrical Generators • Motors • LV/MV transformers • Inverters • Wiring	• Bus-bars • Switchgears • MV/HV transformers

In addition to the two lists in Table 2.2.4-1, one should also mention the subsea connectors as part of the core electrical components in a MRE array.

Producing this type of electricalis equipment requires expertise in designing systems to be applied in the marine environment. As an example, such expertise should guarantee that subsea electrical equipment is protected for long periods of immersion under (high) pressures, or subsea connectors have watertight connections.

Different manufacturing strategies may be implemented for the electrical components. Typically, core electrical components are designed and engineered to allow flexibility in the choice of manufacturing and assembly facilities. Depending on the size of the equipment, the final assembly should allow the load-out to be made at a port/quayside for transport either to the installation port or directly to the site.

Figure 2.2.4-8: Pelamis engineers assembling motor generator sets (on the left), offshore substation leaving manufacturing facility (on the right).

Other major mechanical components for the wave and tidal industry, such as gearing boxes and bearing systems, should be made of steel or similar alloys. However, critical components such as bearings may be made of elastomers like in the offshore wind industry (see photo on the left side of Figure 2.2.4-9). Seals are also often made of elastomers. Sealing components for the wave and tidal industry are likely to be of utmost importance to protect the sensitive areas of the machines and ensure their stability.

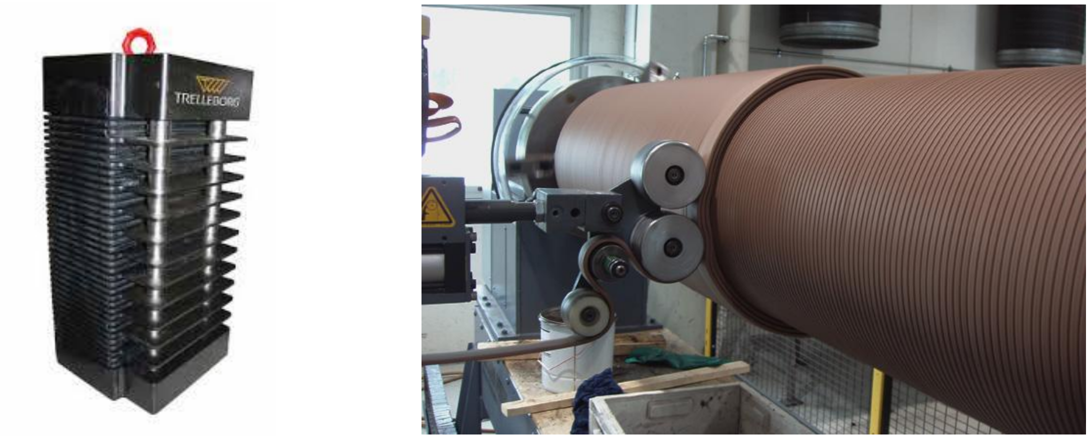


Figure 2.2.4-9: Elastomer bearing (left) and elastomer sealing (right) produced by Trelleborg and designed for the offshore wind industry [17]

Another important task to conduct prior to placing the structure in water is to apply a protective coating. In particular, painting and coating of the steel members, where specified, should be carried out as far as practicable in the shop, under appropriate conditions of humidity and protection from extreme weather [4]. Applying adequate coating can lead to significant cost reductions compared to unprotected solutions. For instance, appropriate coating may delay initiation of corrosion by 10 to 20 years.

In section 2.2, the traditional manufacturing procedures for offshore equipment were discussed. Steel and concrete structures fabricated for offshore applications shall fulfil the wide range of standards that have been developed essentially for the Oil & Gas sector. Electrical components, and in particular subsea cables, also benefit from the experience of the offshore telecommunication industry.

MRE arrays will feature not only well-established offshore equipment but also customized components and, most likely, use advanced material solutions such as composites for tidal energy blades. The development of large scale MRE farms shall spur the centralization of the manufacturing activities in the vicinity of the assembly and installation ports. Below, Section 3 characterizes the logistic requirements associated with the assembly and installation of MRE arrays.

In

Table 2.2.4-2, the key parameters considered in the selection of ports and shipyards at the procurement and manufacturing stage are summarized:

Table 2.2.4-2: Key logistic requirements influencing the selection of port, vessels and equipment for the procurement and manufacturing phase

Component / site data type	**Parameter(s)**	**Unit of measurement/ Format**	**Related infrastructure characteristics**
Components & sub-assemblies	Transport type	Road, sea, air	Port access to receive the components previous to installation
	Transport dimensions	Truck dimensions, vessel dimensions and draft, etc.	
	Number of units	See sections below for each specific component	Dimensions of workshops and storage facilities while waiting for installation
	Dimensions	See sections below for each specific component	
	Weight	In months since request	Crane capabilities, loads, etc.
	Delivery time	In months since request	Schedule (storage, ports and vessels for loading)
Assembly strategy	Facilities close to port	Steel, concrete, composite manufacturing (yes/no)	Facilities at port or close to port
Environmental conditions	Distance to site	Distance in km	For minimizing transit times for installation and O&M
	Bathymetry	At port	For access
	Wave height, wind & current speed and tidal range	Extreme values	Operational limit conditions for the transport of components

Table 2.2.4-3 indicates the relative position of the procurement and manufacturing in relation to the other phases of a project.

Table 2.2.4-3: Typical planning of the installation of a static subsea cable in the context of a MRE project

Sequence of the logistic phase	**Description of the interactions with other logistic activities**
What usually comes before?	Project and site development
What usually comes after?	Assembly and installation phase of the different components that are supplied
What can be done simultaneously?	Reception and works of different components and subassemblies

3 ASSEMBLY AND INSTALLATION REQUIREMENTS

Once the authorization for the industrial development of a MRE array are validated, the project developer team can assign the operators to proceed to the offshore installation work. Chapter 3 plunges into the details of the methods for the assembly and installation of the three main MRE array sub-component:

- Electrical infrastructure (Section 3.1)
- Moorings and foundations (Sections 3.2 & 3.3)
- Wave and tidal devices (Section 0)

3.1 ELECTRICAL INFRASTRUCTURE

The grid connection of an array of offshore renewable energy devices implies the implementation of tailored logistics. In section 0, the main stages for the assembly and installation of the electrical infrastructure of a MRE array are depicted. The methodology presented in section 0 is applied to help the reader understanding the logistical challenges associated with this costly development phase.

3.1.1 STATIC SUBSEA CABLES

In 1811, the first installation of a submarine subsea power cable was operated in Germany [18]. As the industrial exploitation of offshore territory has almost continuously grown since then, subsea operations have significantly improved. The installation of static subsea power cables (also often refer to as "export cables" in the context of a MRE project) is composed of several steps such as:

- The survey and cable routing,
- The trenching of the soil,
- The laying and tensioning of the cable,
- The protection of the cable,
- The cable landing and
- Possibly the installation post-survey.

The purpose of the static subsea power cable is to connect the offshore grid connection point (usually located at the substation) to the onshore grid entry point.

Arguably, the installation of submarine cables can be seen as one of the most critical logistic activity over the course of the grid connection of a park of offshore renewable energy devices. Indeed, the cost of installation of submarine cables represents one to three times the price of the cable itself [19]. Below, five of the main operations necessary to carry out the installation of an export cable are described. As for most complex marine operations, there exist a large variety of techniques to install a static subsea cable. Consequently, the technical description below does not cover all alternatives possible to conduct the installation of a submarine cable but rather discusses the most common approach to operate this logistic phase.

3.1.1.1 SURVEYING

Surveying operations usually occur before and after the installation of a subsea cable. The installation of submarine cable requires a thorough study of the morphology and geology of the seafloor together with a good characterization of the environmental conditions (in particular current speeds). This step often called the pre survey cable route, and allows the project manager to gather critical data for defining the best cable route, cable design and cable installation procedure.

Figure 3.1.1-1 shows a survey vessel capable of performing the geotechnical and geophysical analysis as well as bathymetric surveys of the seafloor. Some of the specialized equipment fitted with such vessels may include (the list below is by no means exhaustive):

- Deck cranes and winches or A-frame to maneuver subsea equipment from the deck to the sea
- Multibeam ecosounders to draw the morphology of the seafloor
- ROVs, sub bottom profilers, samplers, corers, gradiometers, Cone Penetration Testing (CPT) to analyze the soil conditions

Figure 3.1.1-1: A survey vessel in operation [20]

3.1.1.2 PREPARE THE VESSEL AND LOAD THE CABLE

The total weight of the cable is one of the most important factors to be considered when selecting an appropriate vessel to perform the installation. This metric naturally affects the requirements of the payload, which can go from less than 1000 to 7000 tons, but also the cable storage structure where the choice typically of turntables (also called carousel) or tanks for the larger cables or drums (also designated reels) for smaller ones. Other important factors for the vessels selection are the deck space (to accommodate the burial tools), positioning capabilities and bollard pull.

The most common vessels used for installation of power cables are:

- <u>Cable-Laying Vessels (CLV)</u> – large dedicated vessels, purposely built for power cable installations, are generally equipped with fixed turntables with large payloads.

- Adapted Barge or Multi-purpose Vessel – For submarine cable projects with short cable lengths, it is not mandatory to employ a costly dedicated CLV. Other vessels can be equipped with suitable gear for cable laying tasks, in particular smaller turntables or drums, and have been typically used for installing in-field cables of offshore wind turbines, with cable lengths of 400-800m.

Depending on whether the cable can be coiled or not, the loading capacity of the vessel may need to be verified. Generally, dynamic positioning (DP) vessels are required for cable laying operations in deep water. The DP systems allow the calculation of the appropriate power requirement for the vessel engine and thrusters in order to compensate for the wind, wave and current that are measured by equipment fitted in the ship.

In wave and tidal energy parks, the wind, waves and currents are generally very strong, hence finding a suitable weather window may be difficult. Furthermore, one should consider that the operational working limits of a vessel may vary depending on the task that is currently being performed. As a result, determining the vessel with the most suitable turntable capacity and the DP strength turns out to be sometimes difficult. Additionally, a requested vessel may be booked for several years due to a long list of projects to be accomplished and may not be available.

As soon as the pre-survey cable route is completed, the installation phase of the submarine cable can be planned. Before departing from the port, the cable should be rolled in the drum located on the deck of the purposely built barge or the CLV. Such cable loading operation is supported by an arm guiding the circular motion of the cable. The cable storage structure can be a permanent or temporary equipment fixed to the deck of the vessel. The main characteristics of a cable storage structure are usually its dimension and tonnage capacity [21]. The loading capacity of the deck must withstand the total weight of the storage structure containing the cable.

Because of the typical lengths of export cables used in wave and tidal projects (between 5km-50km), the cable loading onto the turntables is typically required to be done directly from the factory, avoiding complex logistics [16]. Depending on the cable size and equipment capacity, the loading speed can range from 3-20m/min, making the overall process several days or weeks long. The time consumption of loading the cable together with the transit time to the site can be longer than the laying time itself.

Other equipment such as the ROVs and the tensioners necessary to handle the trenching and laying operations are also moved and secured to the free deck space of the CLV using conventional cranes and sea fastening techniques.

Figure 3.1.1-2: A cable being loaded in a carousel [15]

3.1.1.3 TRENCHING

The installing phase generally employs one CLV suited to operate the trenching, the laying and some aspects of the protection stage of a submarine cable. In most cases, the seafloor is trenched in order to guide the route of the cable and prepare its protection. Depending on factors such as the soil conditions or cable characteristics, three main methods for creating a trench can be used [22]:

- Ploughing: This method has been known and used for many years, and simply consists of a passive subsea cable plough that digs the soil by shear, as it is towed on the seabed by surface vessels. Each plough have different bollard pull requirements, as example the Sea Stallion plough requires a vessel with a bollard pull of 50ton. This is one of the most economical trenching methods, and is suitable for sandy, clayey and gravelly soils to water depths up to 1500m [22]. Under good conditions, the trench speed rate can be close to 18m/min [23].

- Water Jetting: Consists of using a water-jet system that injects pressurized sea water to fluidize the sea-bottom sediments, allowing the cable to sink down in the trench which is almost simultaneously covered by the fluidized material that falls back into the trench [24]. Jetting is widely used for burial of cables near crossings of existing pipelines and cables, as well as in very soft clays which may not be able to support a plough. Jet plows have an ability to bury a cable already laid on the seabed and are able to operate close to existing installations with minimum risk of damage. Water jetting can work in water depths up to 40m. This method can achieve progressing rates of 3-9m/min.

- Other Mechanical Trenching Techniques: For hard rock bottom, there exist ROVs that use rock-cutting chainsaws to excavate a trench. These have to be operated within diver limitations (40m water depths) and a have slow progressing speed of 2m/min. Dredging is another technique that can be chosen at a pre-trenching stage. Different types of dredging vessels can be used allowing for an almost unlimited trench depth [22].

Figure 3.1.1-3: A traditional cable plough being towed [15]

Also, due to the soil conditions it may not be possible to pre-trench. The trenching and protection stages are closely related since they both serve the purpose to position and ensure the protection of the submarine cable. It is very common that cable laying and cable burial take place simultaneously to the trenching using a cable plough or jetting sledge [25]. However, depending mostly on the soil conditions and the morphology of the seafloor, the trenching and protection stages may need to be independently performed.

A photo of a submarine trencher featuring a water-jet system is provided in *Figure 3.1.1-4*. Such machines are embedded with advanced communication and control systems allowing the operator to manipulate the vehicle from the vessel [26]. The new generation of submarine trenchers are able to operate in a large range of operational depth (down to 1000 meters) and for a large variety of soft seabed conditions (mostly clay and sand). However, many submarine ROV trenchers are limited to operate in shallow water which can be an issue in the case of MRE. Divers may assist the installation of a submarine cable at shallow water. Indeed, as a cable comes ashore it may be suspended by floats and guided into position by small boats and divers. For hard rock bottom, there exist ROVs that use rock-cutting chainsaws to excavate a trench.

Figure 3.1.1-4: The HYDRO PLOW submarine trencher of Prysmian in operation [15]

3.1.1.4 LAYING THE CABLE

As the CLV is preparing the route of the cable through trenching, the grapples and the laying engine cooperates to feed the cable down to the seabed. Most commonly, the laying engine is a Liner Cable Engine (LCE) with a cable feeding speed capacity exceeding the operating speed of the CLV. The LCE is composed of hydraulic and electrical technologies with fully integrated power, drive and control systems. During the operation, tracking of the cable is continuously monitored. LCE are also equipped with a brake system that allows the flow of cable to be controlled or stopped if a problem arises. In Figure 3.1.1-5, a CLV in operation is shown and an example of LCE is provided in Figure 3.1.1-6.

Figure 3.1.1-5 - The Prysmian CLV Giulio Verne in operation [15]

Figure 3.1.1-6 - A Linear Cable Engine used to handle offshore cable laying [15]

The use of tensioners to facilitate the placement of the power cable is also highly recommended. Indeed, the tensioner is tightly integrated with the carousel/turntable to compensate for cable movement regardless of the motion of the vessel. This allows better control of the cable laying and avoiding over tensioning. The working principle of tensioners is to provide a grip force on the cable by means of a number of caterpillar type track units mounted on a common support structure and powered against the cable by hydraulic cylinders.

Additional auxiliary equipment including straighteners, clamps, winches, sheaves and support rollers also support the cable handling needs.

3.1.1.5 CABLE LANDING

Landing the submarine cable can be a costly and challenging logistical exercise. Often it is possible to trench the cable directly through the beach zone. In this case the cable laying vessel is brought as close to the landing spot as possible. The free end of the cable is passed from the vessel and floated to shore using buoyancy aids. The cable is then passed through a cable trenching plough which itself is connected to a winch located onshore. The winch pulls the cable plough up the beach to the low water mark. The plough will lay and bury the cable simultaneously. When past the low water mark, the cable plough stops burial operations, the towing cable is released manually from the plough and the plough is pulled back towards the cable installation vessel where it is recovered. Further burial of the cable, between the low water mark and the onshore shore jointing pit (where the transition from the subsea cable to the land cable is made), is done using land based excavation equipment. The location of the jointing pit will depend on the specific project and will be influenced by the location of the onshore substation as well as other factors. It could be on the beach itself or several kilometres from the beach.

In cases where the jointing pit is far from the beach the subsea cable may have to be pulled for some distance overland. This can be a challenging logistical operation requiring a winch powerful enough to pull the cable ashore as well as land based excavation equipment to trench and bury the cable on land. The installer must also be careful not to exceed the pulling length of the cable when carrying out this operation as doing so will permanently damage the cable. With all installation and burial operations completed the cable joint is made at the onshore jointing pit. This connection will have both a strain termination, in the event that any tension is introduced into the beach section of the cable, as well as electrical and data transmission connectivity.

An alternative to the trenching method is to use horizontal directional drilling (HDD). With this method a, drilling rig, usually located onshore will establish a conduit under the beach zone and out to open water. The cable is then pulled though the conduit using a winch. Lengths up to about 1000 metres can be achieved. The length is limited both by the capability of the drill and the maximum pulling length of the cables. The conduit should typically have a diameter of at least 2.5 times the cable diameter to allow it to be pulled through and to prevent heat build-up which will de-rate the cable. The conduit should be kept as straight as possible as any bend will increase the resulting pulling force. Figure 3.1.1-7 illustrates the HDD procedure.

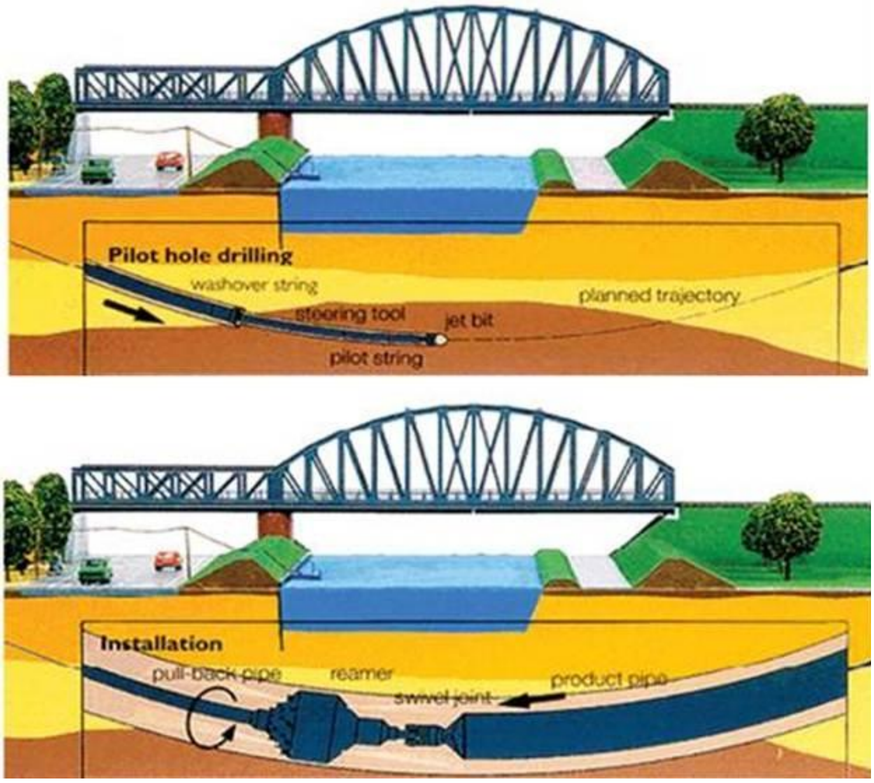


Figure 3.1.1-7: Directional Drilling Procedure

The rigs used for HDD are often fairly large and so project developers and installers will have to ensure that there is a suitable place to locate the rig. Transporting the rig to site can also be a logistical challenge and again installers will have to ensure that there is suitable access to the site to allow the rig to be transported. Material removed during the drilling process will also have to be removed from site and disposed of appropriately.

3.1.1.6 PROTECTING

It is critical to protect a submarine cable from any potential severe damage in order to avoid expensive maintenance and increase the lifetime of the cable. To achieve a satisfying protection, there exist different methods which differ to comply with the geophysics of the seafloor and the associated standards for submarine cable protection. Cable protection primarily serves the purpose to manage the hazards caused by fishing activities and the exposure to areas of abrasive geology. Avoidance of vessel anchorages is also highly advisable to preserve cable system lifetime [27].

Protection in near shore areas is effected by cable burial using burial ploughs which correspond to the aforementioned water-jet system trenching machine. Additionally, the cable may be fitted of articulated pipe in environmentally sensitive or high abrasion areas. Cables are typically buried 1 m and exceptionally up to 10 m beneath the seabed. Multiple cables in the same area are typically buried some distance apart from each other to allow for safe maintenance.

Cable burial is widely considered to be the most effective cable protection technique [23]. In 1997, a Burial Protection Index was implemented to provide guidance in the burial choice. The BPI recognizes that different seabed soils do not react the same way to trawling, fishing gear or anchors.

Based on the survey results the installation and engineering team select a suitable burial depth and suitable burial tool. This is based on experienced assumptions and is very contractual so as not to accept a big risk (reasonable endeavors clauses). The burial tool may be a combination of tools due to soil properties and cost. As a general principle, one could state that soft soil requires deeper burial while hard soil conditions require shallow burial. This is based on the principle that in hard soil, it is harder for an anchor to penetrate and reach the cable.

There exist alternative methods to cable burial in areas where burial is not feasible or recommended (e.g rocky soil and large water depth) which consist of rock placement or concrete mattress. Rocky Dumping Vessels (RDV) as shown in *Figure 3.1.1-8*, also called rock placement vessel, are fit-for-purpose vessels designed to execute rock placement with high precision. Concerning the concrete mattress, similar vessels can be used to transport concrete mats and position them down to the seabed by means of cranes and winches or some form of trigger controlled from the vessel. Divers may also be required to assist the positioning of the mattress. Rock or concrete mattress placementare generally not done over long distances.

Figure 3.1.1-8: Rock placement vessel of DEME in operation [20]

3.1.1.7 INTER-ARRAY CABLES

The in-field connections between MRE devices also require the installation of inter-array cables. This latter type of cable is also laid on the ground such as the export cable. Therefore, many of the installation techniques presented in this section 3.1.1 equally apply to inter-array cable. However, connecting inter-array cables often brings slightly different logistical challenges than the installation of an export cable as previously introduced.

One peculiar issue related to inter-array cable is the proximity. Due to the relatively small area where the cable must be routed, careful considerations should be maintained while maneuvering. Navigation, positioning and safety implications become more demanding. In general, the installation of inter-array cables makes use of smaller vessel and equipment that can be more readily operated.

When pile foundations are used, a J-tube is attached to the outside to serve as a conduit for the electrical cable (more detailed in section 0). The cable must be fed up through the J-tube via a winch. The process of feeding the cable usually requires divers and/or an ROV and is sensitive to tidal, wave and current windows [28].

3.1.1.8 SUMMARY OF THE KEY LOGISTIC STEPS

In summary, one can distinguish 6 steps leading to the typical installation of a static submarine cable in, as shown in Figure 3.1.1-9

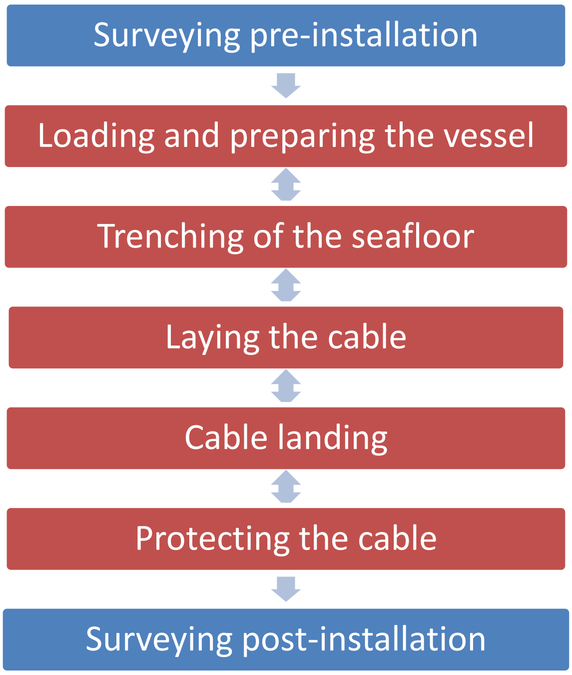


Figure 3.1.1-9: Flow-chart of the sequence of the logistic operations during the installation of a static subsea cable (blue boxes represent the starting and final operations of each phase)

As mentioned before the trenching of the seafloor and the cable protection are often considered part of a common logistic exercise. Cable laying is either done simultaneously with the burial or done step by step (more than one vessel working in series). If the trench is in soft ground and there is a time lag between the vessels working in series, the trench may collapse.

As previously mentioned, the sequence of the logistic operations presented in Figure 3.1.1-9 is very project specific. The experience of export cable installation from existing test sites (e.g EMEC, BIMEP, Paimpol-Brehat, etc.) tends to suggest that the challenges of cable laying in highly energetic areas often bring unexpected issues. Finding the most cost efficient solution may lead to revision of the original plan such as modifying the cable route or the choice of the cable itself in order to be able to use a cheaper or more readily available set of vessels and equipment.

In Table 3.1.1-1, the most important relations between the inputs of the WP5 lifecycle logistics module and the selection of the suitable set of vessels, port and equipment to carry out the installation of a static subsea cable is introduced. In general, no physical characteristic of the components necessary for this logistic phase has been seen as critical in the choice of the port. Note this prevision implicitly assumes that the lifecycle logistics module will ensure that the suitable vessel(s) selected can be accommodated in the corresponding port(s).

In short, the dimensions and weight of the cable as well as the seabed conditions are the three most significant parameters to consider when deciding what vessel, trenching and cable handling equipment should be utilized from a purely technical perspective.

Table 3.1.1-1: Key logistic requirements influencing the selection of port, vessels and equipment for the installation of static subsea cable

Component / site data type	**Parameter(s)**	**Unit / Format**	**Related infrastructure characteristics**
Static cable	Number of units	Number of sections	Size of vessel and carousel (or turntable)
	Length	length per section	
	Weight	Weight in kg/m	Deck loading of the CVL, equipment at port, etc.
	Minimum bending radius in m	Radius (m)	Choice of the carousel/turntable and cable handling equipment
Seabed conditions	Type of soil and layer thickness	Rock/mud/sand...	Type of vessel and equipment to be used for trenching, monitoring and protecting the cable
	Bathymetry	Depth (m)	Type of subsea equipment/personnel
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 3.1.1-2 indicates the relative position of the installation of a static subsea cable with respect to other major logistic phases in the context of the deployment of an array of wave or tidal energy devices [25].

Table 3.1.1-2: Typical planning of the installation of a static subsea cable in the context of a MRE project

Sequence of the logistic phase	**Description of the interactions with other logistic activities**
What usually comes before?	Cable supply, installation of onshore substation and onshore cables, installation of foundations (in some cases)
What usually comes after?	Possibly the installation of offshore substation depending on the type of substation and/or connectors
What can be done simultaneously?	Installation of connectors between the cable and substation / or dynamic cable may be done simultaneously

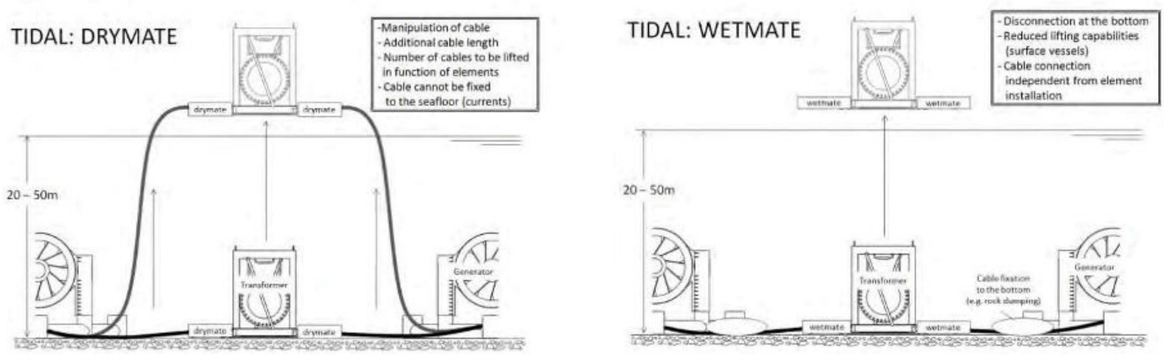
3.1.2 OFFSHORE ELECTRICAL CONNECTIONS

Making the electrical connections can be one of the most challenging activities carried out during the construction of a marine energy farm, especially for projects where the environmental conditions can lead to significant delays (incurring additional costs). The task is intimately linked with the cable laying and protection tasks and will often, though not always, be carried out in conjunction with these tasks. In this section, the electrical connection phase is considered as a discrete logistic phase, but clear indication where this process can be combined with other logistic phases is given throughout the text and summarized in Table 3.1.2-2.

The number and nature of connections that need to be made will be project specific and will depend on the number and type of the individual devices in the farm, layout of devices within the farm, whether or not an offshore substation is present, types of connectors that are used and the number of transmission cables to shore. Despite this it is possible to get an idea of the types of connections that need to be made, and what logistic activities are involved by considering a generic ocean energy converter farm layout. Individual devices are likely to be installed with connectors to allow them to be removed for maintenance or repair. Depending on the array layout, connectors will also be likely to be used to connect radial strings to the collection hub or junction box or to connect individual devices into the cluster collection point. However, the type of connector used is the most important consideration when defining this logistic phase.

Two types of connection are possible, which are referred to as “wet-mate” and “dry-mate”. With a dry mate connector the connection must be performed out of the water, usually on-board a suitable installation vessel. Wet-mate connectors are used when the connection takes place subsea. The choice of connector will generally be selected as a trade-off between installation cost, vessel availability and operational costs, and will impact on the logistic operations of the overall electrical installation process.

Prior to the electrical connection process, the specific layout of the array will have been decided. This allows points where electrical connections are required to be identified during the pre-installation phase. A detailed consideration of the site characteristics and techno-economic analysis will also be performed to identify the most suitable type of connector method. Figure 3.1.2-1 illustrates the difference between the procedure for making a wet mate and a dry mate connection.



(a) dry mate (b) wet mate

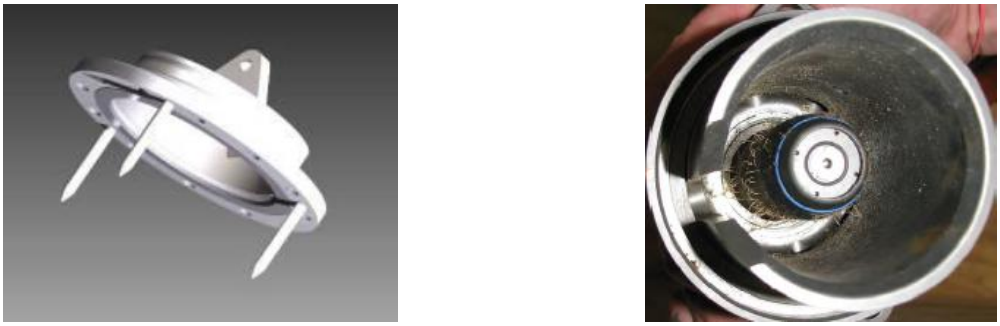
Figure 3.1.2-1: Comparison of dry mate vs wet mate cable connection processes [29].

The site characteristics will also determine the techniques utilised to protect the cable. This should also be considered from the perspective of the connection, as excessive movement of the connector can cause damage due to abrasion. Some connector manufacturers recommend housing the connector in a specially designed mating frame so that the connector is not resting directly on the seabed [30]. An example of this is presented in Figure 3.1.2-2. These housings are expected to be heavy (up to 2 tons) and resistant enough to ensure the connector motion and abrasion is limited, but some manufacturers recommend an additional connector stability analysis prior to the installation to understand the necessity of adding mattresses to stabilise the cable and protect the connector.

Figure 3.1.2-2*: Junction box designed specifically for the wave and tidal industry* [30]

Due to the time between installation phases, which may range from short-term (to complete construction of an array) to longer-term (if a modular construction approach is adopted to allow for array expansion in future developments), some connector halves may be left on the seabed for extended periods of time. This is also true if devices are removed from the array. In both situations, appropriate steps must be taken to ensure that the electrical connectors are not damaged. Manufacturers recommend placing end caps, such as that shown in Figure 3.1.2-3, on the connectors to protect the contacts from water ingress and marine growth in the connector (which can lead to over-heating when the connector is re-energised).

Figure 3.1.2-3 includes both an example of end cap and also an example of marine growth. The use of end caps should be established early on in the logistic schedule to ensure that electrical connection procedures are compatible.



(a) connector end cap

(b) marine growth on the inside of connector

Figure 3.1.2-3: Subsea cable connector end caps [31]

Due to the significant differences between the logistic phases of the two connector types, these are now divided into two discrete sections.

3.1.2.1 WET-MATE CONNECTORS

There are three main connections methods available for wet-mate connectors:

- ROV mateable
- Diver mateable
- Stab-Plate

A graphical representation is given in Figure 3.1.2-4. In the offshore Oil & Gas industry ROV mateable connectors are most commonly used. This is because Oil & Gas installations are typically in deep water where the use of divers is challenging. This method will have a cost implication as the developer would have to hire the ROV and a suitable vessel, from which the ROV is deployed and controlled. In shallow water diver mateable connectors would be considered; however, marine energy farms are likely to be located in areas exposed to strong tidal currents and energetic wave climates which will be challenging for divers. Thus, in many instances the use of ROVs may be preferable.


(a) ROV mateable (b) diver mateable (c) Stab plate

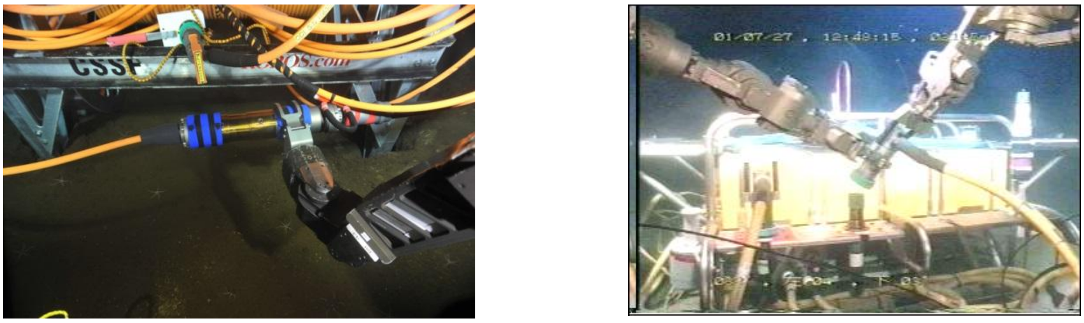
Figure 3.1.2-4: Types of wet-mate connectors [32].

<u>Prepare the vessel and equipment</u>

As discussed above, the specific type of wet mate connector will dictate the exact vessel and/or personnel requirements. If ROV wet mate connectors are to be used, then this equipment must be loaded onto the vessel and the vessel must include lift capabilities to lower and retrieve the ROV during operation. This also negates the need for a dockside crane. As the ROV is normally tethered to the vessel by an umbilical during operation, this cable must also be loaded (the physical connection can be performed at dock or at sea).

<u>Connection</u>

During the actual wet mate connection phase, the ROV will be lifted from the vessel using the crane system and operated from on-board the vessel. Examples of wet mate connection by ROV are shown in Figure 3.1.2-5. Connector end caps can be removed by ROV prior to the physical connection [33]. Alternatively, a team of divers will deploy from the vessel to perform this operation.


(a) Cable termination assembly by ROV ROPOS[6] (b) subsea wet mate connection [34]

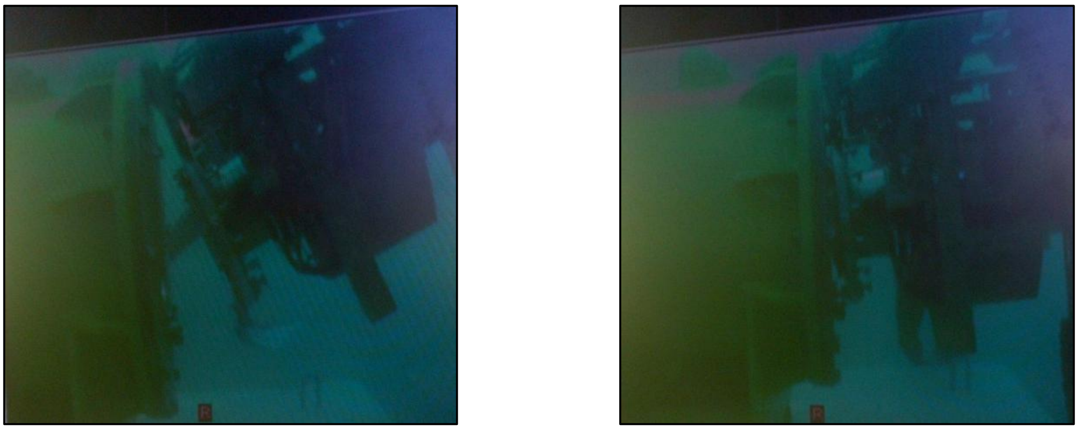

(c) connection to subsea substation [35] (d) connection to subsea substation [35]

Figure 3.1.2-5: wet mate connection by ROV.

It should be noted that using a ROV to perform such a task can be difficult at sites with strong tides/currents and there are usually only short periods during slack water when such an operation can be performed. So although it is possible to perform the task with an ROV, conditions at the site may be such that the connector has to be brought to the surface to remove the end cap/loop back unit.

Visual and electrical testing

Once the connection has been made, it has to be tested to appropriate standards. In order to check the correct operation of the submarine connector different solutions can be applied:

- A series of water detection sensors, which communicate using an additional signal conductor in the cable, can be installed throughout the electrical network to detect possible water leaks due to an incorrect electrical connection.
- Electrical tests (such as resistance measurement) can be performed from the land substation and/or from the installation vessel. In these cases the cable ends shall be accessible and properly prepared in order to connect the measurement equipment.

Following the successful electrical connection, the connection equipment will be returned to the vessel deck and secured at the designated area.

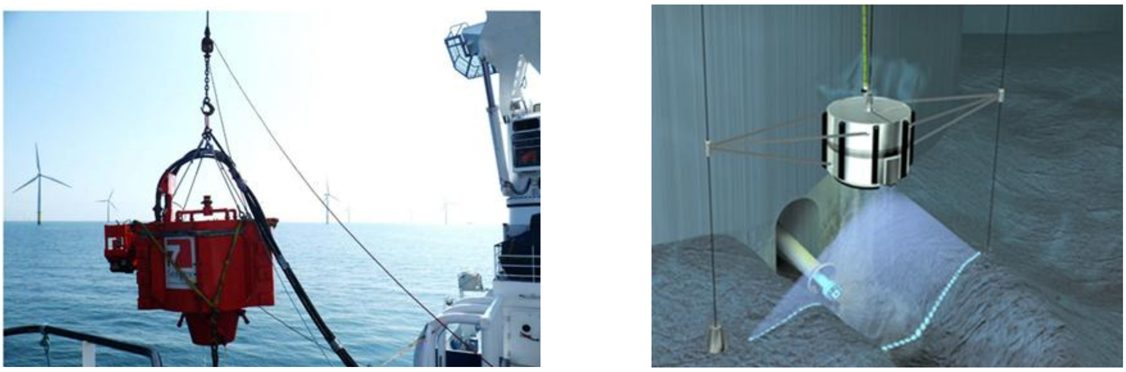
3.1.2.2 DRY-MATE CONNECTORS

As the dry mate connection/disconnection must be performed in a dry atmosphere, the connector and its terminations have to be lifted to the surface. This increases the required lifting capabilities on-board the vessel and the vessel must also have a dry covered area on deck where the connection can be made.

Cable protection removal

It is clear that with a dry mate connector, a cable service loop, which is approximately 3 times the water depth for each side of the conductor, is required to enable the device to be lifted to the surface [29]. This excess cable will be laid on the seabed during periods of operation. However, due to the high currents present at most wave and tidal sites, the cable must be protected on the seabed to prevent cable movement. This excess cable can be protected by trenching, rock dumping or concrete mattresses. To reverse the trenching and rock dumping process, specialist subsea excavation equipment is required, with examples given in. Figure 3.1.2-6. This excavation equipment is designed to be adaptable to operate from a large number of offshore installation vessels, including DP vessels, jack-ups and moored barges [36]. The weight of this equipment ranges from 4.6 – 6T, with footprints between 5m^2 – 10m^2 [36], [37].

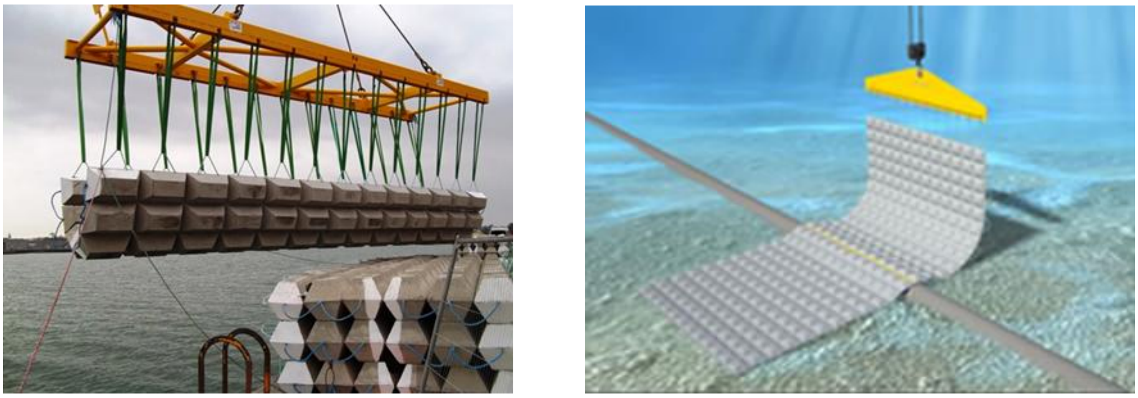
The use of concrete mattresses allows for less disturbance within the array boundary and has also been successfully demonstrated in the MRE environment [37]. The removal of cable protection mattresses is a diver and vessel intensive operation, and bringing the mattress to the surface is considered a dangerous operation [37]. However, the mattresses can be temporarily repositioned during the connection operation instead. Prior to repositioning the concrete mattress, the mattress and surrounding area are inspected by diver and/or ROV to ensure that no part of the mattress is buried or damaged. The mattress is then connected to a steel frame via a set of polypropylene ropes or wire strops by diver or ROV and maneuvered to the new position. A steel frame of weight 1.5T, with 13.2m^2 footprint can safely handle concrete mattresses up to 24T [38]. Although the conventional frame is connected to two parallel edges, novel systems are available in which the mattress is lifted from one end, as demonstrated in Figure 0-7. The frames are generally available for manual (i.e. diver) release, acoustic release or ROV release. Further guidance on handling of concrete mattresses is available in [39].



(a) SeaVex [36]

(b) HydroDigger [40]

Figure 3.1.2-6: Subsea excavation equipment



(a) traditional handling system [41]

(b) modified lifting system [42]

Figure 3.1.2-7: Comparison of concrete mattress installation processes

<u>Connection</u>

Prior to the connection stage, the ROV/dive team move into position to attach the electrical connector to the vessel lift system. Once secured, the electrical components are raised to the surface; depending on the connector terminations, the electrical components lifted are the connector itself plus one of the following:

- A cable connector with a cable termination as shown in Figure 3.1.2-8 (a), plus a cable length approximately 3 times the water depth
- A sea-bed mounted device as shown in Figure 3.1.2-8 (b), plus a cable length approximately 3 times the water depth

(a) component lifting
(Nacelle connection of HSUK at EMEC)

(b) dry dock connection
(Wello Wave Energy device at EMEC)

Figure 3.1.2-8: Examples of the dry mate electrical connection process [43].

The components are then transferred to the dry deck area where the electrical connections are made. The typical reported duration for this activity is around 2h [43], [44].

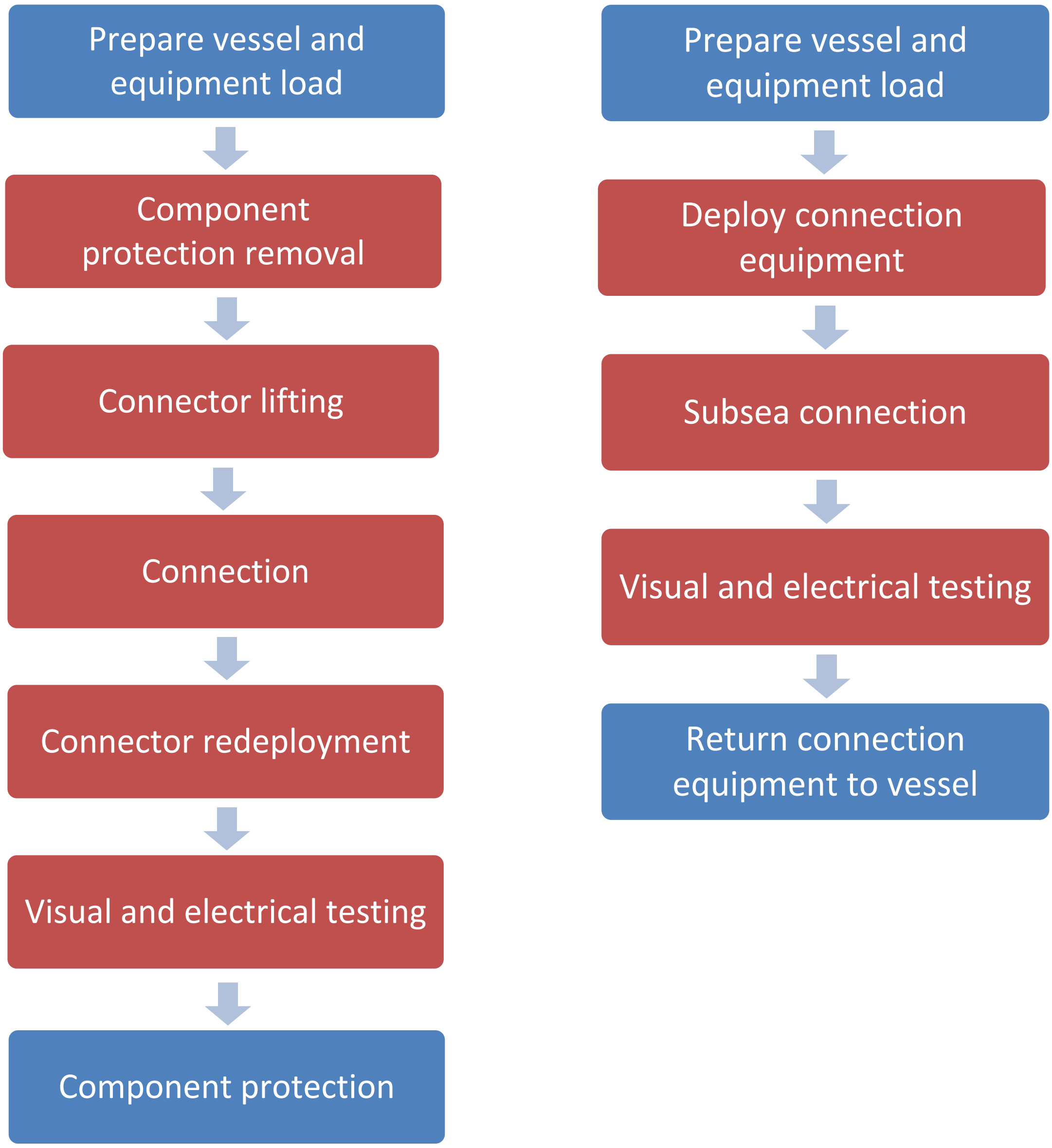
Post-installation

Following the successful completion of the electrical connection, the component will be inspected and tested. The connectors are commonly fitted with loop back units to allow the fibre optics and LV/MV cores to be tested prior to the system being energized. These tests will normally be required by the local grid operator prior to the system being energized.

After this, the component is redeployed to its specified location using the vessel lift system (as displayed in *Figure 3.1.2-9*). Any cable protection materials that were disturbed during the pre-installation activities will have to be returned to ensure that the reliability of the array is not compromised. For example, if concrete mattresses are repositioned during the electrical connection process, they will have to be reattached to the steel frame and moved back into position (following the process outlined previously in this section). If rock dumping is to be (re)applied, this will increase the logistic requirements and cost and it is likely that a Multicat vessel and/or specialised rock dumping vessel would be required to perform these operations. However, this can be combined with the cable laying activity (defined in section 3.1.1) to lower the overall cost.

Figure 3.1.2-9: Returning Wello WEC connector to the seabed [43].

The flowchart for dry mate connectors and wet mate connectors is presented in Figure 3.1.2-10.



(a) dry mate (b) wet mate

Figure 3.1.2-10: Flow-chart of the logistic operations during the offshore connection phase.

Table 3.1.2-1: Key logistic requirements influencing the selection of port, vessels and equipment for the offshore electrical connection of MEC devices

Component / site data type	**Parameter(s)**	**Unit / Format**	**Related infrastructure characteristics**
Connector	Type	wet-mate or dry-mate	Type of lifting and/or subsea equipment/personnel to connect cable
	Number of units	Units	Sufficient deck space, large enough crane/A-frame/lifting equipment for loading and operations
	Dimensions	In meters	
	Weight	Weight (kg)	Deck loading of the vessel, crane/A-frame/lifting equipment
Static cable	See static cable section	See static cable section	Requirements to connect connector to static cable (and umbilical) cable, cable protection to be removed, or re(applied), etc.
Seabed conditions	Type of soil	Layer characteristics (rock/mud/sand...)	Type of vessel and equipment to be used for trenching, monitoring and protecting the cable
	Bathymetry	Depth (m)	Type of subsea equipment/personnel
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 3.1.2-2: Typical planning of the offshore electrical connections in the context of a MRE project

Sequence of the logistic phase	**Description of the interactions with other logistic activities**
What usually comes before?	Installation of array cables (possibly including cable protection)
What usually comes after?	Pulling up of array cables to surface piercing substation topside module (if present); Connecting dynamic cables; Energise and system tests
What can be done simultaneously?	Installation of array cables and cable protection; Connection between the intra-array cables and substation

3.1.3 DYNAMIC SUBSEA CABLES

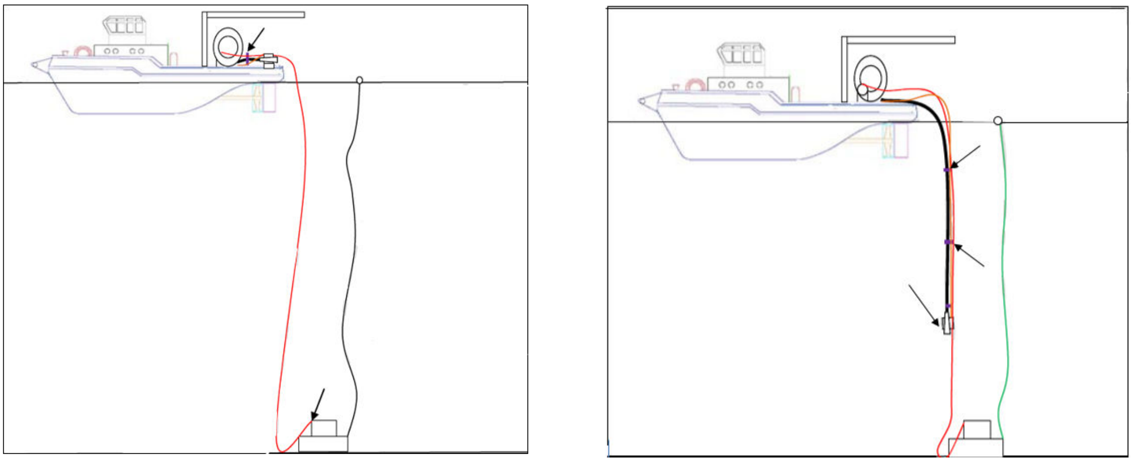
The purpose of umbilical cables in ocean energy arrays is to connect floating energy converters and/or surface piercing platforms to the static seabed electrical components. This process represents one of the most challenging installation phases and one where components are particularly susceptible to damage. It must, therefore, be carefully controlled. The cables are normally custom designs to withstand the dynamic loading conditions of a specific site, and this is also true for the installation process. Although some experience can be extracted from the Oil & Gas sector for the connection to surface piercing platforms, the connection of a large number of floating converters will require novel installation processes.

As such, it is hard to define a typical installation process. However, the information presented in this Section gives an appreciation of the complexity of the tasks involved. This includes a full description of the connection of the two previously outlined sections of the offshore electrical network: the floating converter to subsea umbilical cable and the subsea to surface piercing platform umbilical cable. This stage complements the actual electrical connection process between the two components, and the required equipment and logistic considerations for this are presented in section 0.

3.1.3.1 SURFACE-TO-SUBSEA UMBILICAL

The connection of the floating converter umbilical to the subsea electrical infrastructure, e.g. a subsea substation, is a challenge unique to the MRE environment. Due to the harsh environment, surface converters are likely to include a specially designed dry mate umbilical connection which is included in the device float-out. One can refer to the Pelamis WEC example [45]. The steps outlined in this section consider the vessel based installation process of an umbilical which can subsequently be attached to a connection; however, many of the steps discussed are applicable to OEC with pre-packed umbilical connections.

Figure 3.1.3-1 gives an overview of the main steps of the process, with further details included in the subsequent text. This process assumes that wet mate connectors are utilized for the subsea electrical connection to avoid the necessity of raising the subsea electrical component. If a dry mate connection is required, then the connection has to be raised or can be made during the component installation phase.



(a) connect guide wire
(b) deploy cable

Figure 3.1.3-1: Overview of umbilical cable installation [35]

Vessel Preparation

During the installation process, several pieces of equipment are required. This will normally include: ROV, guide wire and the umbilical cable. The exact installation requirements will be specified by the cable manufacturer, with further details of the vessel characteristics for cable loading and offloading given in section 3.1.1. Depending on the desired umbilical cable configuration, additional components may be required:

- Free-hanging catenary: this does not require any additional components.
- The 'Lazy wave' configuration requires the use of distributed buoyancy modules at a particular part of the cable to ensure mid-water suspension. The buoyancy modules are normally custom built and designed for installation on-board the vessel, as illustrated in *Figure 3.1.3-2*.

Figure 3.1.3-2: On-vessel installation of distributed buoyancy modules [46]

Furthermore, divers will generally be required to check connections and provide support at various stages during this complex process.

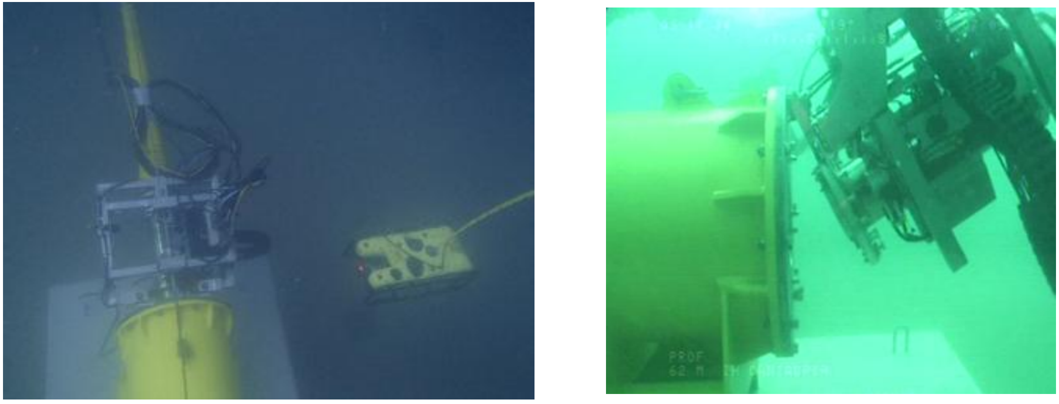
Pre-Installation

Prior to cable installation, a guide wire will be attached by divers to the target electrical component. This will typically be a thin steel wire which will be united at the end of the installation process. The purpose of this is to help guide the ROV and cable during the installation process; the tension of this guide wire is carefully monitored and adjusted during the installation process to ensure that the desired mechanical properties (bending radius, stress at connections) are not breached.

Cable installation

During the installation stage, the umbilical cable and ROV, are carefully overboarded and lowered along the guide wire by the cable offload system. It is important to maintain a positive lead between the vessel and the target electrical component, as this helps to keep the correct tension in the guide wire and avoids loops in the cable. Once the cable is within a predefined distance (typically around 5m), the vessel position will be manoeuvred to carefully adjust the guide wire tension to facilitate the electrical connection. This process is represented by the images in Figure 3.1.3-3.

(a) guide wire connected to component (b) umbilical cable and ROV being overboarded



(c) cable and ROV during installation phase (d) cable and ROV at connection phase

Figure 3.1.3-3: Surface to subsea umbilical cable installation [35]

Electrical connection

As previously discussed, it is assumed that the subsea connection of the converter to subsea umbilical will require wet mate connectors. Please refer to the wet mate connector procedure and logistic requirements outlined in section 3.1.2.1.

Post-installation

Following the successful completion and testing of the electrical connection, the ROV will be recovered to the vessel and stored on deck. The final stage of the process will be to disconnect the guide wire from the target electrical component, which will be brought back to the vessel using a winch system.

3.1.3.2 SUBSEA-TO-SURFACE UMBILICAL

The installation of the subsea to surface umbilical requires a different approach to that of the surface to subsea umbilical. Fixed surface piercing structures normally include J-tubes to facilitate the cable transition from subsea to the electrical components located on the topside module. J--tubes are widely used in the Oil & Gas and offshore wind sector and the umbilical installation techniques are expected to be similar in the MRE environment. Further details on the J-tube design and performance requirements are included in DTOcean Deliverable 3.1 [47].

As well as the team on-board the installation vessel, this logistic phase will also require a team on-board the fixed structure to conduct and monitor operations.

Vessel preparation

During the installation process, several pieces of equipment are required. The vessel will transport a ROV and the umbilical cable to site. Divers will generally be required to check connections and provide support at various stages during this complex process.

The exact installation requirements will be specified by the cable manufacturer, with further details of vessel specification for cable laying available in section 3.1.1. The umbilical cable will be transferred onto the vessel, with the length and weight determining the carousel requirements. Due to the high wave and current loading expected at the site, the use of bend restrictors and bend stiffeners is recommended to avoid cable over-bending. The need for these components will be determined by cable dynamic analysis and will generally be required at the termination point with the connector, e.g. the cable end entering the static structure. Although it is feasible to connect the cable support structures offshore, they will normally be installed prior to vessel loading and accommodated on-deck. J-tube seals may also be connected along the umbilical cable prior to departure to ensure a watertight seal around the J-tube entrance. These components, and some examples of overboarding procedures, are given in Figure 3.1.3-4. While they do not significantly alter the cable dimensions, additional space requirements around the carousel should be considered when selecting the vessel.

(a) connector end bend stiffener and lift assisted overboarding [48]

(b) overboarding bend stiffener using cable chute [49]

(c) J-tube seal and cable protection system [50]

(d) J-tube seals [51]

Figure 3.1.3-4: Examples of cable protection equipment and over boarding procedures.

<u>Guide Wire and Pulling Line Deployment</u>

The subsea to surface umbilical process begins from the fixed surface piercing structure. Following construction, the structure will be equipped with a suitable winch, or pulling system to perform the umbilical installation. This may be a temporary system which must be removed by the vessel after the operation is complete [52]. If the cables are to be pulled before the topside module, i.e. the area with where the umbilical cable(s) will ultimately be connected, arrives on site, then the cables will be connected to temporary frames. It is assumed that these temporary frames will be installed as part of the surface piercing structure phase, if required.

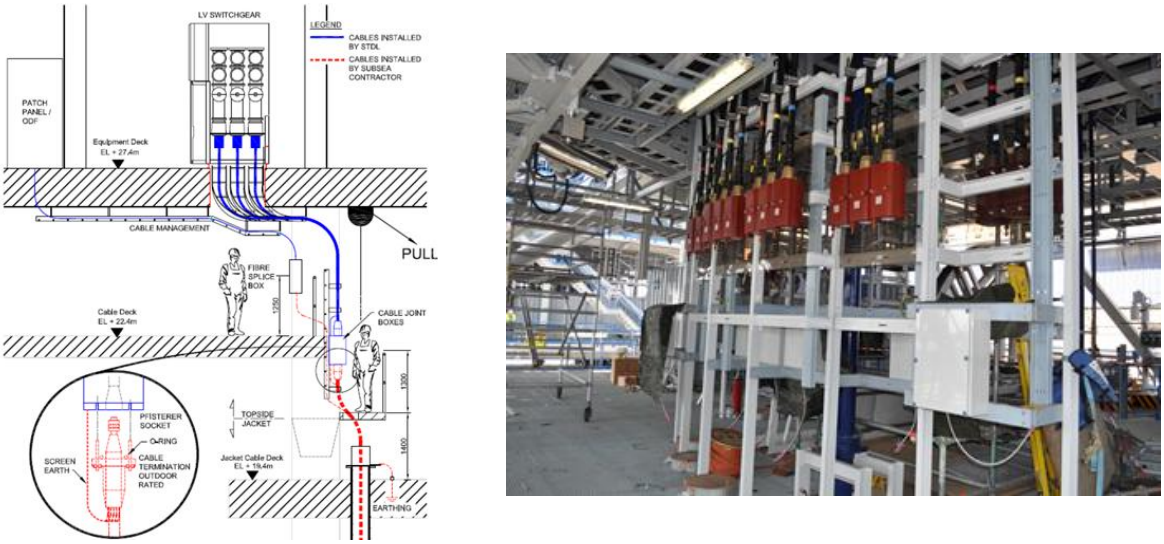
As the J-tube may get contaminated prior to umbilical installation, an enclosure cap is usually used to seal the subsea end. The area around the bellmouth entrance will be inspected prior to removal and cleared if necessary. Divers can vacuum the area, in a process taking 0.25 – 2hrs [53]. Once the area is deemed acceptable, the ROV will be deployed and the enclosure cap will be removed. The guide wire is then pulled towards the cable laying vessel (CLV)/barge and the ROV is recovered on deck. Once the connection has been established between the CLV and the fixed structure, a heavier pulling line may be connected to the guide wire and paid out from the fixed structure for the pull-up procedure.

Umbilical cable installation

To install the umbilical cable, a connection is made between the guide wire/pulling line and the end of the cable. The cable is then laid in an S-shape to create enough slack for installation using the grapples and laying engine of the CLV. In the next step of the operation, the umbilical cable laid on the seabed is pulled toward the fixed structure by the pulling system on the fixed structure. During this step the position of the vessel will be carefully controlled to ensure correct tension along the cable, and to avoid kinks in the cable. The umbilical cable will enter the J-tube and be brought up and out the top of J-tube.

Umbilical cable termination

Once the cable has been successfully pulled out the top of the J-tube, it is ready to be dry connected to the switchgear. A typical cable pulling and connection diagram is shown in Figure 3.1.3-5. If the topside module is not yet installed, the umbilical cable will be connected to the temporary frame. The subsea end of the umbilical will be either connected to the subsea unit (if not performed during a previous project phase) or capped for connection during a later logistic phase.



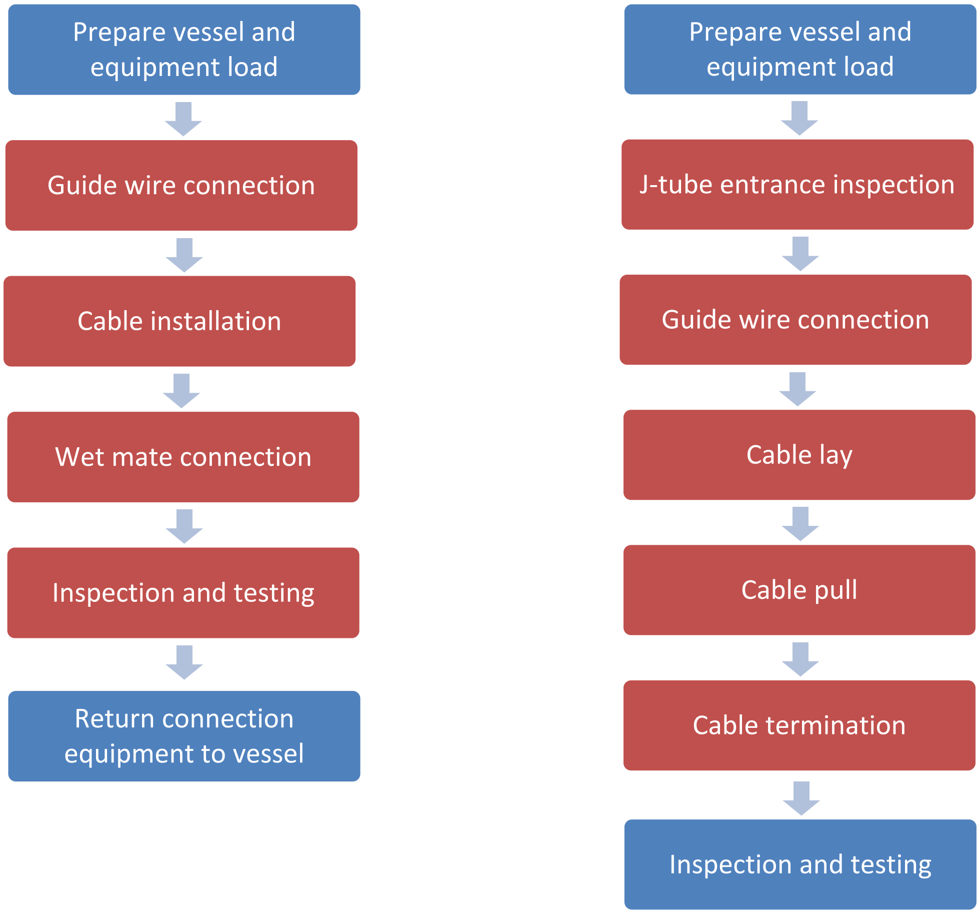
(a) cable pulling and connection diagram (b) offshore cable connection

Figure 3.1.3-5: Topside umbilical termination [54]

Inspection and Testing

Following the installation phase, the electrical connections will be inspected and tested in accordance with the relevant standards. As the ROV used during the process is recovered before the cable is laid, the process is then deemed complete. However, additional testing along the cable route, and particularly at the J-tube entrance, may be performed. If so, the ROV and/or dive team will be deployed and recovered within this stage.

Based on the description provided in the previous section, the installation of the umbilical cable is broken down into individual steps. The flowchart is presented in Figure 3.1.3-6.



(a) surface to subsea (b) subsea to surface

Figure 3.1.3-6: Flow-chart of the logistic operations during the installation of umbilical cable

Table 3.1.3-1: Key logistic requirements influencing the selection of port, vessels and equipment for the installation of the umbilical cable

Component / site data type	Parameter(s)	Unit / Format	Related infrastructure characteristics
Umbilical cable	Number of units	Number of sections	Deck space and size of winch system
	Length	Length per section	
	Weight	Weight in kg/m	Deck loading of the CLV and lifting / pulling equipment
	Minimum bending radius of cable (or protecting pipe)	Radius (m)	Type of winch system and cable handling equipment
	Type of umbilical configuration	Free hanging, lazy, lazy-s	Affects number of components and thus deck area, loading and equipment
	Installation strategy	connector --> device; device --> connector; device --> device	Type and size of lifting equipment
Connector	Type of connector	wet-mate or dry-mate	Type of lifting and/or subsea equipment/personnel to connect cable
	Weight of connector	Weight in tn	
Seabed conditions	Depth	Depth (m) along the cable route	Type of vessel, divers or equipment to be surveying and monitoring cable laying
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 3.1.3-2: Typical planning of the installation of a Surface to Subsea umbilical cable in the context of a MRE project

Sequence of the logistic phase	Description of the interactions with other logistic activities
What usually comes before?	Installation of connectors to static cable; connection of device to mooring sytem (if not pre-connected)
What usually comes after?	Connection of the converter to the umbilical (if not pre-connected, e.g. Pelamis); testing and commissioning
What can be done simultaneously?	Installation of connectors; installation of devices (if umbilical pre-connected)

OFFSHORE SUBSTATION

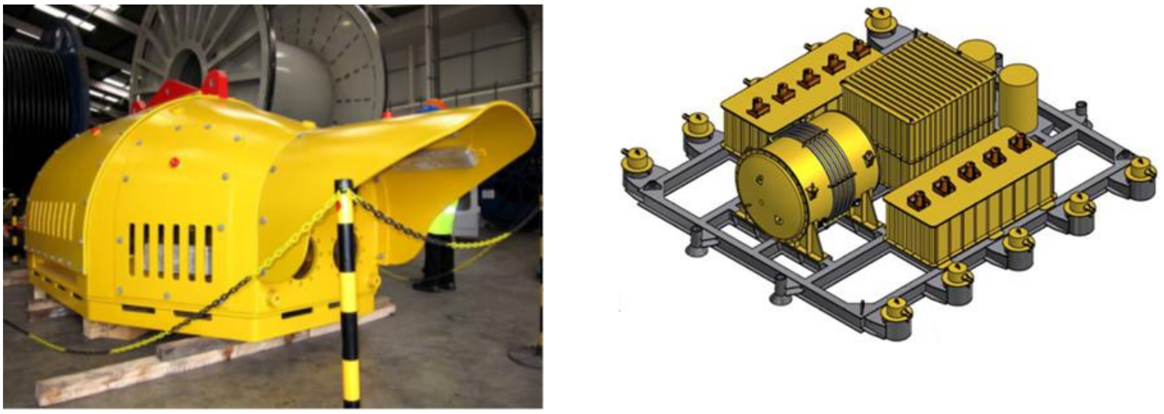
The inherent losses in transmitting power from offshore arrays to the onshore network may significantly reduce the commercial viability of a project. To improve efficiency, offshore substations are used to increase the transmission voltage close to the point of energy extraction. Although the main purpose of the offshore substation is to transform to higher voltage for transmission to shore, there are several other important features which may be included in the design, e.g. switching functionality to connect/disconnect equipment and house protection equipment, monitoring/SCADA devices, harmonic filters and reactive compensation to satisfy (onshore) grid compliance.

The offshore substations used by the offshore wind industry build on experience from the Oil & Gas sector, and most designs consist of a foundation support structure and 'topside' module (which houses the electrical equipment). These large steel structures are the heaviest lifts of the offshore installation process, and also require long fabrication times (up to 2 years) [55]. However, due to differences in array size and location, the solutions employed in the offshore wind industry may not be directly transferrable to MRE projects. Therefore, this section includes the main approaches applied in the wind industry and alternatives which may be more suitable within the MRE space. To maintain a clear structure, this has been divided into subsea substations and surface piercing substations.

3.1.3.3 SUBSEA MOUNTED SUBSTATIONS

Due to the expected size and location, subsea substations may provide a more economically viable, and environmentally friendly, collection solution for MRE developments than the surface piercing platforms commonly found in the offshore wind industry. The operations outlined in this section are described with respect to a subsea substation unit, i.e. a dedicated group of electrical components consisting of a transformer and switchgear/protection equipment, but is also generally applicable to a subsea collection point which may be used in star type collection networks or in small arrays close to shore. No distinction is made between the two and the term subsea unit is used in the remainder of this report.

The subsea unit will generally be a bespoke design and, as yet, there is no standardized approach. This is illustrated in Figure 0-1, which displays designs from a number of developers. The unit will consist of housed electrical components, the exact configuration of which will be project specific, which must be secured to the sea bed. This is normally achieved using a gravity structure, as this represents a lower cost than the operations required for piling [56] and allows for use of cheaper materials [54]. The subsea unit is typically transported to a site already connected to the base, but additional techniques may also be employed to ensure on-bottom stability. The largest, and heaviest component, will be the power transformer and this will have a significant bearing on the physical characteristics of the subsea unit. Values for transformer-less units are approximately 0.4T/MVA – 2T/MVA [57], [58]; while subsea units with transformers are approximately 6T/MVA – 15T/MVA [54], [59]. It should be noted that these values are included for illustrative purposes only and are highly dependent on the specific functionality of the subsea unit, which can vary considerably, and based on proposed design solutions. If a concrete foundation is used, the dimensions and weight will be analyzed according to the met-ocean conditions. However, an approximation is that the weight will be similar to combined weight of the electrical components [54].



(a) Wave Hub [56] (b) subsea collection point with transformer [54]

(c) Prysmian [35] (d) subsea collection point with transformer [60]

Figure 0-1: Examples of subsea units

Fabrication

The subsea unit will be fabricated at a suitable manufacturing plant. If required, the unit will then be transported to the port for loading.

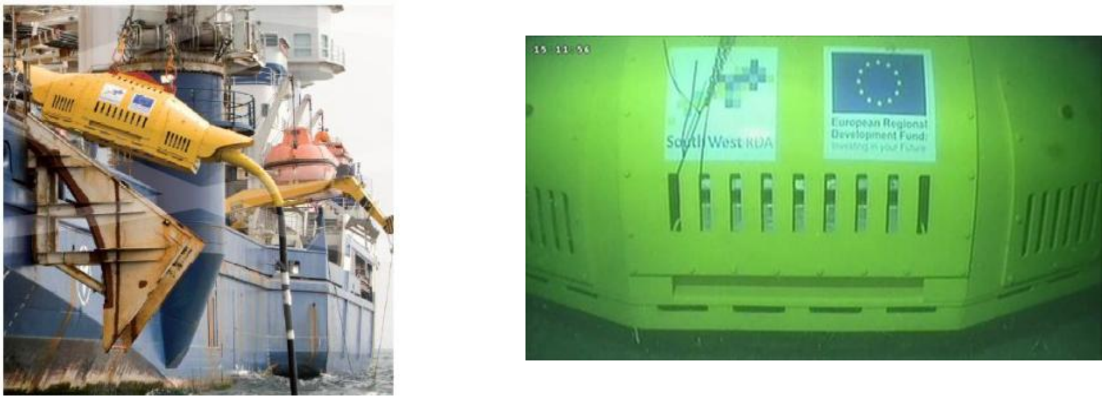
Vessel requirements and unit loading

The primary vessel requirement for the installation of subsea unit(s) is to provide secure storage during transportation and lift gear for a safe and controlled offload. The space requirements will be determined by the number of units and the footprint. Similarly, the capability of the lift system will be sized to meet the physical specification of the unit (i.e. footprint and weight). Before departing from the port, the subsea unit will be lifted onto the deck, using either a dockside crane or on-board lift system, and securely fastened. Divers and/or ROVs will be used to monitor the installation and should be accommodated on-board the vessel.

Other factors that should be considered during vessel selection are the parallel logistic phases, as the installation of the subsea unit and electrical connections can be performed in the same logistic phase. It is also possible to combine this with laying the array cables. The vessel requirements for these phases are discussed in section 3.1.1 and 0, respectively, and are not repeated here. One additional feature of the subsea unit which should be considered when selecting an appropriate vessel is the presence of pre-installed cables. This places four additional requirements on the selected vessel: the ability to secure the cable, the ability to load the cable onto the storage system, the ability to fasten the subsea unit at the carousel location and the ability to safely offload the cable during installation. One method to achieve this is to modify the cable carousel, as illustrated in Figure 0-2.

(a) unit on modified cable carousel [57]

(b) unit being lowered into water (crane perspective)



(c) unit being lowered into water (cable chute perspective) [61]

(d) unit secured on seabed [62]

Figure 0-2: Example of subsea unit installation process using modified carousel aboard DeepOcean

<u>Seabed preparation</u>

As the subsea unit is placed on the seabed, it may be necessary to prepare the area prior to deployment. Seabed preparation consists of the removal of soft, mobile sediments and/or the levelling of an area by addition of gravel or rock dumping [63]. Sediment removal can be performed through suction dredging, with typical production times of 1000-7000 m3/h [64]. Both rock dumping and suction dredging are techniques which may be required during other logistic phases, i.e. foundation installation and cable lay, so the use of specialist equipment should be coordinated.

Installation

Prior to the installation phase, the subsea unit will be connected to the vessel lift system and the ROV/dive team move into position to monitor the installation process. Then the unit is lowered to the seabed. Following this, the dive team will disconnect the rigging and may attach a messenger line with surface buoy to mark the position of the substation.

Subsea unit protection

Depending on the type of gravity ballast and site specific sea state conditions, additional on-bottom stability and scour protection may be required. Rock dumping will help to stabilise and protect the unit [54], and can be coordinated with the cable protection phase. For more details, please refer to section 3.1.1.

Based on the description provided in the previous section, the installation of the offshore substations is broken down into individual steps. The flowchart is presented in Figure 0-3.

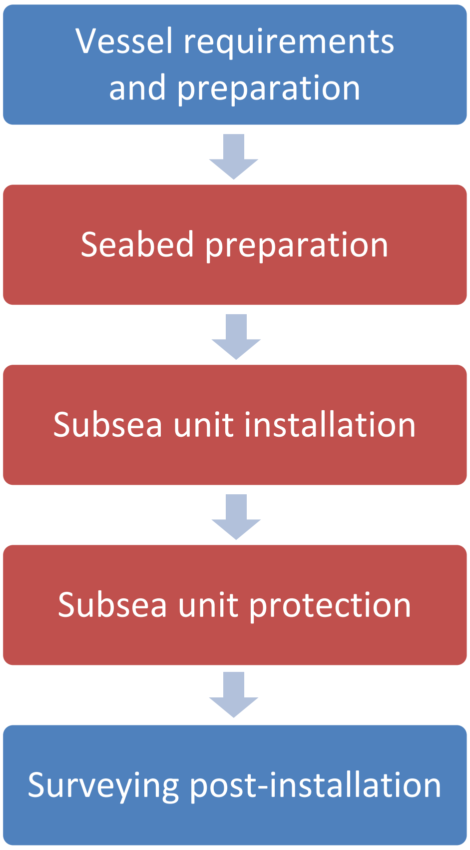


Figure 0-3: Flow-chart of the logistic operations during the installation of a subsea substation

Table 0-1: Key logistic requirements influencing the selection of port, vessels and equipment for the installation of an electrical subsea substation.

Component / site data type	Parameter(s)	Unit / Format	Related infrastructure characteristics
Support structure	Type	e.g. Gravity based or other	Sufficient deck space, large enough crane/A-frame/lifting equipment for loading and operations (vessel and port) for load, deck area, seafastening…
	Number of units and subcomponents (if relevant)	Units	
	Dimensions	In meters	
	Weight	Weight (kg)	
Substation / collection point	Dimensions	In meters	
	Weight	Weight (kg)	
Transport & Installation strategy	Location and method	At site, at port, etc.	
Static cable	See static cable section	See static cable section	Requirements to connect substation and static cable. Ability to store cable. Ability to offload cable.
Seabed conditions	Type of soil	Layer characteristics (rock/mud/sand...)	Type of vessel and equipment to be used for trenching, monitoring and protecting the cable
	Bathymetry	Depth (m)	Type of subsea equipment/personnel
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 0-2: Typical planning of the installation of an electrical subsea substation in the context of a MRE project

Sequence of the logistic phase	Description of the interactions with other logistic activities
What usually comes before?	Static cables (export and/or array cables)
What usually comes after?	Connect array and export cables; Energise and system test
What are commonly done simultaneously?	Installation of array cables; Protection of cables and subsea units

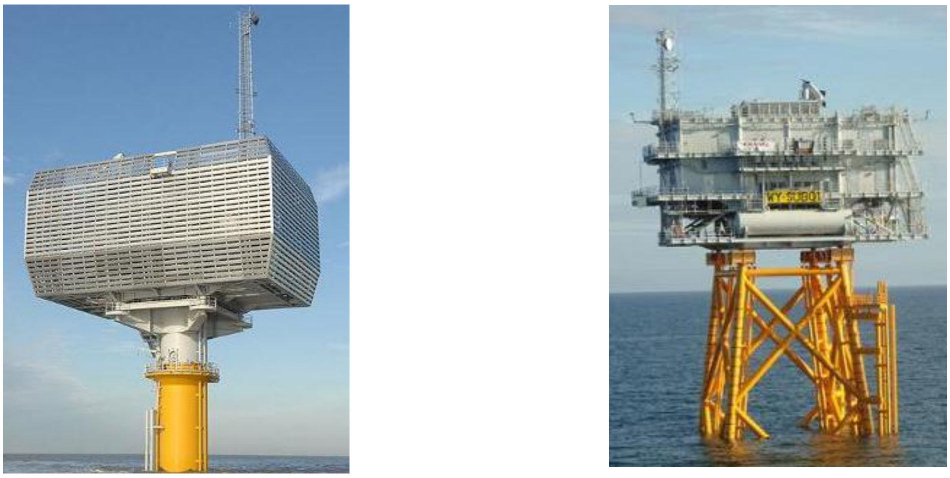
3.1.3.4 SURFACE PIERCING SUBSTATIONS

The major logistic operations of the offshore surface piercing substation design can be divided into two activities: support structure and topside module deployment. The electrical design of the topside module will be the determining factor of the size and weight of the offshore platform, and this load will define the requirements of the support structure. Therefore, the order of these tasks will be coordinated.

For clarity, these are presented as discrete stages. Where stages overlap, or can be combined, this is discussed within the text and illustrated in the flow chart included in Figure 0-14.

<u>Support structure</u>

The two most commonly used types of support structure for offshore substation platforms are monopile and jacket. These are compared in Figure 0-4. A number of factors will determine the most appropriate solution, including the size and weight of the topside electrical design, water depth, seabed ground conditions and metocean conditions [65]. Due to the different logistic requirements, this section has been separated into the logistic requirements for monopile and jacket support structure deployment.



(a) monopile support structure (b) jacket support structure

Figure 0-4: Offshore surface piercing substation support structures [66]

<u>Monopile</u>

Pile installation is described in detail in section 3.3. The following is a summary of the main stages for a monopile installation with the objective to hold a platform carrying an offshore substation.

<u>Monopile support structure - surveying</u>

The main outcomes from surveying for offshore substation design are seabed conditions and metocean conditions. A scour survey will also be required.

Monopile support structure – pre-installation activities

Scour protection may be required to protect the foundations. The options include: protective aprons, mattresses, flow energy dissipation devices and rock and gravel dumping [67].

Monopile support structure - fabrication

Monopiles are normally constructed from welded steel tubular sections. The monopiles will be fabricated at a suitable construction yard and, if required, transported to the port.

Monopile support structure – loading and preparing the vessel (transportation)

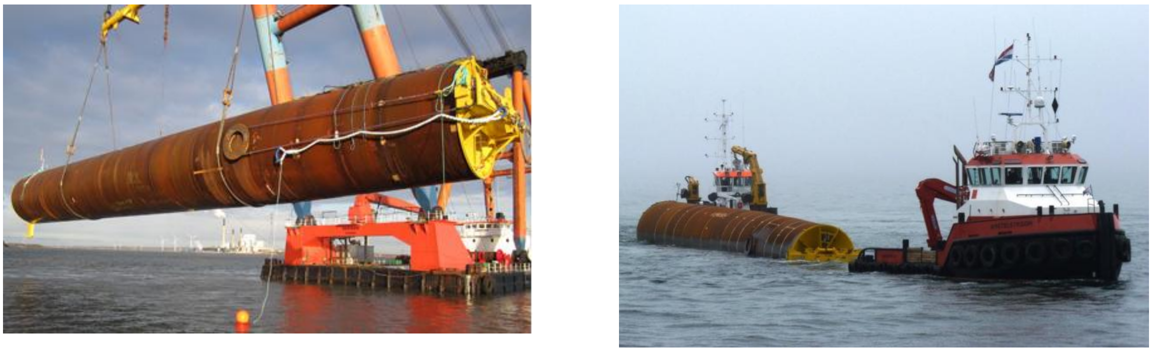
The total weight of the monopile structure can range from approximately 400 – 700T [66]. This total weight consists of: the monopile itself, ranging between 200 – 350T, the transition piece (150 – 200T), additional steel support, which may weigh up to 100T, and J-tubes, which can weigh up to 20T [66]. Monopiles may be transported to the offshore site by jack-up vessel, barge or floated-out. The monopoles can be loaded directly from the port to the transportation vessel by a self-propelled modular transporter (SPMT) or via crane lift. Once the loading stage is complete, the structure is seafastened to the vessel. To float-out, the ends of the monopile are capped and the structure is towed to the site. The transportation options are illustrated in Figure 0-5 and Figure 0-6 .

In offshore applications, monopile structures are widely selected as the turbine foundation. Therefore, great numbers must be transported, and large (i.e. jack-up or barge) vessels offer an advantage over towing individual monopoles. As the offshore substation will require one monopile only, float-out will eliminate the need for specialised transportation. However, larger vessels allow for the transport of multiple sections in one operation, as illustrated in Figure 0-5 (b), which should be considered logistic requirements.

(a) jack-up vessel [68]

(b) barge [69]

Figure 0-5: Monopile transport by vessel.



(a) monopile with capped ends [70]   (b) capped monopile being towed [71]

Figure 0-6: Monopile transport by flat-out

Monopile support structure - installation

The standard method for installing piled structures is to lift or float the structure into position and then drive the piles into the seabed. The monopile manoeuvre may require the use of specialised equipment, such as upending and grip tools, while the driving process is achieved using either steam or hydraulic powered hammers. The handling of the monopile and required hammer equipment will require the use of a crane, and jack-ups are the most widely used vessels for the installation of monopiles [66]. Following installation, the monopile is cleaned of marine growth. The cleaning process is performed by specialist high pressure water equipment which is lowered onto the monopile via crane. This process can take up to 2 hours [72]. Following this, a transition piece is fit over the monopile and secured by grouting. Grout may be mixed on the installation vessel or mixed onshore and transported to the offshore site.

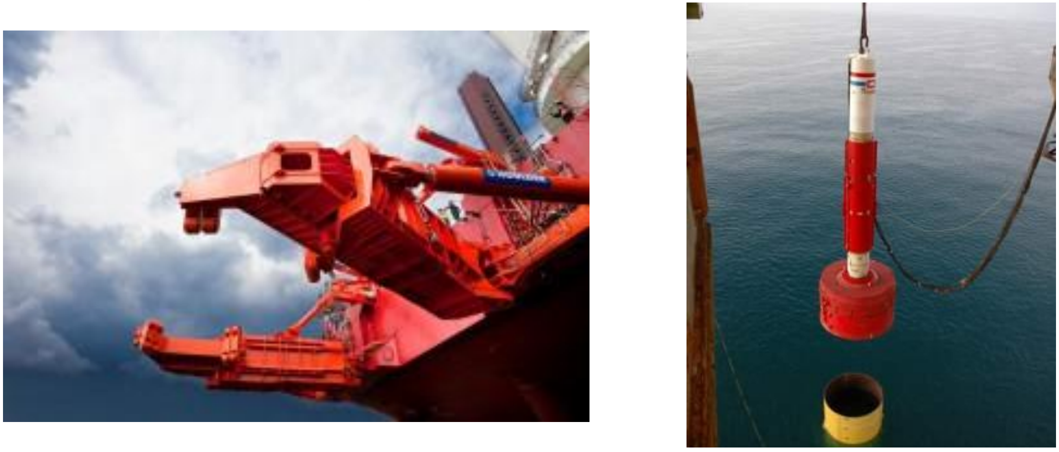
The process may be defined in the following steps [67]:

1. Up-ending pile by jack-up crane vessel with buoyancy assistance if necessary
2. Monopiles lowered to seabed location, with pile weight providing initial seabed penetration
3. Installation of monopiles progressed by driving (piling), vibration, drilling or a combination as required by site specific soil conditions and technical and economic viability
4. Installation of transition piece, alignment and grouting

A graphical representation of the monopile installation process is given in Figure 0-7.

(a) monopile upending tool [73]

(b) lift into position [69]



(c) monopile grips [74]

(d) hydraulic hammer [73]

(e) cleaning process [72]

(f) transition piece [75]

Figure 0-7: Overview of the monopole installation process

Monopile support structure – post-installation activities

Additional scour protection may be installed following completion of the monopile foundations. The options include [67]:

- Protective aprons
- Mattresses
- Flow energy dissipation devices
- Rock and gravel dumping

Jacket

Alternatively to the pile foundation, a jacket structure may be used. The following description gives an overview of the different stages for the installation of a jacket structure in the context of a top-site mounted offshore substation. Such structure is not expected to be used as foundations for wave or tidal devices.

Jacket support structure -surveying

The main outcomes from surveying for offshore substation design are seabed conditions and met-ocean conditions. A scour survey will also be required.

Jacket support structure – pre-installation activities

Scour protection may be required to protect the foundations. The options include [67]:

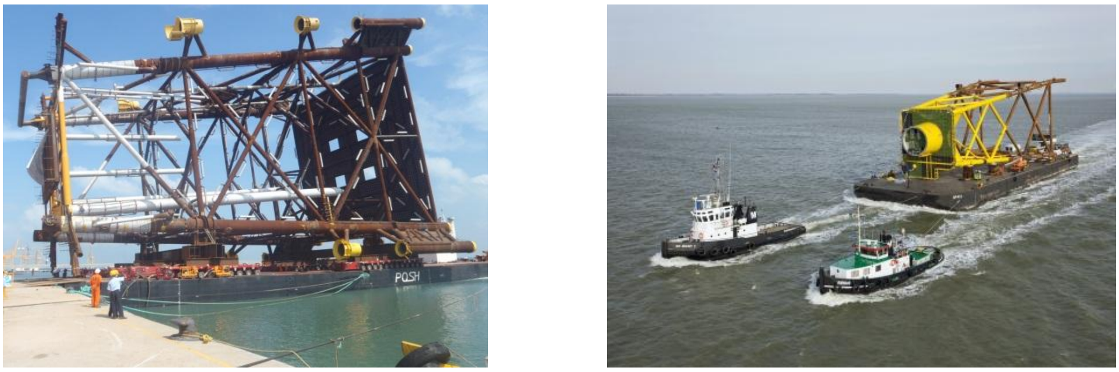
- Protective aprons
- Mattresses
- Flow energy dissipation devices
- Rock and gravel dumping.

Jacket support structure – fabrication

The steel structure will be fabricated at a suitable construction yard and, if required, transported to the port.

Jacket support structure – loading and preparing the vessel (transportation)

The weight of the steel jacket structure can range between 500 – 1150T [66]. The jacket structure can be loaded directly from the port to the transportation vessel by a self-propelled modular transporter (SPMT) or via crane lift. Due to the size of the jacket structure, this will typically be towed by barge to the offshore location. Once the loading stage is complete, the structure is sea fastened to the vessel. Examples of the process are presented in Figure 0-8. However, a crane will be required to lift the structure into place and it is important to ensure that this functionality is available at this stage of the offshore substation installation.



(a) vessel loading [69]

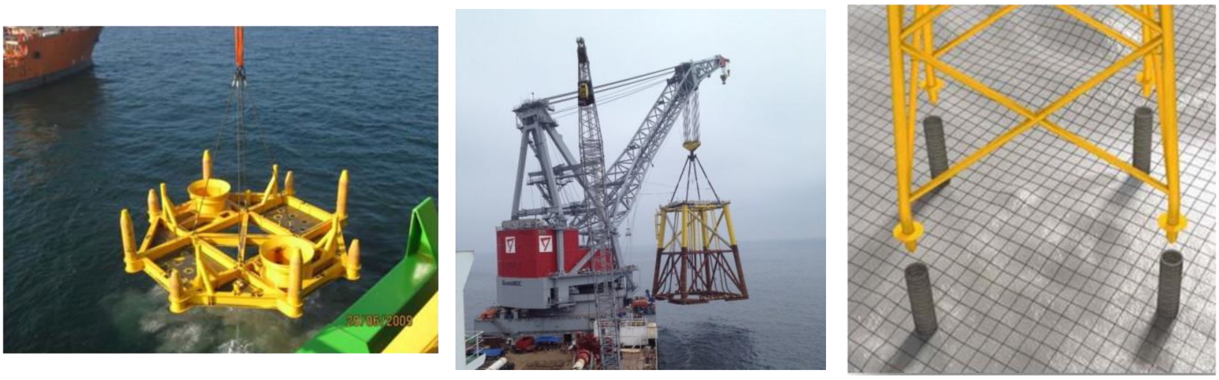
(b) transport to site [76]

Figure 0-8: Jacket support structure transportation process

Jacket support structure - installation

The jacket support is secured to the seabed using driven piles. This can be achieved by either pre-piling or post-piling, with pre-piling being the most widely implemented approach. One important advantage offered by pre-piling is that the installation of the foundation piles can be performed in parallel with jacket fabrication, thus allowing flexibility in the logistic planning process.

During the pre-piling process, a specially manufactured template is used to guide to position of the piles. Once the piles have been lowered into the template, a subsea hydraulic hammer will drive the piles down into the seabed. Once all piles have been inserted into the seabed, the jacket is lowered by the vessel lifting device and guided into the piles. This procedure is illustrated in Figure 0-9. There is generally no need for a transition piece with a jacket structure as this can be designed to fit the topside module directly.



(a) pre-piling template [66] (c) jacket moving [77] (d) jacket in piles [66]

Figure 0-9: Overview of the jacket support installation process

The jacket used in the post-piling process is modified to include sleeves for the piles. The whole structure is then secured by driving piles into the seabed. This technique is not widely used in offshore wind installations, so is not considered in more detail. However, an example of jacket structure with clearly visible post-piling sleeves is displayed in Figure 0-10.

Figure 0-10: Example of post-piling Jacket structure [78]

Topside module – electrical design

The electrical design of the offshore substation will have a considerable impact on the weight of the topside module. A typical offshore wind substation topside consists of two to three decks: the cable deck, the main equipment deck and the roof deck. These are identified in Figure 0-11. The specific requirements of each individual substation will dictate the need for, and the exact layout, of each deck.

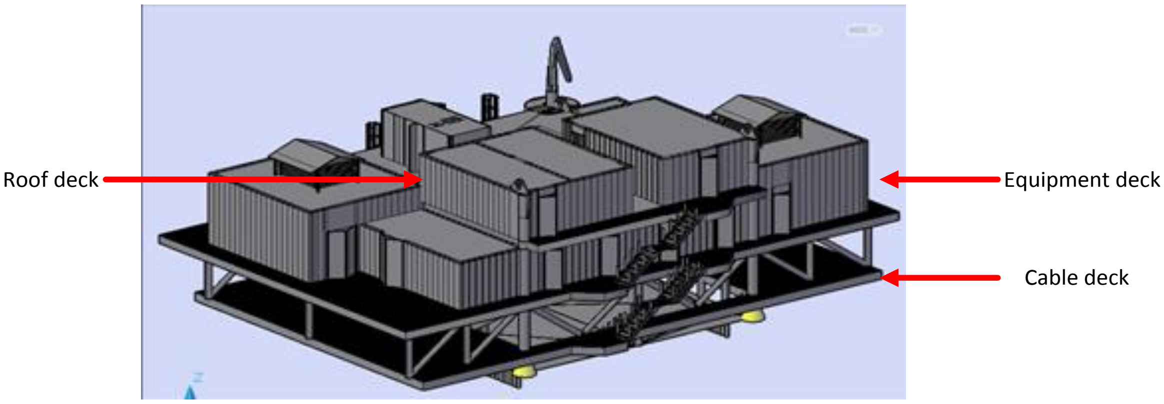


Figure 0-11: Example of generic offshore substation topside module [54]

Topside module – fabrication (pre-installation)

Generally, the entire topside structure will be fabricated by specialized heavy engineering contractors. These are typically turnkey integrated packages and designed to specification as self-contained units. However, the structure fabrication and electrical installation may take place at separate locations. By the end of the fabrication process as much of the internal connections and process will have been completed to minimize the number of offshore operations.

Topside module – loading and preparing the vessel (transportation)

Due to the size of the finished structure, the topside module will normally be transported to the offshore location by barge. At the dock, the substation will be moved onto the barge by SPMT using ramps as displayed in Figure 0-12. All operations performed on the topside must now consider the sensitive nature of the electrical components installed within the steel structure.

(a) topside leaving construction [79]

(b) topside being loaded onto barge [80].

Figure 0-12: Examples of topside load-out.

<u>Topside module – installation</u>

Upon arrival at the offshore site, the topside module is lifted onto the transition piece of the monopile foundation or the top of the jacket foundation. This will be performed by a heavy-lift vessel or jack-up installation vessel. This final stage is shown in Figure 0-13.

Figure 0-13: Installation of topside module onto foundation [66]

Based on the description provided in the previous section, the installation of the offshore substations is broken down into individual steps. The flowchart is presented in Figure 0-14.

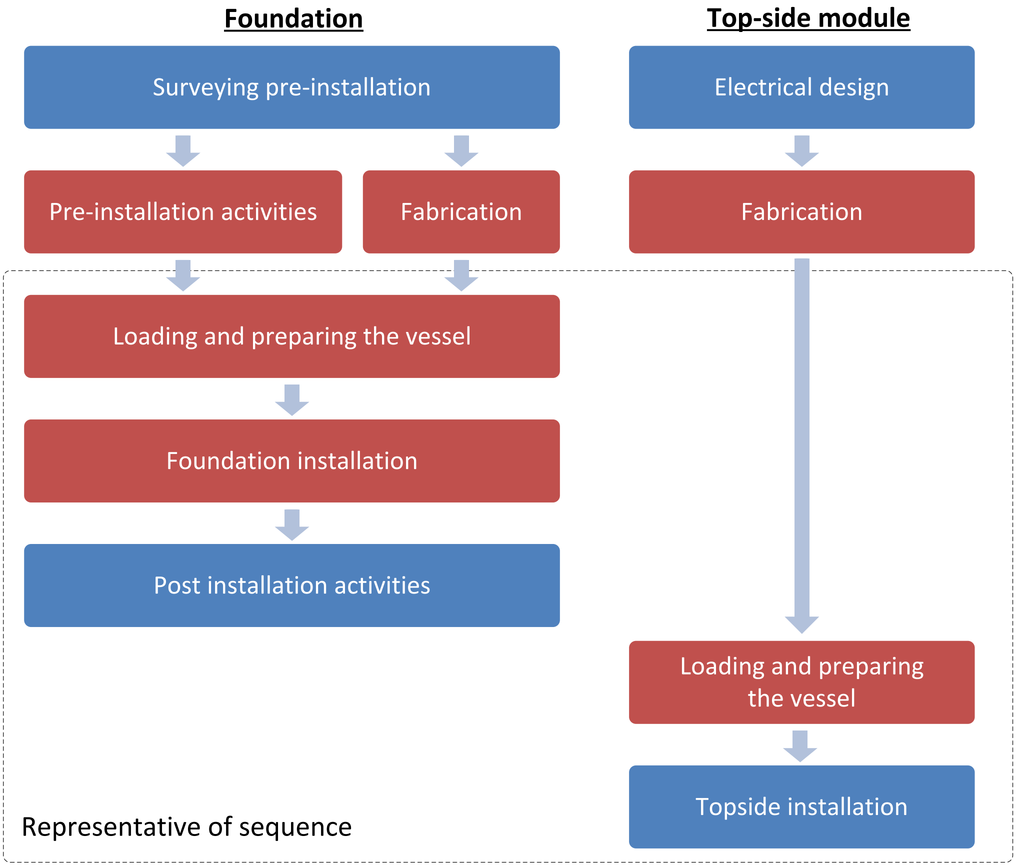


Figure 0-14: Flow-chart of the logistic operations during the installation of an offshore surface piercing substation.

The flowchart in Figure 0-14 sets-out the required installation sequence. However, it is possible to transport more than one component at a time, if suitably long installation weather windows are available. This is demonstrated in Figure 0-15, which shows the substation foundation and topside being deployed in the same operation.

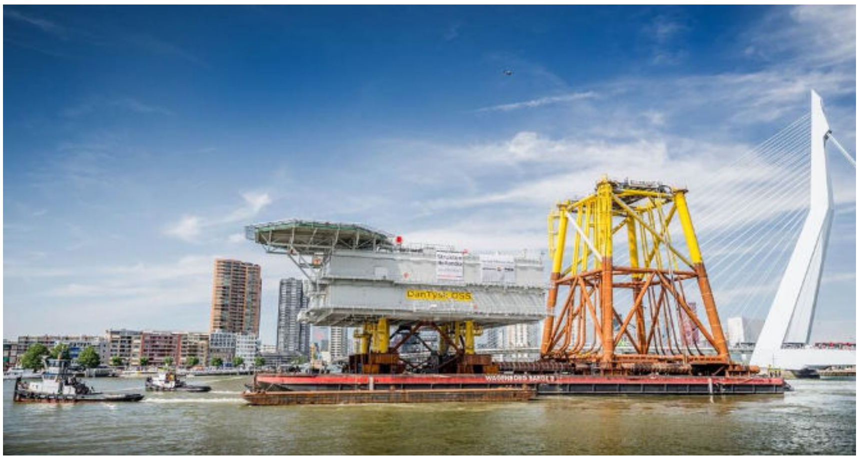


Figure 0-15: Transportation of substation foundation and topside in same logistic operation [66]

Table 0-3: Key logistic requirements influencing the selection of port, vessels and equipment for the installation of surface piercing substations

Component / site data type	Parameter(s)	Unit / Format	Related infrastructure characteristics
Support structure	Type	Units	Choice of vessel and port must be suitable for the system selected
	Number of units and subcomponents (if relevant)	Units	Sufficient deck space, large enough crane/A-frame/lifting equipment for loading and operations, seafastening, etc.
	Dimensions per component	Length x Width x Height (m)	
Topside module	Dimensions	In meters	
	Weight	Weight (kg)	
Transport & Installation strategy	Location and method	At site, at port, etc.	
Static cable	See static cable section	See static cable section	Requirements to connect substation and static cable
Seabed conditions	Type of soil	Layer characteristics (rock/mud/sand...)	Type of vessel and equipment to be used for trenching, monitoring and protecting the cable
	Bathymetry	Depth (m)	Type of subsea equipment/personnel
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 0-4: Typical planning of the installation of surface piercing substations in the context of a MRE project

Sequence of the logistic phase	Description of the interactions with other logistic activities
What usually comes before?	Installation of array cables (of the topside section, but maybe done after the substation foundation installation)
What usually comes after?	Pulling up of array cables to substation/connection of export cable to the topside module; Energize and test system
What can be done simultaneously?	Installation of the OEC foundations with substation foundation

3.2 MOORINGS

The main consideration in reviewing the logistical phase of any mooring installation is that it shall be conducted in a safe, economic and technically competent manor, using suitably qualified installation vessels, handling equipment and personnel. At the current stage of maturity of the wave and tidal sector, numerous mooring configurations for floating and semi-fixed devices are envisaged by the developers.

However, the experience of mooring installation in the Oil & Gas industry will serve as the reference for the wave and tidal sector. In the near future and possibly even in the long term, water depth at the deployment site of MRE farms are very unlikely to exceed 100-150 meters. Furthermore, moorings in the case of some wave energy concepts may be substantially influencing the system dynamics so that it plays a crucial role not only in terms of energy production performance but also for survivability. The share of the mooring costs, including installation costs, can therefore represent up to 20% of the total CAPEX [81].

3.2.1 INSTALLATION VESSEL SELECTION

The installation of large permanent mooring systems has been well established in the Oil & Gas sector for many years however since MRE devices are more likely to be installed in locations where there is a lack of expertise and equipment commonly used in offshore installation, consideration to use smaller vessels, equipment and installation techniques is vital to ensure cost effective installation can be made. However it should also be appreciated that most anchor handling vessels (AHV; Figure 3.2.1-1) or even work boats (WB; Figure 3.2.1-2) can hardly work in high tidal currents or high wave conditions and therefore more specialist vessels might be the only option in some locations.

Figure 3.2.1-1: Typical Anchor Handling Vessel [82]

The design of the mooring system should have taken into account the type of mooring, water depths across the site and dynamics required for the system and while wire and chain have been the traditional mooring solutions, synthetic ropes have the capability to offer a more dynamically compliant system and given their use in the Oil & Gas industry over the past two decades are likely to feature in MRE mooring systems.

Figure 3.2.1-2: Typical inshore Work Boat [82]

The base case assumption for this stage is that the mooring installation and hook-up of the MRE will be completed in two phases. The first phase comprises the installation of the anchor along with any ground chains and mooring lines and the second phase will consist of the final hook up to the MRE device (this phase will not be covered specifically in this part but is covered in further detail in section 3.4). Such 2 step installation procedures can be seen as a widespread approach.

In this section 3.2, five traditional steps pertaining to the installation of a mooring system have been considered, i.e.:

- Loading from port to vessel
- Transportation to site
- Anchor penetration and positioning
- Mooring lines deployment and tensioning
- Post-anchor installation

3.2.2 LOADING FROM PORT TO VESSEL

As previously mentioned, it is likely that vessels used for installation would be smaller than or not as sophisticated as those used in the offshore Oil & Gas industry. It may therefore be necessary to load multiple times at the port to accommodate and transport all the mooring equipment or alternatively look at utilizing a storage barge for transporting the mooring equipment to site. It is important to ascertain what port charges are to be levied for storage, stevedore, crane use and the berth as all factors can have a considerable impact on the overall costs of installation.

Depending on the type of vessels used for installation, consideration should be taken as to whether the mooring line assembly including anchor, ground chains and synthetic mooring should be connected on shore during the load out. This could save considerable time, cost and be a safer solution.

Care should be taken when loading any mooring equipment on the applicable vessels to ensure that no damage is caused as this could invalidate the integrity of the whole mooring assembly. Anchors will generally not require any special loading procedures but advice should be sought from the supplier prior to loading commencing. Ground and fairlead chains should be secured in suitable bundles and again secured to prevent movement during shipment.

Synthetic mooring lines will normally be supplied on wooden or steel transport reels depending on the size and length of the moorings, however these reels are generally only supplied for shipment purposes and as such mooring lines will need to be re-reeled onto either an installation reel or onto the integral winch of the AHV or installation vessel.

It is envisaged that in most cases the length of the mooring ropes will be in the region of 100-200 meters and therefore the need for back tension on the rope is not as critical as for deep water sites that are commonly found in the Oil & Gas sector. However, a load of approximately 5% of Minimum Breaking Load (MBL) is recommended [83]. When re-reeling, the reels should be placed a minimum of 15 meters apart as indicated in the sketch below (Figure 3.2.2-1). The take up reel should be driven and it is also recommended that the shipment reel should be either driven or at least have a brake capability to ensure that the reel cannot freely rotate and allow the rope to become slack and drag on the ground. During re-reeling a forklift, ideally fitted with a roll-box attachment should be used to traverse the rope particularly in the transition from one layer to the next.

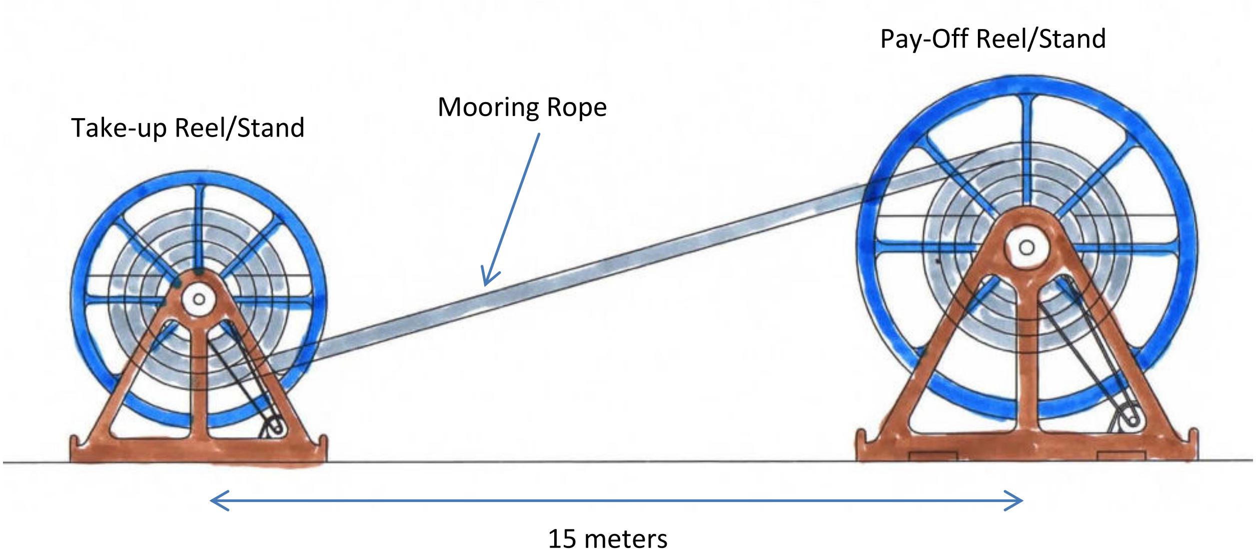


Figure 3.2.2-1: Typical reel stand arrangement *[84]*

Prior to re-reeling, the free end of the rope should be secured to the reel/winch with a suitable webbing sling which should be placed through the eye and then secured to the reel or rope underneath in the case of an installation winch using a suitable shackle. This will ensure that the rope cannot deploy unsecured from the winch during installation. The outboard eye is to be similarly secured using another webbing sling placed through the eye and then connected to a suitable forerunner line.

3.2.3 TRANSPORTATION TO SITE

As with the Oil & Gas industry it is predicted that most port locations used as the base for mooring installation will be relatively close to the proposed site location and therefore long deep sea voyages are not predicted. During transport all equipment must be correctly secured with lashings cradles etc., to ensure that equipment cannot move or come loose during transit. In addition to the fastening operation, synthetic ropes should be protected against abrasion and UV.

Once the hardware equipment is well secured, the AHV and/or the other vessels (e.g workboat and barges) can ship to the site following the most efficient route while respecting the safety standard.

Figure 3.2.3-1: Typical layout of mooring equipment stored on installation vessel deck ready for transport

ANCHOR PENETRATION AND POSITIONING

Prior to installation of the anchors, a survey should be conducted on the anchor locations and installation corridors of the mooring lines to check that the areas are clear of obstruction and debris. The installation corridors should be cleared of any debris and obstructions that could cause a hazard or damage to the proper and safe installation of the mooring lines and anchors.

It is predicted that most MRE devices will be moored using a taut or semi-taut mooring systems and will use synthetic mooring ropes. In the majority of MRE deployments anchors to be used will be one (or more) of the list below:

- gravity anchor
- pile anchor
- drag-in (or drag-embedment) anchor
- direct embedment anchor

All of which are capable of withstanding both horizontal and vertical loads. Depending on the size of the anchor to be installed, the mooring line could be used to assist installation but in some cases a second remotely releasable line will be used by the AHV to lower the anchor to the sea bed.

In most instances, it is suggested that the mooring line would be pre-attached to the anchor and ground chains as post-installation attachment using an ROV will involve extra costs. If a second work line is used for installation of the anchor this should also be synthetic to reduce the risk of damage to the mooring line (which has been documented in the case of a wire rope [85]).

The type, number and position of the anchors will be computed by the moorings and foundations module and by using this output the logistics of the installation can be planned. The installation of the anchors should follow the manufacturer's or supplier's guidelines and relevant design practices and due care should be taken to ensure that the anchors have achieved sufficient embedment before final hook-up of the MRE device.

Pile anchors

Pile anchors (unless suction type detailed in section 3.3.3) will require installation in advance of the mooring line hook up (Figure 0-1). This procedure will be almost exactly the same as the installation of pile foundations described in section 3.3. The only major difference is that the piles will be required to be installed with an attachment point for the mooring lines and this will need to be considered when sourcing drilling or hammering equipment. The ground chains would also be pre-installed at this time and would be buoyed off for subsequent attachment to the mooring lines. It may be possible to combine installation of suction caisson type piles with the installation of the mooring system into a single operation to save time and costs, this should be considered when selecting the installation vessel and equipment.

Figure 0-1: Typical pile anchors [86]

Drag embedment anchors, direct embedment and gravity anchors

The installation of these anchor types will be undertaken in a single operation with the mooring lines attached (Figure 0-2). The details of the penetration and positioning of these types of anchors are described in the following section in order to make the reading more fluent.

Figure 0-2: Typical drag embedment anchors [87]

3.2.4 MOORING LINES DEPLOYMENT AND TENSIONING

As previously mentioned it is assumed in the base case that the mooring installation and hook-up of the MRE device will be completed in two phases. In many cases these phases may run immediately after each other.

A typical procedure for installation and pre-tensioning synthetic mooring lines is as follows. The simplest and certainly the most utilized method of deploying a drag-in type anchor is to use the mooring line and it is, therefore, this method which is described here.

All surfaces that the rope will come into contact with must be smooth and free from sharp edges. Relative movement between the rope and any equipment that it will contact during deployment should be avoided. If polyurethane rope eyes are used special care should be taken to avoid contact of the eyes with metal objects such as winch frameworks and other sharp items.

The installation vessel is used to connect the anchor to the ground chain via a suitable shackle and the anchor is then lowered over the stern roller of the vessel. At this moment, it is important to control the chain deployment to prevent induction of twist in the chain. The final section of the chain should be secured inboard using either shark jaws (Figure 3.2.4-1) or a wire leader attached to the work rope.

Figure 3.2.4-1: Shark jaws and guide on AHV deck

The outboard eye of the polyester rope should now be attached to the open link of the ground chain using a suitably qualified shackle. The eyes of the synthetic rope will typically be supplied with either a steel thimble (Figure 3.2.4-2) or spool (Figure 3.2.4-3). Thimbles are normally integral to the rope and are factory spliced in. Spools are generally supplied loose and would normally be installed into the soft eye mooring line on board the vessel just prior to installation.

(a) Steel Cast Thimble - Factory Spliced (b) Steel Thimble and Masterlink-Factory Spliced

Figure 3.2.4-2: Typical factory fitted thimbles [88]

Figure 3.2.4-3: Typical steel spool and shackle [88]

With the mooring line now attached to the ground chain the mooring line can take up the weight of the anchor and chain and the work rope can be released. The anchor can now be deployed which in turn will pay out the chain and synthetic mooring line. Running the rope over stern rollers is allowable during deployment. However the rope should not be repeatedly cycled around rollers for prolonged periods of time. The rope should also not be left for prolonged periods around bends under dynamic loading conditions.

Drums, sheaves and rollers should rotate freely and have a minimum diameter of at least 8 times that of the rope diameter (D/d ratio) unless line loads of more than 10% of MBL are anticipated when a higher ratio may be desirable [83], [84].

The deployment continues until the upper end of the mooring line starts to deploy from the installation winch at which point the rope is secured on the deck using a ‘Chinese Finger’ *(Figure 3.2.4-4)* or other suitably approved method. The rope supplier should be consulted regarding the load limitations of the stoppering method.

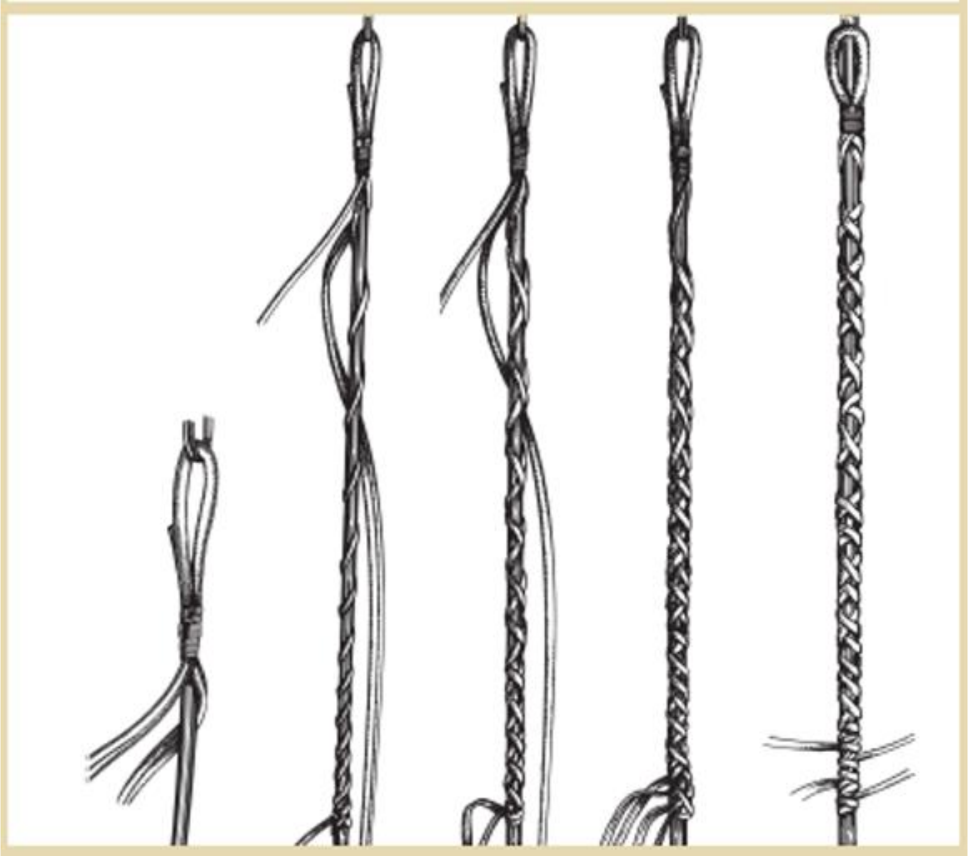


Figure 3.2.4-4: Four part ‘Chinese Finger’ rope stoppers [89]

Depending on whether the mooring uses a single mooring line or segmented mooring line the outboard end should be then attached to either the fairlead chain assembly or the next mooring line segment. When all mooring line segments have been deployed and the fairlead chain attached to the outboard end, the fairlead chain should be secured in the shark jaws or attached to the work rope.

Drag embedment anchor

With the anchor, ground chain, mooring line and fairlead chain now all attached, the anchor is lowered further until at a point just before touching the seafloor at which point the AHV moves slowly forward to ensure the anchor lands correctly.

Once laid on the seafloor and the mooring line has been paid out, the AHV can increase the tension in the line and this will start to embed the anchor into the seafloor. This should be increased until the required proof load tension is reached to ensure correct anchor penetration. The load should then be held for a set period as required by class.

In order to remove initial constructional stretch and pre-tension of the mooring line, a tensioning program is desirable. The ropes should be pre-tensioned to the desired load, typically up to 40% of MBL in polyester however the load maybe significantly different in other materials [83] and held for a period of up to one hour. Further pre-tensioning of the moorings may be required during the hook-up phase or after longer periods in the mooring due to further constructional bedding in and creep.

An alternative installation method for drag embedment anchor by moving the AHV consists of keeping the vessel at a fixed position while the anchor line is coiled until the anchor achieves its ultimate embedment depth. In Wang et al. [90], the installation method by winching the anchor line and the other method by moving the vessel are analyzed and compared.

Self-explanatory animation movies produced by Vryhof depict very clearly the installation of drag-embedment anchors in two configurations:

- Single line installation (most common approach) [91]
- Double line installation. Note that this method slightly differs from the single line installation. From a logistic standpoint, one should note that an additional tug boat is required to pull the second line on the opposite direction to the dragging direction [92]

Concerning the tensioning operation, a Vyrhof's animation movie offers yet another valuable visual explanation [93].

Gravity anchor

The anchor can now be lowered to the seafloor with the mooring line and fairlead chains attached (Figure 3.2.4-5). The anchor should be lowered carefully, not exceeding a rate described by [94]:

$$v_{max} = \frac{W_{bv}}{66A_v}$$

Where:

v_{max} = maximum descent rate (m/s)

W_{bv} = buoyant foundation weight (kg)

A_v = vertical projected foundation area (m^2)

The rate should be further decreased before contact with the seafloor to prevent possible damage to the foundation. It is best practice not to lift the foundation after the initial touchdown has occurred. For heavy structures such as most of gravity anchors, it is often required that the vessels are equipped with a Heave Compensation (HC) system to ensure accurate and safe positioning of the anchor during the lowering phase.

Figure 3.2.4-5: Gravity anchor being lowered into water [95]

Direct embedment anchor

Direct embedment anchors are installed by forcing a plate beneath the sediment to achieve sufficient bearing capacity. This embedment may be done by:

- Driving or vibration methods. This involves forcing the anchor beneath the seafloor with a hydraulic ram or hammer (Figure 3.2.4-6). In certain conditions vibration may also be used to embed the anchor.
- Water jetting methods. High pressure water jets are used to liquefy the soil beneath the anchor. The anchor becomes embedded and the soil reforms above the plate to provide holding capacity. Water jet systems have been described in section 3.1.1
- Gravity drop methods (the reader is directed to the information on torpedo piles in section 3.3)

The installation vessel will have to be equipped with the correct equipment to embed the anchor plate. Larger vessels may be needed to install anchors of this type (see descriptions provided in section 3.3).

Figure 3.2.4-6: Direct embedment anchor attached to driver ready for deployment [86]

Once the anchor is embedded the driving, vibration or jetting equipment will be recovered to the seafloor. A test load should follow and be applied to ensure that the correct bearing capacity is achieved before buoying off the mooring line ready for the MRE device to be hooked up.

Pile anchors

If pile anchors are used then the piles should have been installed in a previous logistic operation. In order to connect the mooring system to the anchor ROV or diver support will be required. The end of the mooring chain will have to be lowered to the seafloor with ROV or diver and attached to the eye at the top of the pile manually. The exception to this is suction piles which can be installed simultaneously with the mooring lines (the process is the same as for the suction piles as described in section 3.3). As with other anchor systems once the buoy has been pre-tensioned it can be buoyed off ready for hook-up of the MRE device.

3.2.5 POST-ANCHOR INSTALLATION

After pre-tensioning the mooring line can either be secured to a surface pennant buoy to await the hook up phase or in some instances could be temporarily laid on the seafloor.

In normal operation it is recommended that the mooring ropes are not allowed to contact the seafloor however pre-installation/pre-laying the ropes on the seafloor may be proposed as part of the installation process but approval should be sorted from the applicable classification society in order to do this.

Any approval must ensure that the qualification is closely tied to the installation and handling procedures which will cover points such as maximum allowable loads during installation, seafloor condition and current, as well as particle sizes etc.

It is recommended that the mooring line is supplied with a suitably qualified filter to prevent particle ingress as a minimum to 20µm [83].

3.2.6 INSTALLATION OF OTHER MOORING SYSTEM COMPONENTS

Mid-water buoys

In many cases the mooring lines, ground and fairlead chain and anchors will form the entirety of the mooring line configuration however, in cases of shallow water additional mooring equipment such as mid-water buoys may be required to ensure that the mooring lines do not contact the sea bed during normal operations or to sustain pre-tension in the mooring line assembly (Figure 3.2.6-1). It is desirable to install such equipment at the same stage as the mooring line installation however, this may not always be possible if the mooring ropes are to be pre-laid on the seafloor.

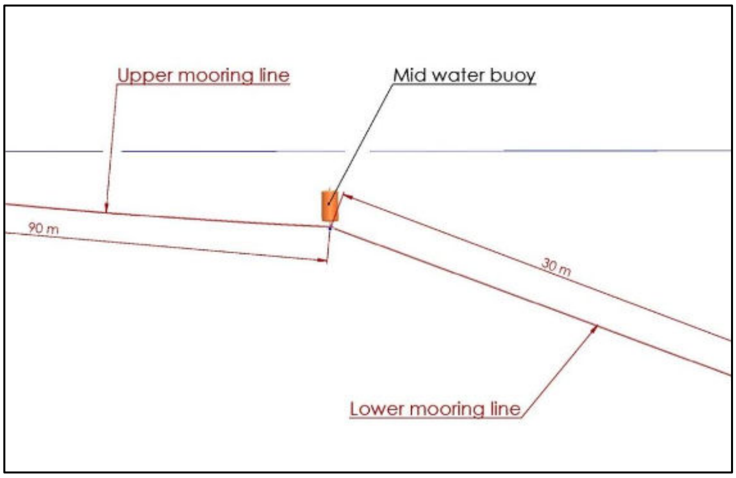


Figure 3.2.6-1: Typical mid-water buoy assembly [96]

Pre-tensioning of the mooring prior to hook up can be achieved either with the AHV remotely pulling the fairlead chain through the chain stoppers (Figure 3.2.6-2) on board the MRE device with its work wire or with other tensioning methods such as a windlass or hydraulic jack on board the MRE device. The mooring lines should be pre-tensioned in sequence, with opposing mooring lines tensioned one after the other.

Figure 3.2.6-2: Typical chain stopper [97]

<u>Clump weights</u>

If a clump weight is going to be used on the mooring system then it will be attached to the anchor chain and deployed at the same time as the anchor installation. As this adds a significant amount of mass to the mooring system it must be confirmed that the installation vessel and equipment is rated to a sufficient capacity.

3.2.7 SUMMARY OF LOGISTIC STEPS

In all cases of mooring installation, a manual shall be issued covering all activities for each phase of the installation, pre-tension and hook-up. The manual shall include all procedures and documentation required and shall clearly demonstrate that the mooring can be safely installed.

To summarize, there are 6 steps leading to the typical installation of anchor and mooring lines assemblies, as shown in Figure 3.2.7-1:

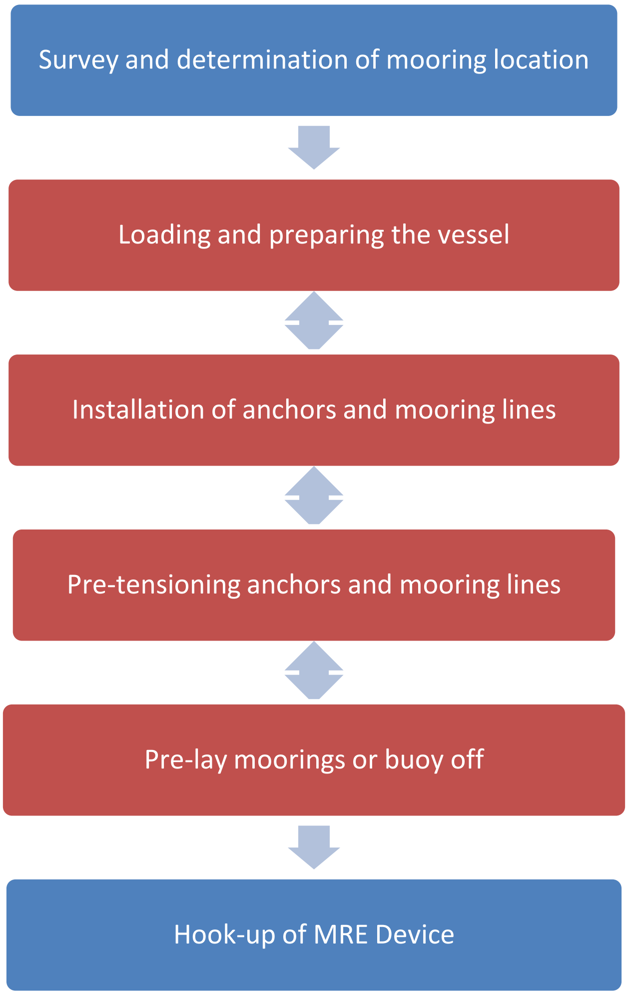


Figure 3.2.7-1: Flow-chart of the sequence of the logistic operations during the installation of the anchors and mooring lines

Table 3.2.7-1: Key logistic requirements for mooring system installation

Component / site data type	**Parameter(s)**	**Unit / Format**	**Related infrastructure characteristics**
Anchoring system	Type	N/A	Choice of vessel and port must be suitable for the anchoring system selected
	Number of components	Units (anchors, moorings, buoys, etc.)	Sufficient deck space, large enough crane / lifting equipment at vessel and port
	Dimensions per component	Length x Width x Heigh (m)	
	Weight per component	Weight (kg)	
Transport & Installation strategy	Location and method	At site, at port, etc.	Type of crane / lifting equipment at vessel or port for load, deck area, seafastening, etc.
Seabed conditions	Type of soil	Rock/mud/sand... and thickness (m)	Type of vessel and equipment to be used for selected anchoring system may differ in different seafloors
	Bathymetry	Depth (m)	Type of subsea equipment/personnel
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 3.2.7-2: Typical planning of the installation of a mooring system

Sequence of the logistic phase	**Description of the interactions with other logistic activities**
What usually comes before?	Manufacture of anchors, mooring lines and components superstructure; Transportation of equipment and anchors to port; Installation of pile anchors (if utilised).
What usually comes after?	Hook-up of MRE device.
What can be done simultaneously?	Multiple installations can be completed simultaneously if vessels are available.

3.3 FOUNDATIONS

Tidal stream turbines are located in sites with flow conditions, which may be sufficiently energetic or turbulent to remove sediment from the seafloor and expose the underlying rock. At these sites, piles will need to be installed by drilling down into the rock and grouting the piles in place or by designing a foundation with sufficient mass to withstand the loads experienced by the turbine. Wave energy sites may have a variety of different seafloor geologies and environmental conditions, fixed wave energy converters may also be secured by piles (either hammered or drilling) or gravity foundations (e.g. Figure 3.2.7-1).

Figure 3.2.7-1: (left) Andritz Hydro Hammerfest turbine HS1000 [11] *and (right) Aquamarine Oyster wave energy converter* [98]

Floating devices will have a mooring system that can be secured to the seafloor by anchors (see section 3.2) or foundations (gravity, driven pile, torpedo pile or suction caisson). The logistic steps associated with the installation of each type of foundation are described in section 0.

3.3.1 INSTALLATION VESSEL SELECTION

The largest cost associated with the installation of foundations for wave and tidal arrays is the cost of a suitable installation vessel (Figure 3.3.1-1). Wave and tidal energy is a new area of maritime operations and as such there is not yet a class of vessels designed specifically for the installation and maintenance of foundation structures of marine energy devices. Whilst conventional installation vessels (such as those used by the offshore Oil & Gas sector) are designed to operate in the open ocean, the extreme conditions of particular MRE sites (i.e. high current velocity tidal sites) may mean that many piling and drilling vessels struggle to operate in these conditions. This means shorter operating windows, increased downtime and potentially vastly increased costs. The availability of vessels also has a direct influence on charter costs (Figure 3.3.1-2). Most offshore construction vessels and jack-up rigs are limited to operations within a maximum current speed below that of a tidal race. With the peak flow of some proposed tidal energy sites over 5ms^{-1} suitable weather windows need to be sought to use conventional installation vessels [99].

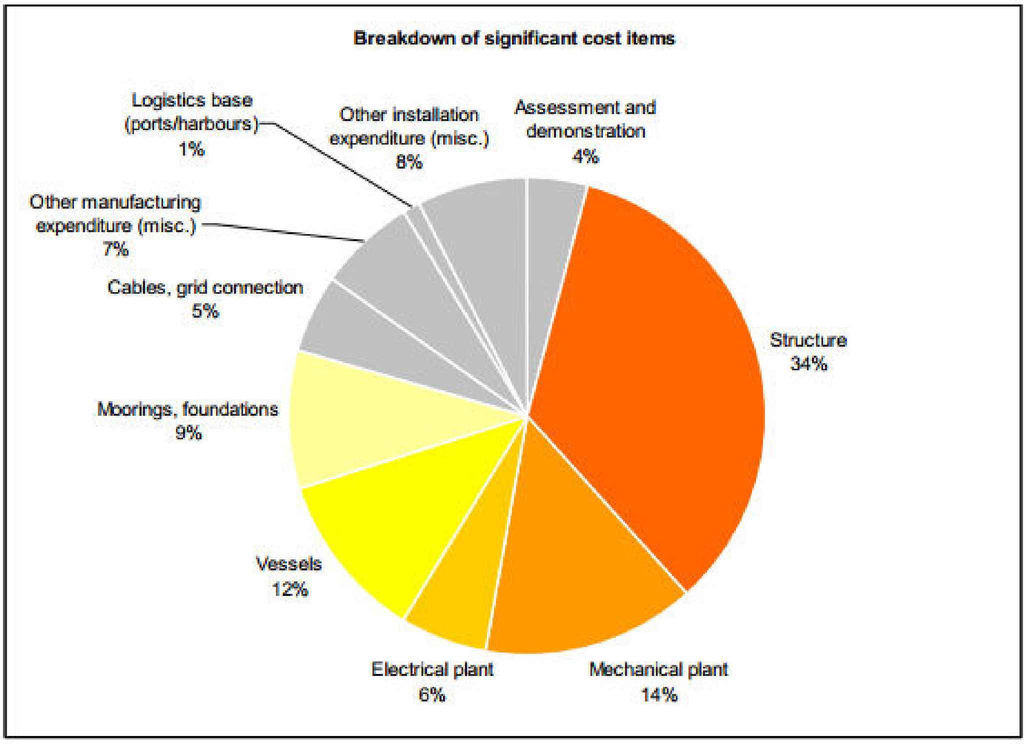


Figure 3.3.1-1: Construction and installation expenditure for a hypothetical 50MW MRE plant [100]

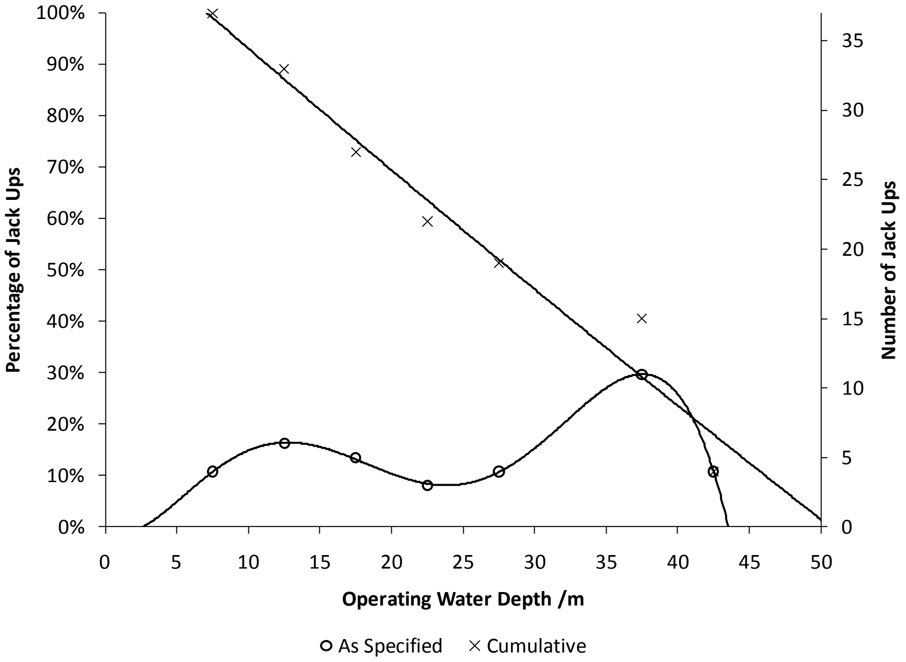


Figure 3.3.1-2: Jack-up barge availability with operating water depth [101]

A new class of DP vessels designed specifically for operations in fast tidal areas is being developed. In order to reduce the levelised cost of energy (LCOE) of tidal stream energy to a commercially viable level, the installation costs will need to be significantly reduced. Vessels which are able to operate throughout the whole tidal cycle will be able to complete tidal installation projects in less time and at a considerably lower cost than currently available options. One such example is the HF4 tidal installation vessel designed by Mojo Maritime, this vessel is designed to hold station and conduct drilling and installation operations in up to 5ms^{-1}, covering the full range of tides at most proposed sites [102].

Lower cost approaches may also be appropriate. Tension Technology International are currently working on a cable laying mooring concept for a standard barge with no special mooring equipment that will be able to operate in a 10 knot tidal current and waves of Hs=1.5m. It has been found that through the use of floating ropes and 'fish' type buoys it is possible to prevent surface buoys and mooring lines from being dragged under in high current conditions.

Some examples of vessels that could be used to install foundation systems for wave and tidal arrays include:

- Offshore construction vessel (OCV) with DP capability e.g. ‘North Sea Giant’ (Figure 3.3.1-3). These are large vessels which are usually equipped with powerful crane facilities and they can be fitted with drilling or piling equipment. These ships have DP capabilities however they are usually limited to being able to operate in a maximum current of just 1 or 2ms^{-1}, but are able to operate in moderate waves. They are typically large vessels hence may be able to transport foundations for several devices on a single excursion. OCVs will have a comparatively high cost to charter compared to smaller vessels.

Figure 3.3.1-3: An example of an Offshore Construction Vessel [102]

- DP crane barge e.g. ‘Rambiz’ (Figure 3.3.1-4). Crane barges are available across a large range of sizes from smaller vessels with the capability to lift just a few tonnes up to gigantic vessels with cranes of several thousand tons lift capacity. Drilling and piling equipment can also be fitted. They have DP capability, although, they are not usually able to operate in the fast currents of a tidal race during spring tides and they are limited to operations during periods of low sea states.

Figure 3.3.1-4: An example of a Crane Barge [102]

- Jack-up barge e.g. ‘Seacore Excalibur’ (Figure 3.3.1-5). These vessels are not suitable for deep water installations, fast flowing tidal races or rock seafloors. The legs are designed to embed into the sediment to provide a secure platform for work operations. Once established on site, they provide a very stable platform (or deck) from which to operate drilling or piling activities. Jack-up barges may be self-propelled or towed by another vessel. They are extensively used to install offshore wind turbines and throughout the Oil & Gas sector.

Figure 3.3.1-5: Example of a Jack-Up Barge [103]

- Taylor-made vessels are being designed e.g. ‘Mojo Maritime HF4’ or are in use e.g. the ‘OpenHydro Installer’ barge (Figure 3.3.1-6). As the tidal industry develops, it is likely that a new class of vessels will be produced to cater to the emerging market. The HF4 vessel concept includes a responsive DP system which allows the vessel to hold station at a tidal turbine site throughout all phases of the tidal cycle. A drilling rig, crane and ROV operations could all be included in the design. The concept could be applied to single hull, catamaran or barge-shaped vessels.

Figure 3.3.1-6: (left) HF4 vessel designed by Mojo Maritime [104][105] *and (right) OpenHydro Installer barge* [106]

3.3.2 TRANSPORTATION FROM PORT TO SITE

In offshore wind, port location relative to manufacturing sites and transportation networks determines the transport costs of blades, nacelles and foundations [107]. Foundations can be built at site or transported to the staging area by vessel, while most other components are expected to be transported over land to the assembly port.

The size and mass of piles and the foundation design need to be considered when deciding on the choice of port from which to launch the installation. The infrastructure at the port must be able to accommodate the vessel and transfer the piles and equipment on board (i.e. using dockside cranes). Many of the proposed wave and tidal sites are in remote locations possibly a long distance from large commercial ports, and it is likely that some compromises will have to be made when deciding on which ports are the most suitable. The main considerations are:

- Road or rail access to transport piles to the port
- Available space to store piles and equipment
- Sufficient water depth for installation or transportation vessels
- Large enough dock for vessels
- Crane facilities on the dockside for loading/unloading
- Distance to the installation site

The piles and foundation structural material will need to be loaded onto the vessel using either crane facilities on the dock, a mobile crane on the road/rail transportation vehicle or a crane on board the installation vessel or transport vessel. Clearly any crane and lifting equipment will need to have sufficient loading capacity.

The foundation(s) and installation equipment will need to be transported to the site either on-board the installation vessel itself or on a separate transporter. The decision on which option to use will depend upon the distance to port, the size and type of the installation vessel, the number of installations and the sea conditions. For single devices and small array installations, it may be possible to carry all the necessary piles and equipment on the installation vessel in a single journey; this has the advantage of not requiring a second vessel and therefore may be a lower cost option which does not require extra time to transfer piles between transport and installation vessels. Larger installations will almost certainly require multiple trips to port or to a larger transportation vessel with accommodation facilities for the crew. Another possible option is for the installation vessel to tow a transportation barge which can then be moored close to the site in a sheltered location and used to re-supply the installation vessel without requiring repeated trips to port.

3.3.3 FOUNDATION POSITIONING AND SEAFLOOR PENETRATION

Driven pin pile

Once at the site the vessel will maneuver and hold station by use of a DP system, by mooring or by jacking up. If the vessel is large enough then the structure and drilling equipment may be transported together. Otherwise multiple vessels or journeys may be required.

Depending on the installation methodology, the foundation may either be positioned before the piles are drilled or after. If the foundation is positioned before the pin piles are installed then the drilling rig will be lowered above the tripod legs and the drill lowered through an aperture. In the other case a template is lowered to the seabed to allow the pin piles to be correctly positioned and the drill is passed through the template. The piles are installed first with the foundation lowered over the piles once they have been grouted into place.

Option 1: Foundation lowered first [108]

The foundation structure will be lowered from the vessel and moved into position as the first stage of the operation. Once on the seabed the drilling rig will be lowered into position over the aperture on one of the legs of the tripod. Modern offshore drilling companies [109], [110] provide rigs that will conduct all the necessary stages of the pin pile installation in one self-contained unit (e.g. Figure 3.3.3-1). The units are used to drill down through the seabed whilst the pile is simultaneously lowered as the assembly penetrates the rock. Once the required depth is met the annulus is flushed clean and the grout is pumped into it. Once the annulus is full of grout the drilling rig can be extracted leaving the pile securely fixed to the seabed. For multi-leg support structures this step is repeated for the remaining foundation points.

Figure 3.3.3-1: Bauer subsea drilling rigs [110]

Option 2: Piles installed first [110]

A template is constructed to ensure accurate positioning for the installation of the pin piles. Firstly this is lowered into position on the seabed. The drilling rig is then lowered from the vessel into the correct position above the template. The piles are then drilled and installed in the same way as in the previous option. Once all the piles have been installed the drilling equipment and template are recovered to the vessel. The tripod foundation is then lowered above the piles and slotted into position. A secondary grouting operation will then be necessary to secure the foundation.

The advantage of the first option is that the whole installation can be completed in one operation without the need for a separate drilling template, however it may not be suitable if the installation vessel is not large enough to transport all the necessary components in one trip or if the operating window is too short to enable the entire operation to be completed during one tide cycle. The second option allows for the operation to be interrupted between individual stages, for example if adverse weather occurs (i.e. a storm) the template can be left in position and the operation recommenced after conditions improve. The second option would also allow for the installation operation to commence without the need for the foundation structures to be present on site. As the operational windows can be small and infrequent in a tidal race it may be useful to commence drilling operations while foundation structures are being assembled elsewhere or transported to site.

There exist alternative penetration techniques to standard drilling that can be used for other designs of pile foundations. Particularly, at deeper sites, suction and torpedo piles may be favoured as the cost of pile driving increases rapidly with water depth and level of site exposure. Although these two alternative types of pile foundations are unlikely to be selected for the first pre-commercial array of wave and tidal devices, a brief technical description of their installation is presented below for comparative purposes.

Suction pile

Originally, suction piles have been introduced for projects where gravity loading is not sufficient for holding the foundation into the ground. Suction piles feature an upturned bucket (or caisson) at their bottom end (Figure 3.3.3-2). The embedment process is carried out by creating or pushing negative relative pressure inside the bucket with respect to the outskirt pressure which leads to the penetration of the pile in the seafloor. Such methods are only suitable on areas where the upper layers of the seafloor comprise marine sediments. Suction piles are most suited to seabed with soft clay and other low strength sediments [108].

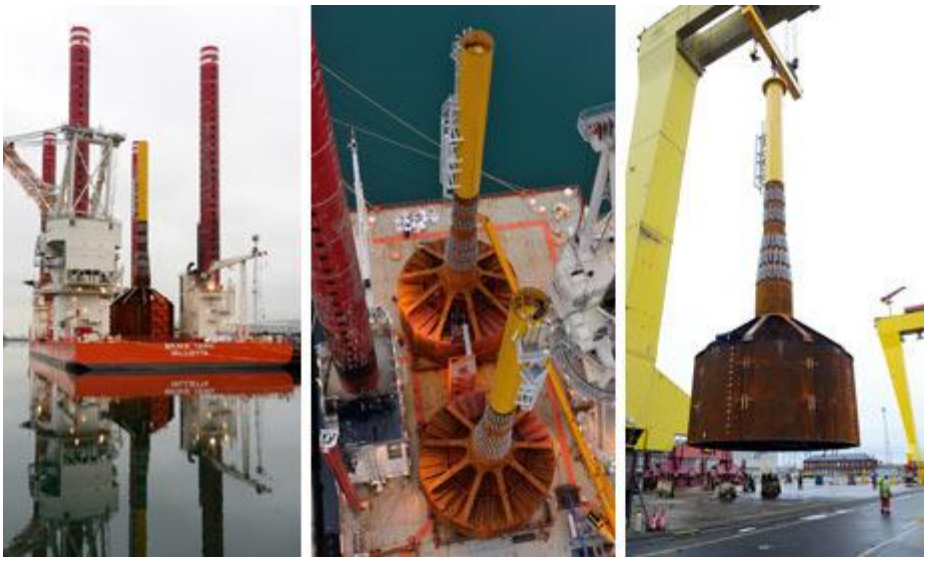


Figure 3.3.3-2: Suction bucket foundations being loaded onto a carried [111]

Installation vessels with DP capabilities can be used to install suction piles. The pile is lowered by means of cranes and/or winches while maintaining the position of the vessel or barge as accurately as possible. As the pile encounters and initially penetrates the seafloor through its own weight, water is pumped out of the caisson or bucket to reduce the pressure inside the caisson leading to the penetration of the caisson/bucket into the seafloor sediment. Divers may also be required to assist this operation. As the design penetration target is reached, the suction system is undocked from the pile and lifted up back to the installation vessel. When the installation is successfully completed, the suction pile acts as a rigid pile capable of resisting both lateral and axial loads [112]. An illustration of this process is given in *Figure 3.3.3-3*.

Lower caisson + suction pump

Caisson touchdown & penetrates initially by own weight

Pump water out from inside the caisson and develops lower inner pressure for installation

Design penetration depth reached

Undock suction pump

Figure 3.3.3-3: Procedure for the installation of a suction pile [113]

Suction piles offer advantages over conventional driven piles such as:

- Quicker to install (about one hour) and easier to decommission;
- No dragging and mitigation of the noise during the installation;

Despite these advantages, suction piles also have some drawbacks, for example:

- Relatively low technology and commercial readiness levels compared to conventional monopole system used extensively in the offshore wind sector;
- Risk of buckling failure [114];

Torpedo pile

In deep water sites, torpedo piles have become a competitive anchoring system option. A torpedo pile consists of a metallic pile with closed tip, filled with scrap chains and concrete. A single vessel, such as an anchor handling vessel, may be used to transport and install torpedo piles [113].

Once the targeted offshore location is reached, the pile is hung from the installation vessel at the specified drop height. Suitable DP capability is also a requirement in order to accurately position the pile above the targeted anchoring point. The pile is then released and, hence, free falls to the seafloor. The embedment of the pile is achieved by the impact of the pile with the seafloor. The penetration response of the torpedo pile varies depending on the seafloor soil conditions [94], [112].

Whilst the manufacture and installation process of torpedo piles are simpler than other foundation types, the installation method is only suitable at deep water sites (over 100 meters). Moreover, torpedo piles do not allow the same range of vertical and horizontal loadings as other technologies. Figure 3.3.3-4 shows a torpedo pile ready to be released from the installation vessel.

Figure 3.3.3-4: Torpedo pile being transported on deck before lowering, hanging and releasing operations into the water [87]

At the current level of maturity of the wave and tidal energy sector, the use of deep water anchoring systems such as suction and torpedo pile is not clearly envisaged. However if it is assumed that the industry will continue to grow commercially, along with the need for exploiting sites with increasing water depths, such alternatives may become technically and economically attractive for MRE systems (Figure 3.3.3-5).

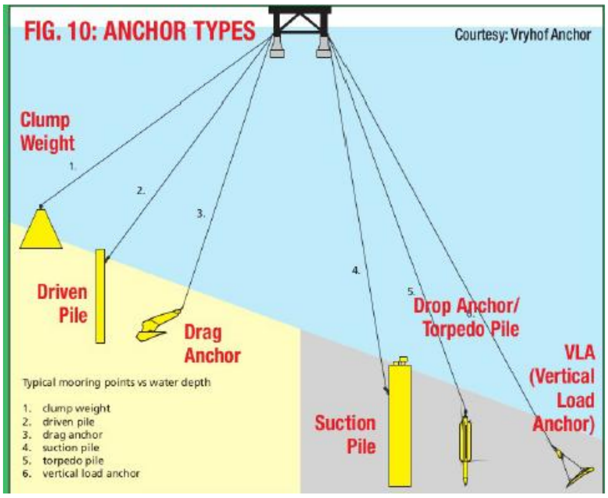


Figure 3.3.3-5: Example anchoring systems [115]

Figure 3.3.3-5 also implies that torpedo piles are used as anchoring system unlike pile and suction piles that can either be anchors or foundation depending on whether a rigid or a flexible mooring line is attached to them. In [116], an animation movie illustrating the installation of a torpedo pile can be visualised.

Gravity foundation

Gravity based foundations work on the very simple principle of adding a sufficient amount of mass to the base of a device to ensure that it remains securely in position when subjected to the environmental loads of the site. The foundation is essentially a large quantity of steel and/or concrete which is either part of the foundation sub-structure or separate weights that can be lowered over the legs of the tripod substructure to hold it in position.

Once the vessel is in position at the site the foundation can be lowered into position on the seafloor and then if separate weights are to be used they can be lowered into the correct place over the legs of the sub-structure. The installation vessel must be equipped with a crane or A-frame which is large and powerful enough to lift the foundation which may amount to a mass of thousands of tons.

If the foundation design is suitable another option is to attach ballast tanks to the foundation structure which can be filled with air and used to float the foundation to the site, once in the correct position the tanks can be flooded with water and the foundation can be sunk into position (e.g. *Figure 3.3.3-6*). An advantage of this method is that the structure can be recovered the same way by pumping air into the tanks and allowing the foundation to float back to the surface. This method only requires a vessel to tow the structure rather than lift it from the deck so a much smaller (and cheaper) vessel can be used.

Figure 3.3.3-6: The WaveRoller wave energy converter, attached to the foundation structure which is sunk by flooding a number of ballast tanks on the sub-structure [117]

3.3.4 POST INSTALLATION SURVEY

Following the installation, all components will need to be surveyed by a Remote Operated Vehicle (ROV) to make sure that the operation has been successful. Installation vessels should be equipped with ROV equipment so that they are able to check before, during or after the installation should any problems arise. ROVs range from small devices capable only of relaying a video image of the underwater structure (e.g. Figure 3.3.4-1) to large work-class submersibles with multiple tools and attachments for subsea operations. Further description of the use of ROVs within MRE arrays is presented in section 4.1.3.

Figure 3.3.4-1: A small VideoRay ROV [118]

3.3.5 SUMMARY OF LOGISTIC STEPS

The main logistic requirements influencing the choice of port, vessel and equipment are summarized in Figure 3.3.5-1.

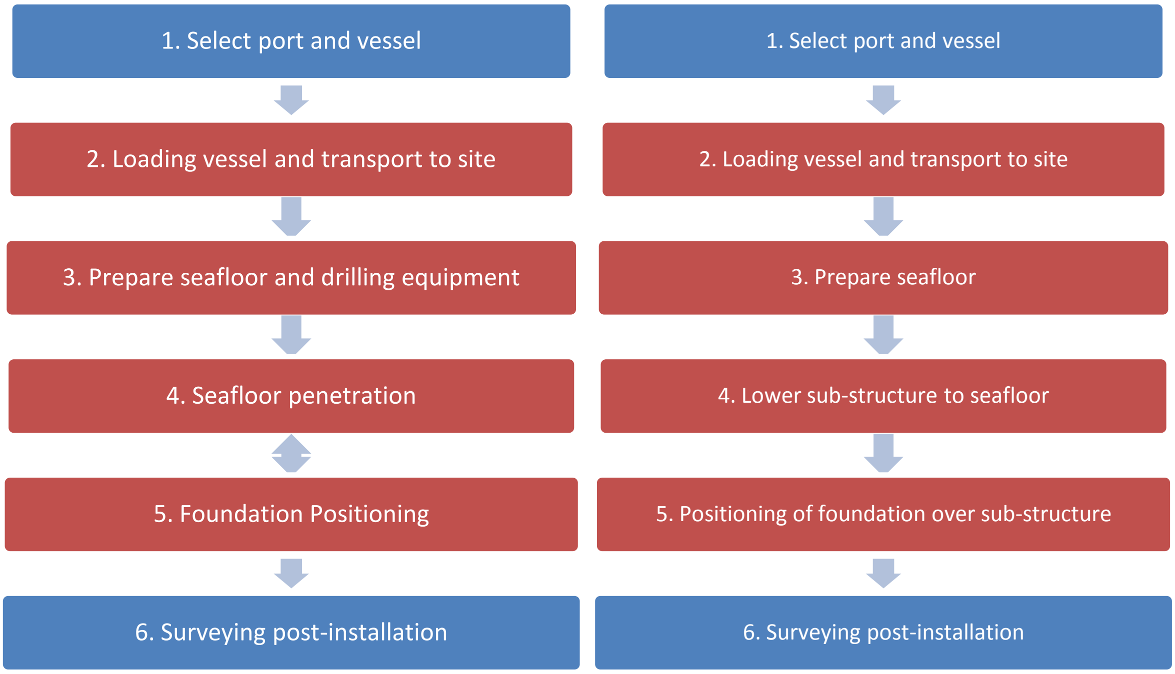


Figure 3.3.5-1: Flowchart summarizing the steps during installation of piles (left) and gravity base foundations (right). Note: the selection of the port and vessel are dependent on the operational and logistical requirements of Phases 2 to 6

As with mooring installations, a manual shall be issued covering all activities for each phase of the installation (Figure 3.3.5-1). The manual shall include all procedures and documentation required and shall clearly demonstrate that the foundation can be safety installed.

Table 3.3.5-1. As discussed in section 3.3.1 the choice of vessel is dependent on its capabilities, cost and availability. Vessel cost and availability are intrinsically linked to the availability of suitable weather windows which are subject to seasonal variations. This has motivated device developers such as OpenHydro to develop their own installation vessels (e.g. the OpenHydro Installer barge introduced in section 3.3.1). In addition the capabilities and location of the port must be considered e.g. smaller ports may not have the sufficient capacity to accommodate larger installation vessels. Lifting equipment at the port will also be a factor in deciding where the most suitable operational base will be. Therefore the time and cost required for transportation to site and device installation is dependent on a multitude of often competing factors [99], [105].

As with mooring installations, a manual shall be issued covering all activities for each phase of the installation (Figure 3.3.5-1). The manual shall include all procedures and documentation required and shall clearly demonstrate that the foundation can be safety installed.

Table 3.3.5-1: Key logistic requirements for foundation installations

Component / site data type	Parameter(s)	Unit / Format	Related infrastructure characteristics
Piles/foundations	Type	Monopile, Gravity based, etc.	Choice of vessel and port must be suitable for the system selected
	Number of components	Units	Sufficient deck space, large enough crane / lifting equipment at vessel and port
	Dimensions per component	Length x Width x Height (m)	
	Weight per component	Weight (kg)	
Transport & Installation strategy	Location and method	At site, at port, etc.	Type of crane / lifting equipment at vessel or port for load, deck area, seafastening, etc.
Seabed conditions	Type of soil	Rock/mud/sand... and thickness (m)	Type of vessel and equipment to be used for selected anchoring system may differ in different seafloors
	Bathymetry	Depth (m)	Type of subsea equipment/personnel
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 3.3.5-2: Typical planning of the installation of a tripod foundation with pin piles

Sequence of the logistic phase	Description of the interactions with other logistic activities
What usually comes right before?	Manufacture of piles and foundation superstructure; Transportation of equipment and piles to port.
What usually comes right after?	Structure will be ready for installation of the nacelle.
What can be done simultaneously?	Multiple installations can be completed simultaneously if vessels are available; Site can be prepared whilst foundations are being transported

A list of guidance documents produced by Det Norske Veritas which are relevant for MRE foundation installation is provided in *Table 3.3.5-3*.

Document number	Title	Publication year
DNV-OS-H101	Marine Operations, General	2011
DNV-OS-H102	Marine Operations, Design and Fabrication	2012
DNV-OS-H201	Load Transfer Operations	2012
DNV-OS-H203	Transit and Positioning of Offshore Units	2012
DNV-OS-H204	Offshore Installation Operations (VMO Standard Part 2-4)	2013
DNV-OS-H205	Lifting Operations (VMO Standard - Part 2-5)	2014
DNV-OS-H206	Loadout, transport and installation of subsea objects (VMO Standard - Part 2-6)	2014
DNV-RP-H101	Risk Management in Marine and Subsea Operations	2003
DNV-RP-H102	Marine Operations during Removal of Offshore Installations	2004
DNV-RP-H103	Modelling and Analysis of Marine Operations	2014
DNV-RP-H104	Ballast, Stability, and Watertight Integrity - Planning and Operating Guidance	2011

Table 3.3.5-3: Guidance documents produced by Det Norske Veritas covering various aspects of marine operations

3.4 WAVE AND TIDAL DEVICES

The assembly and installation of a wave or tidal device is driven by the strategy established by the marine contractor in cooperation with the client (site developer) and the MRE device developer. Recognizing the relatively low commercial readiness level of the tidal and wave industry, no convergence towards standard procedures for the assembly and installation of the different types of devices has been reached, yet. Hence, this section does not intend to comprehensively review the procedures for assembly and installation of all technologies but rather to describe the common logistic characteristics shared between the devices and to highlight some of the methods employed during the limited amount of operational experience gathered by the sector so far. In this respect, assembly and installation strategies for some of the scenarios introduced in Deliverable 1.1 [119] will also be shortly discussed as these will constitute some of the first MRE arrays.

The logistic phases considered common for all MRE devices and discussed in this document are:

- Assembly at port;
- Load out and transportation to site;
- Positioning and connection to moorings/foundations;
- Commissioning.

A detailed description of each of these phases is provided below.

3.4.1 ASSEMBLY AT PORT

When assembly of the MRE devices occurs at the load-out port a number of different activities with various levels of complexity have to be carried out. Consequently, specific port infrastructure and facilities are required. It is clear that availability and suitability of such infrastructure and facilities plays an important role in the marine energy development as a whole. Furthermore requirements will vary depending on device type and deployment strategy. At the current early stage of development the marine energy industry can benefit from the experience of ports in handling and deploying for the wind energy sector. However, particular challenges for the ports and harbour facilities in the implementation of marine energy developments are anticipated [120].

Specific requirements for port infrastructure and facilities have been discussed in section 3.3.1 when dealing with installation of moorings and foundations. It is clear that there is a lot of common ground between these requirements. Although the location of the development site will be an important factor in the choice of a port it is not the only consideration. The following criteria are discussed below in some more detail:

- Proximity of road/rail infrastructure;
- Assembly and marshalling areas facilities;
- Quay length and load capacity present;
- Water depth available.

3.4.1.1 PROXIMITY OF ROAD/RAIL INFRASTRUCTURE

MRE devices in general are of large size and significant weight. Correspondingly, the distance between manufacturing facilities and load out port is important. It would be most effective if manufacturing and assembly of devices occurs as close as possible to a suitable port. However, this is not possible for all projects.

Road/rail transport of assembled devices is likely to be problematic and expensive, so if this would be required potential upgrades to roads/railways need to occur. As an example, the Non-Technical Summary of the Environmental Statement for the West Lewis wave energy site mentions that part of the A857 would need to be upgraded and widened and a new access road would need to be built extending the existing track to the construction site [121].

3.4.1.2 ASSEMBLY AND MARSHALLING AREAS FACILITIES

Sufficient land should be available within very close proximity to quays for the final assembly and marshalling of devices.

Figure 3.4.1-1: Example of sufficient inland area required for offshore wind transition pieces at Westernmost Rough [20]

Requirements for marshalling areas will vary depending on the type of device and number of units to be deployed. It is estimated that for projects of about 10 devices a minimum requirement for land in the close vicinity of the quay will be in the order of 13ha [120]. As the size of the project increases, larger areas would be required in the future For example for a development comprising 50 units and assuming 50 % capacity for marshalling at any one time, land requirements could be in the order of 2.56ha- [120]. For the 40 to 50 Oyster devices at the West Lewis 40 MW wave farm project, it is even mentioned that approximatively 9 ha of total area of land will be used for storage [121].

It is clear that the deployment strategy also affects the fabrication and assembly operations. Some devices in fact, particularly those towed to the installation site, may be better suited to fabrication and assembly in a dry dock environment.

Assembly and marshalling facilities typically include construction halls of sufficient dimensions and cranes with sufficient lifting capacity to handle the different device components. **Error! Reference source not found.** shows some pictures of facilities used for installing the Marine Current Turbines (MCT) SeaGen S MkI tidal turbine and its foundations at Strangford Lough in Northern Ireland.

The turbine and foundation were supplied by MCT as a number of individual components (**Error! Reference source not found.**). The foundation consisted of a 3.5m diameter vertical column made of steel which is arranged on tubular structure with four piles at the corners.

All components were marshalled at the “Harland & Wolff” site in Belfast prior to being assembled at the quay side. A lay down assembly area of at least 15m x 50m was required for marshalling together with lifting capacities up to the full device weight [120]. Component weights during assembly have been estimated at up to 150 tons and up to 500 tons of concrete that are added to the lower column. The turbine and foundation together were then lifted by the heavy lift barge Rambiz and transported to the site for installation.

3.4.1.3 QUAY LENGTH AND LOAD CAPACITY PRESENT

For wave and tidal devices at the current stage of development it is expected that a quay length in the order of 100-200 m will be required e.g. for the assembly of the Pelamis wave energy converter it is estimated that a quayside length of at least 180m is necessary to moor the device prior to deployment [120]. The quay should have heavy load bearing capacity immediately behind the quay walls to accommodate heavy lift cranes. Lift operations in excess of 150t and more are expected, therefore if restrictions exist at certain facilities it may be possible to carry out such lifts using tandem cranes to minimise pad loading on the quay area.

The use of large installation vessels (crane barges, DP vessels and jack-up barges/vessels) for deployment may also provide the means to overcome any restrictions on crane loadings which can be imposed on quay working areas by making the final lift onto the barge using the barge mounted cranes [120].

3.4.1.4 WATER DEPTH AVAILABLE

The load-out port should have a sufficient water depth (without tidal restrictions) in order to accommodate the vessels used for installation of the wave and tidal devices. This is particularly valid for the larger installation vessels. It can be expected that a minimum water depth in order of 6m may be sufficient.

3.4.1.5 FURTHER THOUGHTS

It appears that mainly larger ports will have the necessary infrastructure to provide full support to the marine energy industry. Moreover, it is likely that (smaller) ports are not willing to invest in facilities specifically meant for MRE activities unless attractive revenue can be demonstrated. Nonetheless smaller ports, harbours and jetties may be able to support ancillary activities associated with MRE O&M phases, where proximity to development site may play a considerable role in bringing down operational expenditure (OPEX) of such activities [120].

3.4.2 LOAD OUT AND TRANSPORTATION TO SITE

3.4.2.1 LOAD OUT

MRE devices can be either loaded from the quay side onto vessels or put afloat via quays, dry docks or other launching facilities such a slipways or syncrolifts [123]. Either way a suitable water depth is required. All load-out operations shall be carried out during favourable environmental conditions. Although it is expected that most ports will provide adequate shelter from waves, some considerations have to be made with respect to the tidal range. In fact, tide variation is regarded as a critical parameter for load outs and should be carefully evaluated [124]. Also wind loads should be taken into account especially if crane employment is expected. As far as quay loading is concerned DNV [124] advises that "*Allowable horizontal and vertical load capacities of load out quays should be documented according to a recognized code or standard*" and again "*Calculations showing that the actual loads during load out are equal or less than the allowable loads should be presented*". The quay load capacity is strongly influenced by the bearing capacity of the soil whose strength and settlement should be assessed in the load out area.

In addition to the port facilities' characteristics the suitability of vessels has to be assessed. In particular structural strength should be checked for all possible ballast conditions. Sufficient stability afloat has to be guaranteed during load out operations as well as a minimum under-keel clearance considering the maximum draught, motions and applicable trim and heel [124]. The choice of a load out strategy depends on a multitude of factors such as the geometry and weight of the device, the capabilities of the port facilities and the vessel characteristics.

The four most common load out operations, largely used in Oil & Gas sector that may serve the marine energy industry are [108]:

- *Trailer load out*: multi-wheel hydraulic trailers are brought underneath the structure/device. The structure/device is then lifted onto the deck of the transportation vessel which is placed against the quay wall.
- *Skidded load out*: initially the structure is placed upon steel rails. It is then pushed or pulled by winches onto the deck of the transportation vessel which has to be equipped with skidded beams to take the structure to its final position.
- *Lifted load out*: this is perhaps the most common method employed for MRE devices. Devices are lifted onto the barge deck by means of shore-based cranes or cranes installed on the transportation vessel (e.g. *Figure 3.4.2-1*, two 500t cranes lifting in tandem).
- *Float-away load out*: the device is assembled in a dry dock facility. Once completed the dry dock is flooded or ballasted down in the case of floating dry docks. The structure that floats under its own buoyancy is then towed away by tugs.

Figure 3.4.2-1: Quay wall equipped with heavy-lift crane for Pelamis tube [10]

For the case of MRE devices to be towed to site, the machines need to be ballasted to the desired level of submergence once in the water. For example, for the Pelamis machine over half of the machine's final weight is ballast [10].

3.4.2.2 TRANSPORTATION TO SITE

The process of moving a structure from the load out port to the installation site generally involves loads that are different in magnitude and direction from the in-place loads. The shape, the weight and the cost of offshore structures are, therefore, influenced by these temporary phases.

Generally speaking, MRE devices can be transported either wet or dry. In a wet transport the structure floats on its own hull and is towed by one or more tugs to the offshore site (e.g. Pelamis P2, Oyster, Figure 3.4.2-2 and Alstom/TGL turbine, Figure 3.4.2-3).

Figure 3.4.2-2: The Pelamis towed to site [10]

Figure 3.4.2-3: Alstom/TGL turbine towed to site [9]

In the case of dry transport, the device is loaded onto a vessel and transported to the site. This vessel can be either a flat top barge (self-propelled or unpowered) which then brings the devices to the installation vessel, or the installation vessel itself, e.g. the heavy lifting vessel (HLV) Rambiz in the case of the MCT SeaGen S MkI installed at Strangford Lough, Northern Ireland (see Figure 3.4.2-4). The installation vessel hence constitutes in many cases the transportation vessel as well, in particular for one-off installations.

Figure 3.4.2-4: Transportation of MCT SeaGen S MkI and foundations to Strangford Lough, Northern Ireland [122]

The decision to transport the MRE structures dry or wet depends on different factors. The size, weight and height of the centre of gravity play an important role in this decision. In the offshore wind sector, most transportation is dry. Figure 3.4.2-5 presents an example in which the nacelle and blades were assembled onshore and then transported as a whole to the site. It is expected that for wave and tidal energy devices both wet and dry transportation will be applied based on various technical motivations (e.g. technology type, foundation, etc.). The blades and nacelle can be transported separately or as a together depending on the vessel.

Figure 3.4.2-5: Transportation of Offshore Wind Turbine using jack-up barge Goliath [20]

Cargo barges are towed or pushed by tug boats from one location to another. These barges generally feature a flat top and bottom, and are simply equipped with navigational lights, fairleads and towing points. The tug boat is generally linked to the barge by means of a tow arrangement with two lines of towing bridles. A third line connects the triplate to the winch of the towing tug [108].

Figure 3.4.2-6: Transportation of Offshore Wind foundation jackets using barge [20]

The stability and strength calculation for on-deck transportation for marine energy share similarities with the offshore Oil & Gas sector, however there are some differences. The following engineering studies should therefore be undertaken [108]:

- A route study to evaluate the design environmental criteria;
- A stability study to prove that the carrier vessel meets the requirements of the relevant classification society;
- A structural assessment taking into account the loads associated with the motions and accelerations;
- Seafastening design;
- A local and global strength assessment of the carrier vessel.

Another important factor is the transport route and the distance to the deployment site. If the environmental loads or motions associated with a wet tow are too onerous on the structure, it should be transported dry. Moreover wet tow turns out to be more suitable for slower speed hence shorter distance (speed range of 4-8 knots), whereas dry transportation is the fastest mode of transportation for medium-long distance due to their higher speed (speed range of 12-18 knots). It may also require a re-consideration of the appropriate level of vessel propulsion to ensure an acceptable transit speed [45]. Because of the relative slower speed, tows can only be undertaken at certain times of the year in order to avoid changing of route to seek shelter during storms or harsh environments. All these considerations will, of course ultimately result in a cost factor. Apart from that, there are also environmental aspects. Where the installation may impact natural heritage features through disturbance, such impacts will be mitigated through careful timing of transportation and installation works [125].

3.4.3 ASSEMBLY AT SITE

The assembly at site describes all the logistic operations used to finalise the assembly of the device prior to the connection to the grid and the commissioning phases.

It is important to stress that due to the large influence of weather conditions on the deployment of a MRE device, it is a widely accepted strategy to avoid any type of installation at site if possible. This will result in an increase of available time windows for the overall installation procedure, resulting in a simpler phase management and lower cost.

Due to the lack of general information on the specific logistic phase only two examples are reported hereafter: one regarding the MCT Seaflow and the other regarding the WaveDragon WEC. It is important to highlight that both cases refer to prototype machines, and therefore they cannot be considered significant for the definition of a generic logistic phase.

The Seaflow machine was the first generation of MCT's tidal turbine; the experience gathered from this world's first tidal turbine has been brought into the SeaGen machine. The Seaflow machine was preassembled onshore; then the different components were connected at the site. In order to carry out the assembly at the site a jack-up barge was used (Deep Diver Seacore Figure 3.4.3-1). The barge can work in water depths up to 25 m and with current flow velocities up to 5 knots. The main components were transported on-deck of the jack-up barge and connected to the vertical pile using the crane onboard [126]. The assembly is divided in two phases: assembly of the turbine's support structure on the vertical pile (Figure 3.4.3-2) and assembly of the turbine on the support structure (Figure 3.4.3-3.)

Figure 3.4.3-1- Deep Diver Seacore jack-up barge [127]

Figure 3.4.3-2 - Assembly of the turbine supporting structure on the vertical pile [122]

It is important to highlight that for installing the MCT SeaGen machine, a different installation strategy was adopted, where all of the assembly operations at site were merged with the assembly operations at port.

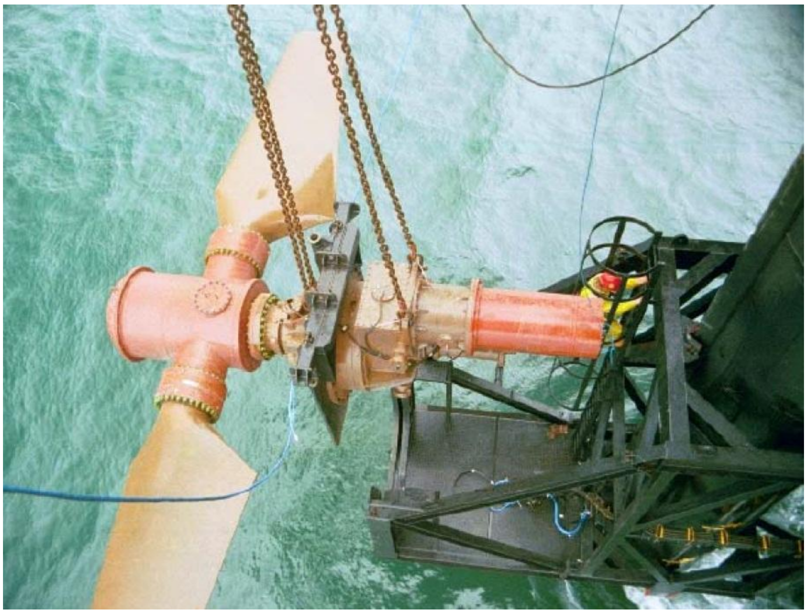


Figure 3.4.3-3 - *Assembly of the turbine on the supporting structure* [122]

The WaveDragon [128] is the second example of MRE machine with assembly at the site operations. There were two main operations at the site: installation of the reflector and installation of the PTO system. The two reflectors have been installed after the installation and commissioning of the WEC, since they are not vital for the system to work. The two reflectors were towed to the site and connected to the main device unit.

Figure 3.4.3-4: The two reflectors during the transportation phase [129].

During the installation a rubber bearing was interposed between the two metal parts in order to reduce the material’s friction and wear (Figure 3.4.3-5)

Figure 3.4.3-5: Rubber bearing lifted (left) and installed on the joint (right) [129]

The second operation at the site was the installation of the PTO system. As for the previous example, this phase was also carried out after the installation and commissioning of the device, since a single water turbine was already mounted on the device prior to the transportation to site.

The turbines were loaded into a small barge and installed in place, right after the installation of the support structure. The operation was carried out with a small crane installed on the barge.

Figure 3.4.3-6: Installation of the turbine support structure (plate) [129]

Figure 3.4.3-7:Turbine installation [129]

For this device the assembly at site was carried out for two reasons:

- First, the device is large enough to have a small displacement response to waves, therefore the operations are less sensitive to the met-ocean conditions.
- Second, the size and arrangement of the reflector did not allow for the assembly at port. The assembly at the site reduced the risk of high loads on the structure, which can have a major impact on the costs of the project.

3.4.4 POSITIONING AND CONNECTION TO MOORING/FOUNDATIONS

3.4.4.1 POSITIONING

Once the MRE device is transported to the site, the transportation vessel needs to be maneuvered to the target location (in case the transportation vessel is the installation vessel) or alongside the installation vessel (e.g. Figure 3.4.4-1). The device needs to be prepared before its installation can start. This includes release of seafastening structures (for dry transportation), starting up cranes and winches and deployment of temporary works.

The overall maneuverability of a vessel will vary depending on: type of vessel; physical size; position, number and power of thrusters; and station-keeping ability in wave and tidal climates. Any increase in the overall size of the transport unit, whether this is due to larger vessels or larger devices in tow, will increase the difficulty of navigation in restricted waterways, such as between devices in an array. Although hydrodynamic efficiency would seem to be the prime concern in setting device spacing, it may be necessary to relax spacing further to allow sufficient access for installation and maintenance activities [45].

By essence, wave and tidal devices are located in energetic sites where the environmental loads experienced by the offshore structures are relatively high (mainly due to wind, wave and current). Therefore, one challenging task is to maintain the position of the installation vessel while approaching the target location.

Figure 3.4.4-1: Barge with jacket foundation positioned alongside the Rambiz HLV [20]

To keep the vessel in the desired position and heading limits, DP systems have been developed and designed for the offshore sector over the past four decades. DP systems consist of a computer control system automatically maintaining a vessel's position and heading by using its own propellers and thrusters. Position reference sensors, combined with wind sensors, motion sensors and gyro compasses, provide information to the computer pertaining to the vessel's position and the magnitude and direction of environmental forces affecting its position [130]**.** The working principle of a DP system is illustrated in *Figure 3.4.4-2*. Based on International Maritime Organization (IMO) publications, classification entities have issued regulations for DP systems in the offshore environment described in classes ranging from 1 to 3. The attribution of the class label number is primarily determined by the redundancy and the reliability of the DP system [131]**.** In short, the DP system’s capability is a fundamental requirement to be verified when selecting the set of vessels and equipment that will serve the wave or tidal device installation. The power system, thruster system, control system and auxiliary system interacting with the global DP system design must all satisfy the expected technical requirements of station keeping performance. A DP feasibility study will be carried out before positioning/installation works take place. *Figure 3.4.4-2* also shows the control command desktop of a DP system fitted in a vessel.

Figure 3.4.4-2: Working principle of a DP system and photo of the Praxis’ DP system [132]

Target location can be held based on only the DP system (e.g. for DP vessels such as North Sea Giant) or by using other techniques:

- a combination of anchors and thrusters may be controlled to hold the position of the vessel;
- Jacking-up at target location for jack-up barges/vessels (Figure 3.4.4-3).

Figure 3.4.4-3: Jack-Up barge in jacked-up position [20]

3.4.4.2 CONNECTION TO MOORINGS/FOUNDATIONS

As the installation vessel is positioned at the target location, the next step is to connect the device to the pre-installed mooring lines or foundation structure. Such an operation is also commonly referred to as “device hook up to the mooring/foundation system”. In this section the cases of a floating wave/tidal energy device and a fixed tidal energy device are considered.

Current practice in the Oil & Gas sector for designing and installing mooring connectors is driven on the one hand by experience and on the other hand by the needs of what is still a developing industry in spite of its relative maturity. Figure 3.4.4-4 displays four different types of connectors for mooring systems used in the Oil & Gas sector.

Figure 3.4.4-4: Example of connectors for mooring systems used in the Oil&Gas sector: rope to chain connector LankoFirst (top right), Bridle plate connection system

The needs of the MRE connectors may differ from those found in the Oil & Gas industry [108]:

- Smaller static loads to carry (in general);
- Operating may occur in a fatigue-rich environment, where the load on a connector will experience large and frequent variations.

Connectors for the renewable sector should hence ideally possess the following qualities [108]:

- MRE devices light weight;
- Good fatigue resistance to complement appropriate static strength;
- Ease of installation;
- Low or zero connector maintenance;
- Low or zero susceptibility to corrosion;
- Ease of disconnection for maintenance of the wave/wind energy device and for its eventual decommissioning

The above list of expected features stimulates the research and development (R&D) towards the design of innovative connector solutions to meet the unique requirements of wave and tidal devices. Consequently, there is no convergence towards standardised connectors and, hence, no well-defined procedures for hook-up operations that can apply to several wave and tidal devices, yet. On the contrary, most device developers have customized specific arrangements for the connection of their devices to the mooring system. Such arrangements can significantly differ from one device to another. Figure 3.4.4-5 shows the example of the Pelamis P2 prototype.

Figure 3.4.4-5:: Photo of the nose of the Pelamis P2 device and the yoke system used for towing and connecting to the mooring system [10]

The detailed analysis of the hook-up operation for this device was reported in Bould's MSc thesis [45]. Whilst onshore, a winch unit was connected near the nose of the P2 and a winch line fed through the tip of the yoke. To facilitate quick connection and disconnection of devices, all mooring and interconnection lines of a device terminate in a single unit known as a tether latch assembly

(TLA). The TLA offers a single "plug and play" point of connection for the yoke section of a Pelamis P2, providing all required mooring, electrical and communication lines.

Once onsite, the connection procedure can be approximated by three main stages, illustrated in *Figure 3.4.4-*.

- Stage 1: the buoy holding the TLA in place is recovered to deck and removed. The line connecting the buoy to the TLA was attached to the winch line and thrown overboard.
- Stage 2: The winch unit connected near the nose of the P2 is remotely started to remove the slack in the line, raising the TLA and straighten yoke of the P2 from a horizontal to a vertical position.
- Stage 3: as the TLA approaches the winch it self-aligns and connects (electrical wet-mate connection) to the yoke, completing the connection process.

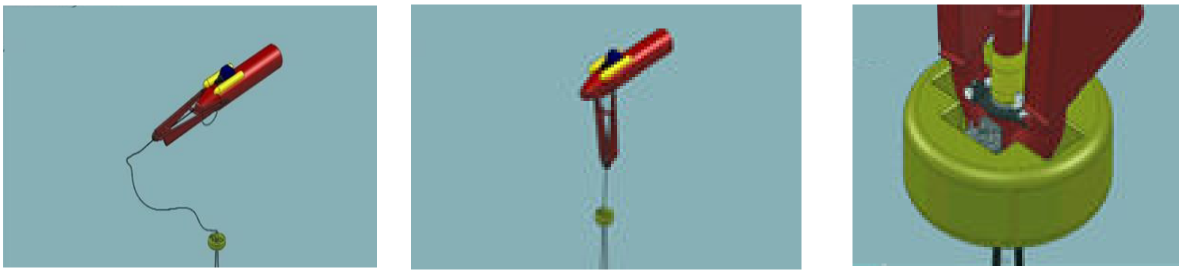

(a) Stage 1 (b) Stage 2 (c) Stage 3

Figure 3.4.4-6: Pelamis Connection Procedure

Power and communication links were confirmed before latch arms and locking pins finalized the link between the yoke and the TLA. During this process, the winch on the P2 remained connected to the installation vessel by the tow line and was dragged from the P2 and back to deck. Thus, the connection of the P2 to mooring, electrical and communication lines can be completed without the need for personnel to land on the device or dive and withalso out heavy offshore lifting operations. Pelamis claim an installation time of 90 minutes from arrival onsite and a disconnection time of 15 minutes [45].

Another example is the OPT power buoy PB PB150, a point absorber type of WEC (Figure 3.4.3-7). A detailedd connection procedure to mooring was also reported in [45]. Once on site, the OPT PB150 was attached to the mooring spread with each bridle connected to a different pre-placed mooring line. The exact procedure for making this connection was not defined, but each mooring line was recovered using the surface float attached during mooring installation, using a boat hook from the tugboat. Presumably bridle connections were recovered and the connections made on the deck of the tugboat. The PB150 was then flipped into its vertical operational position. This was achieved by flooding the ballast tanks in the heave plate with seawater. An additional "trim tank" located in the spar module was partially flooded to make minor corrections to the alignment. The device was then placed in its final position with the float module directly above the spar and the heave plate modules and the whole device being held on station by the mooring spread.

Figure 3.4.4-7: The OPT power buoy being flipped in its vertical position off the North coast of Spain through ballasting [133]

PB PB150To facilitate the modeling of the hook-up operation to a mooring system in the DTOcean lifecycle logistic module of WP5 [1], one may consider the following approach:

- Input to the module: a duration which represents the time to attach the device to the mooring system once onsite. A different value for the disconnection time should be made accessible to the end-user to better reflect the retrieval of the device.
- Logistic requirements for the hook-up operation: Use of a tugboat or anchor handling tug fitted with a winch (potentially also used for transporting the device to the site), e.g. shown in Figure 3.2.1-1, is expected to be suitable. A DP system preferably with strong capabilities is useful when connecting the device to the mooring lines. On the other hand, if installation of moorings, anchors and device is done in one operation, it is possible that different types of vessels are suitable for the whole operation, e.g. jack-up barges/vessels.

Figure 3.4.4-8: The Aramis multi-cat vessel [20]

If the number of devices to be installed rises it could be cost-effective to carry out installation tasks at the same time in a number of locations, therefore employing more vessels. That should be integrated with a vessel coordination system that would ideally take into account also the transit time for the “feeder” vessel from port to site. This would allow for installation activities to continue uninterrupted by transport operations, but comes at the cost of hiring additional vessels [45]. Therefore an optimal combination of installation and transport vessels should be sought by comparing costs of installation and downtime due to transit and the cost of extra vessel charter.

Connection to foundations

This section considers the connection of tidal turbines to their foundations in the case of fixed turbines. It is assumed that this connection did not happen at the quay and the device and foundation are installed separately. This was not the case i.e. for the MCT SeaGen S MkI prototype installed at Strangford Loughwhere foundations and device were installed as a whole.

The top of the foundation will typically consist of a vertical shaft (surface piercing or below sea-level) with some sort of mechanism to connect the turbine(s) to it. Several mechanisms were used when installing the first tidal turbine prototypes. E.g. for the 1 MW Alstom/TGL turbine installed at EMEC, the nacelle, blades and drivetrain are buoyant. A lead wire is brought by an ROV from the buoyant turbine to the vertical foundation shaft and connected to it. This wire is then pulled from the shaft and correspondingly the turbine is lowered on top of the shaft (Figure 3.4.4-9). Once in place, the lead wire is removed.

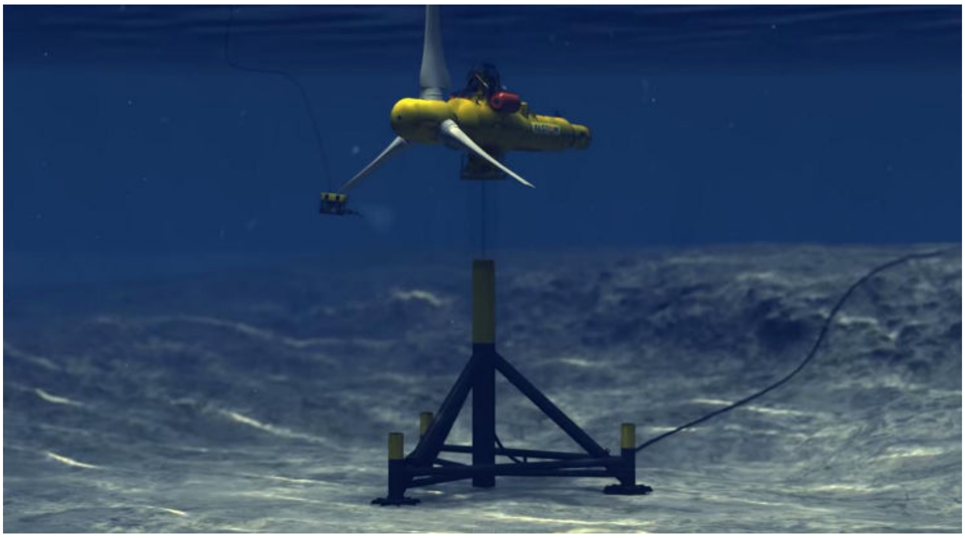


Figure 3.4.4-9: The Alstom/TGL 1 MW turbine installation procedure [9]

The installation of the Voith prototype tidal turbine at the EMEC site was different as the turbine was not buoyant. It was lowered using its own weight on top of the vertical shaft (Figure 3.4.4-).

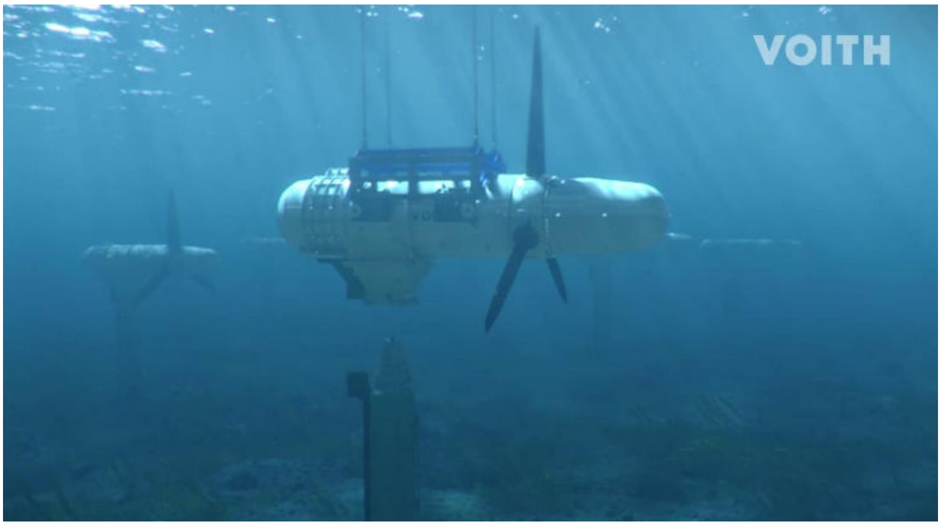


Figure 3.4.4-10: The Voith turbine installation procedure [134]

The lowering procedure in both cases requires adequate guiding techniques, in particular as the device will be subject to at least some tidal currents. The applicability of ROVs in this respect is rather restricted and might cause delays in the overall installation schedule. Alternative techniques exist to keep control of the position of and interaction between the different foundation components, e.g. specially developed frames, strategically deployed cameras, etc.

The number of tidal turbine prototypes installed so far is very limited and there is neither a final design nor convergence on the installation procedure to be followed, yet. It is clear that the two installation processes shown above can be carried out by using smaller vessels with sufficient DP systems to be able to deal with the high currents at site. However, this is only valid for one-off installations for which the foundation has been installed previously. When foundation and device are installed in one go, other vessels, such as jack-up barges/vessels and larger DP vessels could be used for installing both the piled foundations and device in one go. When moving on from one-off devices to large arrays, it is likely that foundations and devices will be installed at different times. Hence, when applying the device installation methodology described above for Alstom/TGL and Voith, vessels with sufficient deck space need to be used so that several devices can be taken on deck for each transport between load out port and site. An alternative is to use barges, which then are towed to the site using tugs that are capable of dealing with the strong tidal currents.

Further thoughts

With regard to the vessels used for installation operations (i.e. connection to moorings/foundations in this section) it is understood from the Oil & Gas/Offshore Wind experience that the type of vessel mobilized for a certain marine job not only depends on the vessel suitability and availability but also on the project scale. For smaller projects, vessel mobilization costs tend to dominate, while for larger projects, the mobilization costs play a less important role and operational efficiencies become more important considerations when deciding what type of equipment should be used [135]. In order to achieve an economically viable solution for the first MRE arrays, installation methodology and design of the MRE device and its foundations need to be properly aligned. This is possible through an early contractor involvement, i.e. a so-called Engineering, Procurement, Construction and Installation (EPCI) contract, which was also discussed in section 3.3.

3.4.5 COMMISIONING

The last stage of an MRE device installation is the official commissioning. In short, commissioning means connecting the device to the electrical network. However, commissioning is often seen as the conjunction of the full procedure for the installation of the MRE machine and hence encompasses the previous four stages aforementioned in section 0.

Technically speaking, the electrical connection of an MRE device corresponds to the logistic phase detailed in section 0. Consequently, the reader is invited to refer to the two applicable cases of wet-mate and dry-mate connection available in section **Error! Reference source not found.** for a full explanation of the process.

At the end of the commissioning stage, the MRE device is officially operational and can feed the onshore electrical network.

3.4.6 SUMMARY OF LOGISTIC STEPS

Three main steps can be identified within Chapter 3.4 of this document operation as shown in Figure 3.4.6-1. Note that the operation “Assembly at site” has not been included in the flow chart since it is regarded as a very specific operation suitable only for a limited number of device and therefore out of scope for a generic description of the overall process.

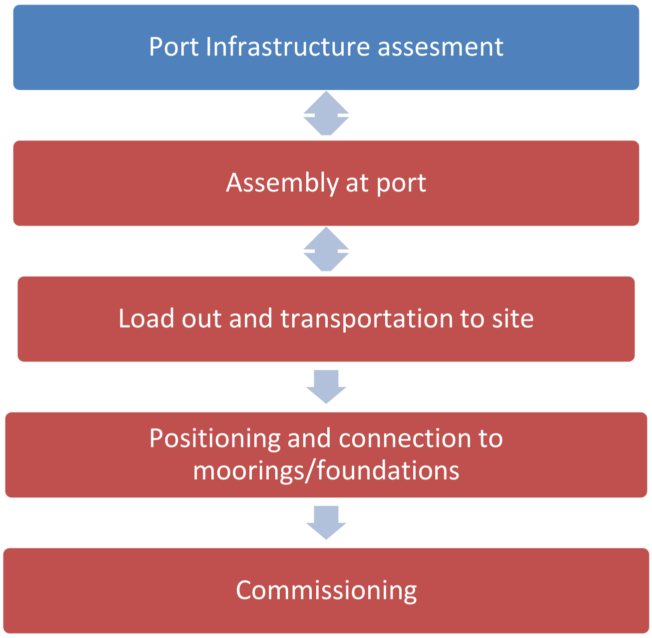


Figure 3.4.6-1: Breakdown flow chart of installation operations of MRE devices

As for the previous sections of Section 3, the following tables compile the key logistic requirements evaluated evaluated throughout the above description of section 0 (Table 3.4.6-1) and discuss the interactions of the assembly and installation of devices with other major phases of the development of a MRE project (~

Table 3.4.6-2).

Table 3.4.6-1: Key logistic requirements influencing the selection of port, vessels and equipment for installation of MRE devices

Component / site data type	**Parameter(s)**	**Unit of measurement/ Format**	**Related infrastructure characteristics**
Device	Number of units	Units	Deck area (if transported on deck), storage at port, berths, etc., number of vessels
	Dimensions	Length x Width x Height (m x m x m)	
	Mass of the device	Weight tn()	Lifting capacity at port and/or vessel, vessel propulsion
	Array spacing	Length in meter (calculated from coordinates)	Vessel type and size
Umbilical	see umbilical section	see umbilical section	Equipment / personnel to connect device and umbilical
Mooring system	see mooring section	see mooring section	Equipment / personnel to connect device and mooring system
Transport & installation strategy	Location and method	Towing, on deck	Deck area and lifting capacity, bollard pull, etc.
Seabed conditions	Bathymetryy	Depth (m)	Type of subsea equipment/personnel
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

~

Table 3.4.6-2: Interactions of the overall operation

Sequence of the logistic phase	**Description of the interactions with other logistic activities**
What usually comes before?	Manufacturing of the device subassemblies; Commissioningc of moorings/foundations (and electrical connections)
What usually comes after?	Plant operation
What can be done simultaneously?	Installation of other devices (with multiple vessels); Installationi of umbilical cable (if not pre-commissioned before)

4 OPERATION AND MAINTENANCE REQUIREMENTS

The following section describes the logistic requirements for the performance of O&M related activities in wave and tidal MRE arrays:

- In the first section, the monitoring of MRE devices and their components is described.
- Section 4.2 describes the relevant interventions at site to access / inspect, maintain or replace MRE array units or some of their components.
- The last section of Section 4.3 highlights onshore interventions, meaning the interventions that need to be carried out at the service port.

To allow for a common understanding of the different O&M intervention types, the following paragraphs give a definition of the different maintenance strategies. Maintenance is defined as the combination of all technical and administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function [136]. Figure 4.1 shows a common classification of maintenance strategies which is based on the standard SS-EN 13306 [137].

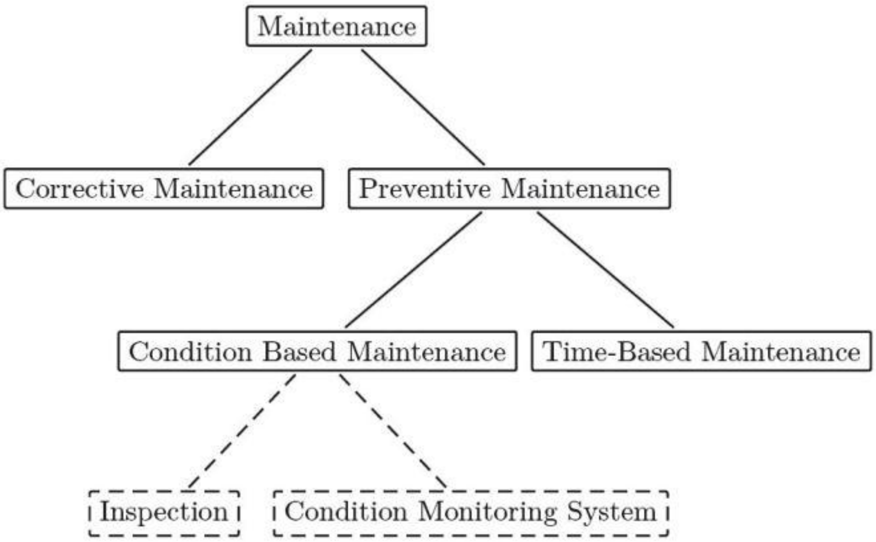


Figure 4.1: Types of maintenance strategies, partly adapted from [137]

The following three types of maintenance will be considered in the DTOcean project [138]:

- **Corrective maintenance** is due to an unexpected failure and is intended to restore an item/component to a state in which it can perform its required function [136].
- **Condition based maintenance** is a type of preventive maintenance based on a response to the monitoring information available [137]. It consists of all maintenance strategies involving inspections (noise, visual, etc.) or permanently installed Condition Monitoring Systems (CMS) to decide on the maintenance actions.

- **Time-based maintenance** is a type of preventive maintenance carried out in accordance with established intervals of time or number of units independent of any conditioning investigation [137]. It is suitable for failures that are age-related and for which the probability distribution of failure can be established based on fixed time intervals.

The maintenance costs are known to be an important part of the life cycle OPEX cost of MRE projects. In offshore wind farms, O&M contributes 15-30 % of the total LCOE [139]. Therefore it is important to develop cost-effective O&M concepts to help MRE projects to be competitive with offshore wind. The optimization of these concepts should address the overall resources (personnel and equipment) required to execute the maintenance activities, which necessarily have to include the logistical support.

One can identify and outline the following considerations when dealing with the logistic infrastructure necessary to carry out O&M of MRE arrays:

- Crew size and their location of accommodation;
- Assignment of special crew, e.g. divers;
- Types of vessels for the transportation of crew and equipment;
- Special needs, e.g. helicopters;
- Types of hoisting equipment, e.g. internal or external cranes;
- Work organization (shift operation, daylight requirements, maximum working duration regulations constraints, crew size per shift, etc.);
- Spare part management, e.g. delivery time, number of spare parts in stock, etc.;
- Maintenance activity duration based on the type (or “class”) of the occurred failure, e.g. inspection/repair/replacement;
- Operational working conditions as a function of the type of vessels and equipment and the type of maintenance action taking into account the working regulation;
- Weight and dimensions of the parts/components which have to be transferred, hoisted and installed;
- Water depth and distance from shore;
- Accessibility of the MRE device for maintenance.

In the course of the work within WP6, a specific set of possible faults and the related maintenance operations, resulting in respective logistic activities, will be defined for each of the components. To restrict the degrees of freedom for these definitions, the number of possible logistic activities will be limited to three main types of O&M interventions:

- “Inspection”: A crew of only a few general purpose technicians (e.g. with mechatronic skills) travels to an MRE device. The technicians perform inspections at the device (maybe with diving or ROV activities) to determine the actual damage or the state of health. Minor repair actions can be done at the site directly. The need for larger maintenance actions will be investigated; the required spare part and equipment will be identified.
- “Small repair”: This O&M intervention methodology will be used for the replacement of light components. This can be done with on-board cranes. Some MRE devices allow replacement of medium weight components, e.g. hydraulic pistons or oil motors with no external crane

equipment required. Therefore, the “repair” requires a larger vessel to transport spare parts and a larger crew with specialized technicians;
- “Major repair”: This intervention type will be used when the replacement of the heavy components is required or if the entire MRE device needs to be lifted out of the water and is placed on board of a large vessel for maintenance actions. Towing back of the entire device is also covered by the large intervention.

4.1 MONITORING

4.1.1 INSTALLATION OF CONTINUOUS MONITORING EQUIPMENT

In terms of logistic requirements associated with monitoring, one can distinguish between offshore equipment continuously measuring and processing data and tools/instruments that are utilized temporarily. Firstly, this report considers the installation of fixed, semi fixed and floating monitoring equipment. For continuous monitoring of MRE arrays, one can list the following relevant types of systems:

- Floating systems: met-ocean buoys, Light Detection And Ranging (LiDAR) buoys, floating offshore masts, etc.;
- Bottom-fixed systems: Acoustic Doppler Current Profilers (ADCP), fixed offshore masts, etc.;
- Device attached systems: condition monitoring units, fault detection units, etc.;
- Satellites.

The installation procedure associated with the latest category (satellites equipment) is not going to be addressed in this report since such instruments are not purposely positioned for MRE projects but for a vast range of applications. However, one can mention that information such as marine trafficking and inputs to hindcast climate modelling can assist the O&M management of MRE arrays. In particular, satellite observations can help ensure that the desired level of safety factor is persevered over the course of a marine operation. While in-situ observations generally offer more accurate data, satellite observations can spatially cover a wider range.

Floating buoys fitted with the chosen set of sensors and instruments are increasingly being deployed and maintained over the surface of the oceans and seas. Mostly, met-ocean buoys measure the environmental conditions around their position. Compared to satellite observations, met-ocean buoys rely on relatively large records of local regular measurements in time and space. The installation of met-ocean buoys generally does not involve a considerable logistic effort due to the inherent small dimensions and overall weight of the equipment. In most cases, tugboats and small workboats can transport or tow the buoy to the deployment site and install it with the support of simple winches and handling equipment. An example of the deployment of the KIC-Offshore test station [140] is illustrated in Figure 4.1.1-1. Met-ocean buoys are useful to provide real-time environmental conditions to the farm operator, notably for safety reasons of a planned marine intervention.

Figure 4.1.1-1: Deployment (left) and retrieval (right) of the KIC-Offshore test station at the Tagus river [132]

Another structure widely used in the wind energy industry is the met-mast. Figure 4.1.1-2 provides photos of a fixed met-mast and a floating spar buoy met-mast. Although such installations may not be as relevant for MRE arrays as it is for offshore wind farms, a customized met-mast could be a useful monitoring instrument for MRE projects.

Figure 4.1.1-2: Installation of a fixed met-mast at the Rampion offshore wind farm, UK (left), towing and positioning of the IDERMAR [133] spar-buoy met mast off the coast of Santander, Spain (right)

In MRE projects it is almost indispensable to install one or several ADCP units at the targeted site location. ADCPs measure real-time tidal flow, wave height, wave direction and wave period data. For tidal resource assessments, ACDPs are the reference instrumentation. One can differentiate between vertical stationary ADCPs (shown on the left side of Figure 4.1.1-3) and horizontal ADCPs that may be directly attached to a tidal turbine (shown on the right side of figure 4.1.1-3). The next generation of seabed mounted acoustic systems is currently undergoing active R&D effortsefforts. For instance, EMEC is reaching the final stage towards the deployment of an advanced acoustic pod [141].

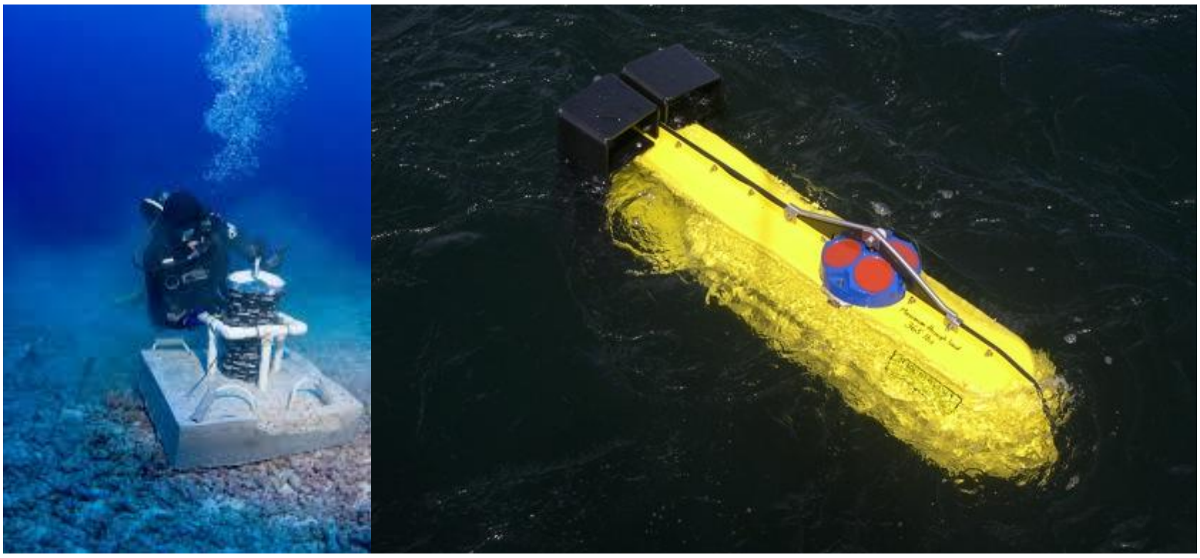


Figure 4.1.1-3: A diver assisting the installation of a gravity based vertical ADCP unit on the sea bottom (left); typical horizontal ADCP unit that can be attached to a tidal turbine (right)

The practice of installing CMS to allow for real time monitoring of assets is becoming more wide-spread [142]. CMS consist of a series of sensors collecting physical data from the functional subsystems of the MRE device and transfers them to a centralised node for processing. The purpose of the entire system is to predict when critical equipment will fail and manage the required workflow to continuously improve reliability and availability of the device. In turn, this allows operators to adopt a condition based maintenance approach that theoretically allows reduced costs compared to both preventive and corrective maintenance strategies.

To date, the majority of CMS utilized in the offshore wind industry have been vibration systems based around the drive train. Vibration based CMS tend to use accelerometers to measure vibrations. Such CMS have proven their invaluable usefulness in offshore wind [143], and hence, one can expect they are also being implemented for the key components on MRE devices. CMS are most commonly directly embedded to the components/structure of interest. The Kastrion CMS shown in figure 4.1.1-4 is an example of CMS embedded in a wind turbine. Innovative solutions for CMS for wave and tidal devices, as developed by the TidalSense project [144], are expected to be increasingly developed as the industry matures.

Figure 4.1.1-4: The Kastrion CMS being tested as part of its development through the KIC-InnoEnergy funding programme [138]

4.1.2 USE OF TEMPORARY MONITORING EQUIPMENT

In addition to monitoring an area continuously from a stationary location (only interrupted for maintenance), monitoring can also be performed dynamically on a temporary basis. Punctual monitoring programmes are often scheduled to assess a specific area/system of an offshore zone.

As introduced in section 3.1.1, survey vessels are designed for monitoring the environmental and geophysical conditions of an offshore site. One can safely anticipate the need for survey vessel campaigns during the service life of an MRE project. Indeed, it would be expected that the evolution of the environmental conditions throughout the lifetime of a project is a requirement to comply with the regulatory framework (issues related to pollution, bio-fouling, etc.). Survey vessels can be equipped with a very broad range of monitoring instruments including all the equipment that will be depicted in the remaining of Section 4.1.2. Other types of equipment used for surveying have been enumerated throughout the report and particularly in Section 3.1.1.

Quite often, divers are required to assist subsea monitoring work. In particular, divers are primarily involved in inspection work or manual operations, which require precise and dexterous handling skills that are outside the range of capabilitie

Figure 4.1.2-1: A diver preparing for subsea work (left) and diver inspecting subsea cable (right), both at EMEC [140].

Autonomous Underwater Vehicles (AUVs) and ROVs are historically the descendants of human based underwater operations. Although records of diving operations demonstrate impressive capabilities (such as depth below 2,000 m in the case of Human Operated Vehicles (HOVs) and deep diving equipment), technological progress driven by the Oil & Gas industry has rapidly stirred R&D towards solutions avoiding the need to have a human operating underwater, mainly for safety reasons.

Both ROVs and AUVs are marvels of engineering, consisting of a complex embedment of motors/propellers, switches, control box, tether, and power electronics protected in a waterproof structure. The vehicles can carry instruments, take samples and conduct surveys, while allowing scientists to follow their progress from the safety of a ship. The main difference between the two is that AUVs operate independently from the ship and have no connecting cables whereas ROVs are connected to an operator on the ship**.**

Nowadays, ROVs and AUVs are one of the most prominent monitoring equipment used offshore. The wide range of offshore applications and services accessible through the use of ROVs and AUVs has naturally led to the realization of classification and standards. Below the five ROV classes as defined by the NORSOK [145] are listed:

- **Class I – Pure observation:** Pure observation vehicles are physically limited to video observation. Generally they are small vehicles fitted with video camera, lights and thrusters. They cannot undertake any other task without considerable modification.
- **Class II – Observation with payload option:** Vehicles capable of carrying additional sensors such as still colour cameras, cathodic protection measurement systems, additional video cameras and sonar systems. Class II vehicles should be capable of operating without loss of original function while carrying at least two additional sensors.
- **Class III – Work class vehicles:** Vehicles large enough to carry additional sensors and/or manipulators. Class III vehicles commonly have a multiplexing capability that allows

additional sensors and tools to operate without being "hardwired" through the umbilical system. These vehicles are larger and more powerful than Classes I and II.
  - Class III A – Workclass vehicles < 100 Hp;
  - Class III B – Workclass vehicles 100 Hp to 150 Hp;
  - Class III C – Workclass vehicles >150 Hp.
- **Class IV – Seabed-working vehicles:** Seabed-working vehicles maneuver on the seabed by a wheel or belt traction system, by thruster propellers or water jet power, or by combinations of any of these propulsion methods. Class IV vehicles are typically much larger and heavier than Class III work class vehicles and are configured for special purpose tasks. Such tasks typically include cable and pipeline trenching, excavation, dredging and other remotely operated seabed construction work.
- **Class V – Prototype or development vehicles:** Vehicles in this class include those being developed and those regarded as prototypes. Special-purpose vehicles that do not fit into one of the other classes are also assigned to Class V. AUV is currently assigned to Class V.

Typically, an ROV embodies a deployment system, also sometimes referred to as Launch and Recovery System (LARS), the control cabin and the umbilical along with the tailored instrumentation [146]. Deck space for the complete ROV system needs careful consideration, as not only is space needed for the ROV itself but also for the stores, maintenance workshop, tool and skid handling requirements as well as the ROV control room, the deployment system to be used and, if appropriate, the tether management system.

There are two main methods of deploying and recovering an ROV [146]:

- **Over the side deployment:** the A-frame of the support vessel lifts the ROV and lowers it into the water via its Tether Management System (TMS).
- **Moonpool/cursor deployment:** the ROV enters the water through a moonpool while being lowered by an A-frame and runs down guide rails or wires in conjunction with a cursor.

While the "over the side deployment" offers a cheaper solution to the moonpool deployment technique, the latter can be performed in harsher sea conditions.

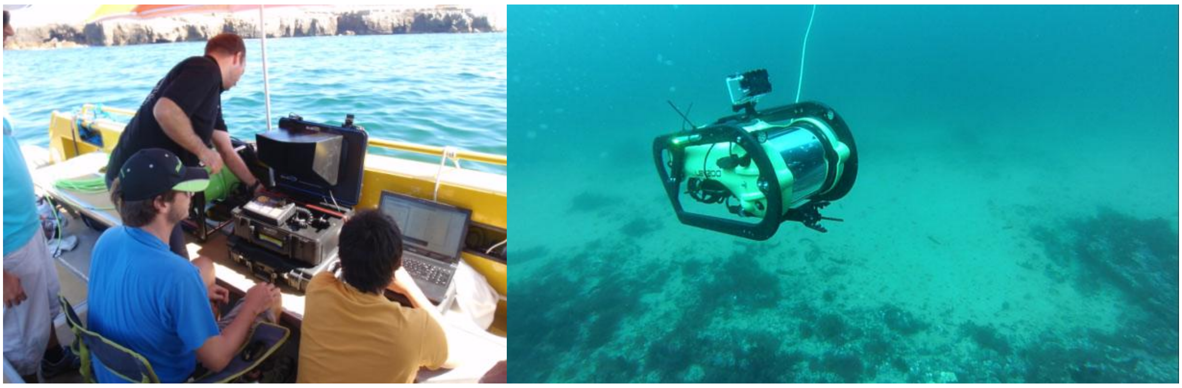


Figure 4.1.2-2: Operational use of WavEC's inspection class ROV [143]

The adaptive monitoring package for MRE devices, as presented by Joslin et al. [147], includes an ROV along with tool skid to support near-field and long range monitoring. Provided the challenging nature of the favourable sites for wave and tidal devices deployment, the use of solutions avoiding the need for divers or any other risky human-driven offshore/subsea operations would be clearly well-viewed from a risk and safety management perspective.

4.1.3 DATA ACQUISITION & PROCESSING

In wind turbines, data acquisition units are normally placed within the nacelle. Given the variety of designs for tidal devices and even more for wave devices, it is difficult to forecast where the data acquisition unit would be best embedded.

Undoubtedly, EMEC is the most experienced testing site for wave and tidal energy technologies. At this location, off the Isle of Orkney in Scotland, a Supervisory Control and Data Acquisition (SCADA) system was installed to transmit the flow of information generated by the offshore monitoring equipment. The SCADA system, based on a global standard General Electric (GE) product, is supported by a historical database which assists the staff in providing verifiable performance and environmental reports to stakeholders [148]. The system provides real-time status information, trends, alarms and remote control around-the-clock to facilitate a safe working environment, comprehensive assessment and safe operation of the plant.

In the future, one can anticipate the progressive standardization of SCADA systems for the wave and tidal sector, as it has been observed in the wind energy industry. The transmission system allowing the transfer of data can have different form. A communication unit is either integrated into the data acquisition unit or stored separately. While ROVs are communicating with the surface vessel through a wire as seen in the previous section, wireless communication is widely utilized for the other monitoring systems. Three wireless communication methods can be met:

- Satellites;
- Radio frequency;
- Global System for Mobile (GSM).

The data is transmitted over secure networks from the site to the data centre where it is verified, processed and passed on to end-users that can post-process the information. Monitoring data from MRE arrays should be invaluable information for technology and project developers as well as operators. The health of the plant including electrical and mechanical performance and communications status, together with the evolution of the environmental conditions, form a package of data essential to understand the behavior of MRE arrays. Engineers and scientists can make use of their expertise to interpret these data accurately. All data should be saved or archived according to industry standards.

4.1.4 REQUEST FOR O&M INTERVENTION

In addition to O&M monitoring programmes that are scheduled on a fixed interval of time basis, CMS and monitoring data coming from other types of equipment can alert the farm supervisor/operator so that an action can be planned in response. When an alarm is triggered the communication unit will send the alarm information and all the relevant data to the MRE farm central database so that it can be evaluated further. Nowadays, most communication units can also notify operators by text, fax or e-mail. Alternatively, a request for O&M interventions can be initiated after a diagnosis of the monitoring data that reveals, for example, a high risk of failure.

4.1.5 SUMMARY OF THE KEY LOGISTIC STEPS

In the description of the above four logistical steps 4.1.1 to 4.1.4, it transpires that monitoring is an integral part of all MRE projects. The need and extent of monitoring at an MRE site should be established in accordance with the initial environmental impact assessment and consenting process. From a deployment and operational point of view, the logistic sequence for O&M monitoring can be represented as drawn in the flow chart in Figure 4.1.5-1:

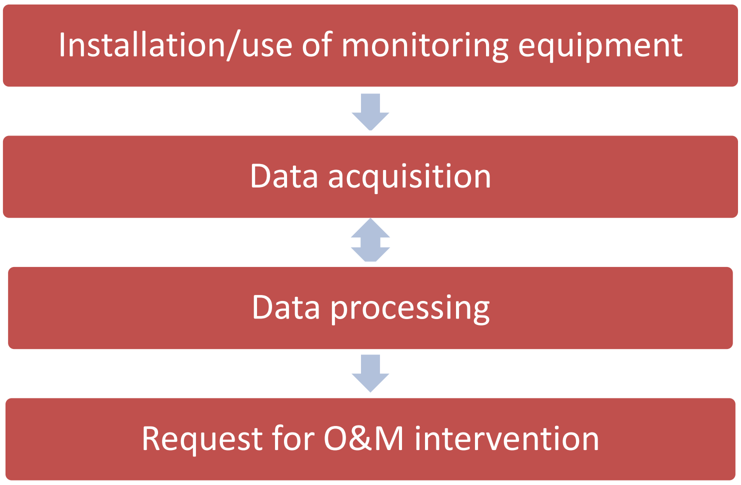


Figure 4.1.5-1: Summary of the key steps for the monitoring phase

Table 4.1.5-1: Key logistic requirements influencing the selection of port, vessels and equipment for the monitoring of an array of MRE devices

Component / site data type	**Parameter(s)**	**Unit / Format**	**Related infrastructure characteristics**
Monitoring equipment	Dimensions and weight	Meters and kg/tons	Deck loading and area of the vessel
Seabed conditions	Type of soil and bathymetry	Rock/sand/mud and bathymetry	Type of foundation for fixed equipment
Environmental conditions	Wave height, wind & current speed	Time series (hs, s, m/s) or statistics (if not available)	Operational limit conditions of the vessels and equipment to be used
Operational water depth	Operational water depth	Depth in meters	Need for divers/ROV

Monitoring activities usually start during or after the commissioning of the prototype or plant. Monitoring will be continuously or periodically done while operating the farm. If any issue is detected when processing the data a request for intervention will be sent and the preparation of the O&M will start.

Table 4.1.5-2: Interactions of Monitoring with other activities

Sequence of the logistic phase	Description of the interactions with other logistic activities
What usually comes before?	Plant installation and commissioning
What usually comes after?	O&M Intervention
What can be done simultaneously?	Plant operation

As previously stated, one can anticipate the development of cutting edge monitoring equipment customized for the MRE sector. The inherently harsh nature of the exploitation sites for MRE imposes new challenges in the design and operational working conditions of monitoring equipment. To date, the areas of high current speed are relatively unknown and unexplored.

Recent developments have confirmed the interest in offering tailor made solutions for the monitoring of MRE arrays. For instance, Joslin et al. [147] are proposing an adaptable monitoring package along with an ROV and custom tool skid to support near-field and long range MRE monitoring programmes.

In the North of Spain, a novel on-board device for the supervision and control of operational hazards in floating MRE units is under developement by Tecnalia [149]. WavEC is also involved in the commercialization of monitoring products receiving funding through the KIC-InnoEnergy (such as the KIC- Offshore Test Station [140] introduced in Section 4.1.1). To date, the most significant progress towards accurate, safe and efficient monitoring of MRE projects can undoubtedly be found at MRE test site centres (with EMEC accumulating the largest share of operational experience).

4.2 ON-SITE INTERVENTIONS

In the context of servicing an MRE wave or tidal array, one can anticipate O&M onsite interventions for the main array components as follows:

- Electrical cables (export cable, inter-array cables and umbilicals) inspection and repair;
- Mooring line inspection and replacement;
- Foundations and anchors inspection and reinforcement;
- Connectors (electrical or mechanical) replacement;
- Inspection/replacement/repair of device components.

It is anticipated that first arrays will either allow to carry out quite a lot of interventions on site or to provide an easy decoupling mechanism to carry out interventions onshore.

4.2.1 O&M PLANNING

Experiences based on offshore wind farm (OWF) operations indicate that O&M evaluation and mobilization is a complex process which involves different stakeholders. A high level of interactions between the various actors of the O&M evaluation and mobilization process is the key to a successful logistic planning.

The structure of stakeholders, infrastructure and interconnections of the OWF in maintenance/repair status are shown in Figures 4.2.1-1 and 4.2.1-2, with the utilization of smaller or larger vessels. It is divided into onshore and offshore activities. The icons are representing parties/stakeholders concerned and the required infrastructure. The arrows between them represent the interfaces as well as the interactions. The types of interfaces / interactions are defined as staff, material, waste, finances and information [150]. Not all stakeholders, infrastructure and interconnections are required for each inspection/repair/replacement activity. This example is also displayed in deeper blue colored boxes in figure 4.2.1-3.

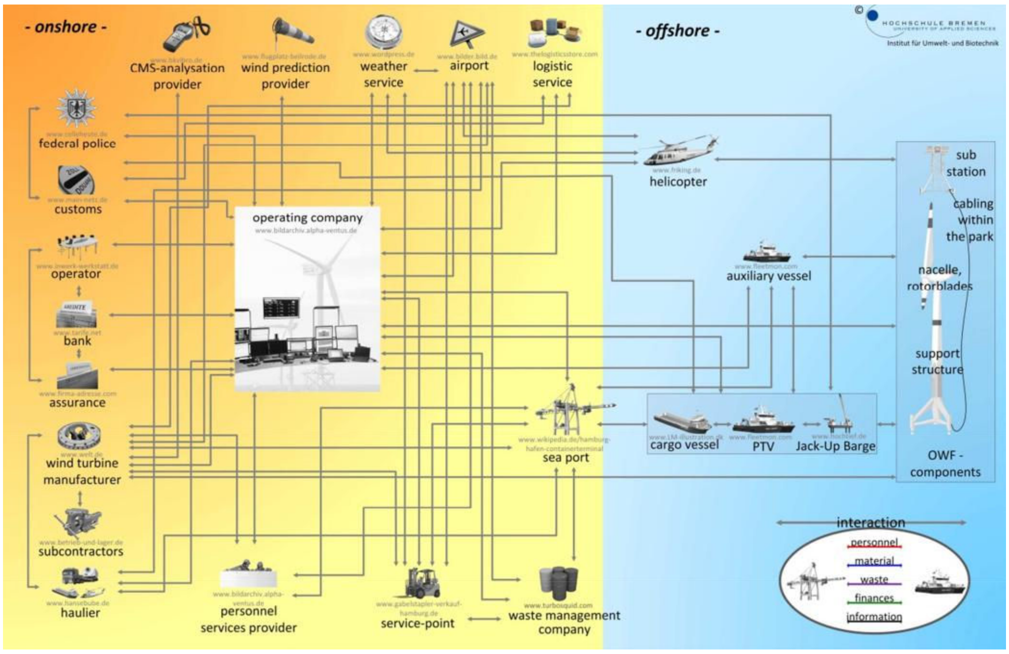


Figure 4.2.1-1 OWF in maintenance status using large vessels [143]

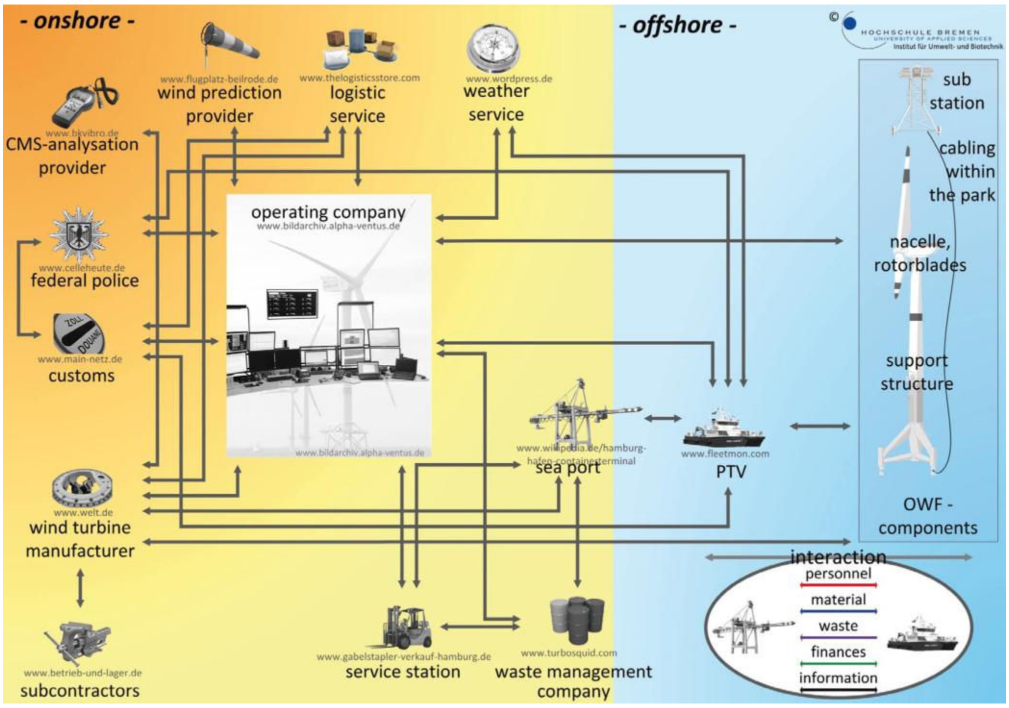


Figure 4.2.1-2 Repair of small components by using a personnel transfer vessel [144]

Based on Figure 4.2.1-3., the maintenance processes inspection/repair/replacement can generally be divided into sub-processes. The first steps correspond to the determination of requirements (this typically follows from monitoring) and the mission planning. It covers the best combination of determined work assignments under current requirements and necessities, e.g. weather conditions and logistics. This process is the basis for successfully carrying out the work assignments on-site of the wind farm. It also has a great impact on expenses and incomes of the OWF [O&M5].

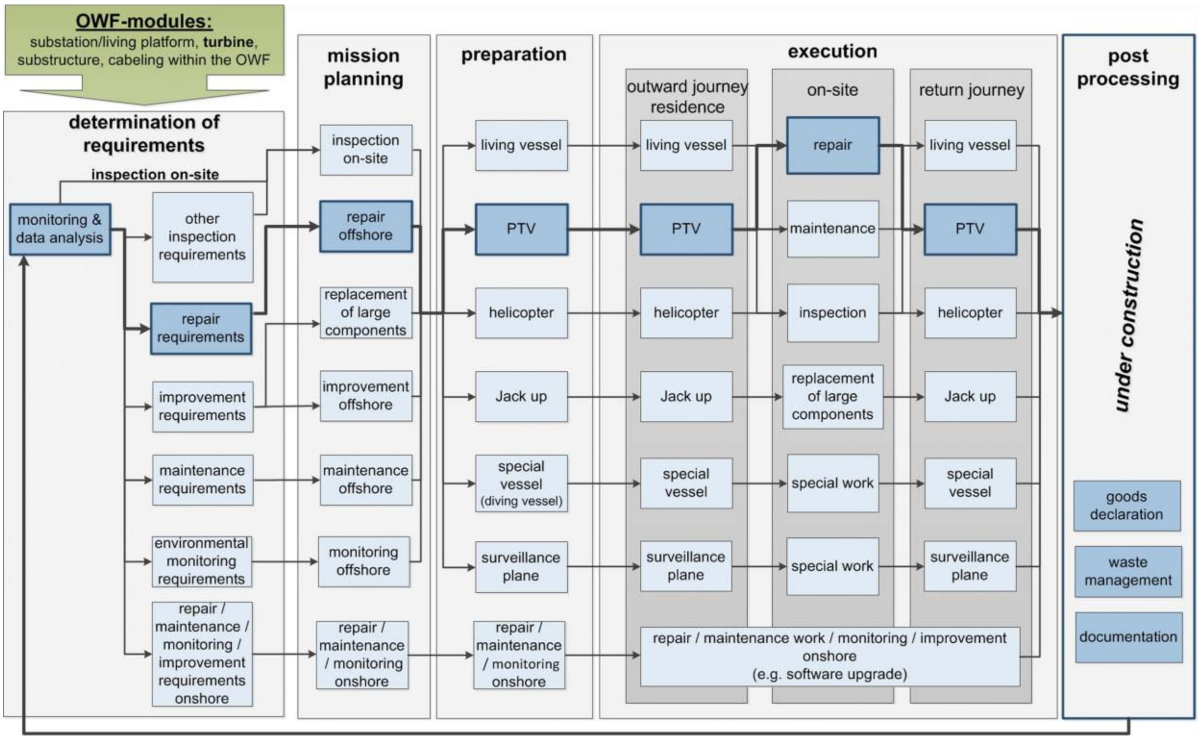


Figure 4.2.1-3 Process map of OWF O&M with highlighted repair of small components process by using a PTV [144]

The latter processes of preparation, execution and post-processing are described in the next sections.

4.2.2 PREPARATION, VESSEL SELECTION AND MOBILIZATION

4.2.2.1 PREPARATION

This task covers the preparation technicians, material, spare parts and tools as well as logistics processes. This is quite a critical part that should always be accounted for as experience from offshore wind has shown. Forgotten or damaged material leads to time delay or abort of a work assignment. Because of difficult weather conditions with narrow time slots for working and high logistic costs as well as restricted availability of special vessels the preparation also has a great impact on expenses and incomes of the OWF [151].

4.2.2.2 VESSEL SELECTION AND MOBILIZATION

Different offshore project phases, from installation via O&M to decommissioning, have different specific vessel needs. All vessels employed in the offshore wind sector can be classified as either construction or support vessels. The first category is used in the installation phase of offshore renewable farms. The second category belongs to the O&M activities which can be divided into Crew Transfer Vessels (CTVs) and vessels to transport heavy maintenance equipment.

Depending on the character of the device damage and technology, different vessels have to be utilized. Ideally, O&M vessels should be available locally but for special operations they may need to be mobilized and the mobilization time should be accounted for.

In the following, the required types of vessels for different onsite O&M interventions are described. The mentioning of the vessel types is ordered by the increase of the ship size and the complexity of the operation.

Crew Transfer Vessels (CTVs):

O&M of onsite interventions which are purely restricted to inspections or to small maintenance actions that do not require the detachment / replacement of larger components can be carried out by using a CTV, manned with common skilled personnel (electricians, mechanics or mechatronics fitter). A basic set of tools and some often used spare parts (screws / bolts / nuts, fuses, small circuit breakers, etc.) can also be loaded to the CTV and taken out to the site. Figure 4.2.2-1 shows a typical CTV. Main parameters for the selection of such a CTV is the transferring speed, the type of access system (maybe specialized systems are required), the operational limits with respect to wind speed and sea state. It is clear that CTVs are only applicable when the MRE system allows maintenance on site.

Figure 4.2.2-1: Fast Crew Transport Vessel Aquata [145]

Subsea support vessel:

A subsea inspection vessel equipped with ROVs may be required for the regular inspection and maintenance purposes of the submerged parts of MRE devices including the moorings and the cablings. Alternatively, this task may also be performed by divers which will be transferred to site (see section 4.1.2 for more information about divers).

A typical vessel equipped for such tasks is the “MSV Olympic Intervention IV” (Figure 4.2.2-2) which is equipped with a dynamic positioning system with single redundancy and is designed for O&G subsea hardware installations, inspection, maintenance and repairs with the help of its two “Magnum Plus” work class ROVs [82]. As described in section 4.1, ROVs are remotely controlled submarine devices which are equipped with video cameras and often have robotic arms which allow the operator to work underwater with the safety and comfort of a boat.

Figure 4.2.2-2: Inspection and maintenance vessel "MSV Olympic Intervention IV" [145]

Selection criteria for subsea support vessels are the operational limits for both the vessel and the ROV. The sea state must allow to submerge the ROV for operation and to retrieve it from the water afterwards. This type of operation will have a limited tolerable Hs value. The ROV itself must be able to cope with marine current speeds at reasonable values (< 1 m/s). The lower the tolerable current speed of the ROV, the smaller the working windows around slack water conditions for the ROV. This could be in particular a problem at tidal array sites, where naturally high current speeds occur. Depending on the distance to the O&M basis at the port and the related travelling time, the subsea support vessel should be able to stay out at the site for several days to perform as much as possible inspection interventions, for example during a neap tide period with considerably lower current speeds. The subsea support vessel typically has limited working range in terms of current speeds. However, a solution could be to anchor the vessel. Maintenance operations can be carried out on site or the support vessel can bring the MRE device on deck and transport it to the maintenance harbor. A wide range of such subsea support vessels exists with different crane capacities, deck space, cost, etc. The choice of the most suitable subsea support vessel is of large importance.

Tugboats for moving of floating components and devices:

Some MRE systems are made to float or have the ability to float, for example the Alstom 1 MW tidal turbine, the Bluetec device by Bluewater or the Pelamis P2 wave attenuator all have the capability of floating for maintenance operations to be carried out. Such concepts avoid the need for high cost heavy-lift vessels for lifting the device on a vessel for maintenance (e.g. Figure 4.2.2-2), nor are divers required (the use of divers is also limited to approximately max. 30 m water depth). Some maintenance operations can be carried out from the floating platform, while others require the MRE device to be towed to the maintenance harbor. The latter requires the use of one or more tugboats, e.g. Figure 4.2.2-3. Apart from the standard equipment on board of a common tug boat (ropes, shackles, chains, etc.), no specialized equipment is needed for the towing of devices or components into or out of an MRE array.

A disadvantage is that the operational limits for such operations are relatively low. Typically, the MRE devices cannot be exposed to high accelerations and the tugboats have a limited, tolerable Hs value.

Figure 4.2.2-3: Tugboat [119]

Specialized vessels for ocean energy:

Plans are made by Mojo Maritime to build a High-Flow Installation Vessel (HF 4), see Figure 4.2.2-4, which is able to hold station in high current flow speeds using a DP system. The vessel is scheduled to be delivered to its owners in the summer of 2015 [104]. Although a large part of the operations - e.g. submerging and lifting of components - require slack tide, the higher current flow operational limits are advantageous for holding position in stronger currents. Maintenance operations can be carried out on site or the vessel can bring the MRE device on deck and transport it to the maintenance harbor.

Figure 4.2.2-4: HF 4 vessel [94]

Also some developers may consider construct or buy their own vessels that fits its specific requirements. An example is OpenHydro, who built its own barge for easy installing and removal of their tidal turbines.

Cable repair ships:

Subsea cables may be damaged due to several reasons. Worzyk [16] mentions fishery and ship anchors as the majority of causes for cable damages. Localisation of the damage is normally made by well-known procedures using the reflection of electromagnetic or optic waves at the fault location of a power cable or fiber optic communication cable. This allows a localisation within a several kilometer range. The exact position can then be made with one of the methods described in section 3.1.1 of this report.

Once located, a cable repair ship with expert cable fitters must sail to the fault location. One end of the cable will be taken up to the surface and a piece of spare cable is connected. After cable connection, the different insulation and shielding layers need to be put back on. After this, the other end of the cable will be taken up and connected with the second end of the spare cable. The length of the spare cable must be about twice the water depth. If the cable is trenched, ROVs might be used to de-trench the cable for lifting the ends and then re-trench it after repair (see section 3.1.1). A detailed description of the whole procedure can be found in reference [16].

Cable repair can be done by relatively small vessels (see Figure 4.2.2-5), since only the spare cable of a few hundred meters length and the repair equipment need to be loaded. The cable fitter crew consists of only a few persons.

Figure 4.2.2-5: Cable repair ship [145]

Mooring and Anchor handling ships:

If a visual inspection of the mooring lines reveals a problem, certain links of a mooring chain can be repaired. As long as the chain is not broken, it can be lifted up until the weak link is on board a ship. The ship requires carrying equipment for repairing mooring links. The chain requires intensive cleaning with a high pressure cleaner. Then the damaged link is cut out and a new one is fitted in. For this purpose, a steel bar is heated and bent to the form of an open link ("U" shaped). Then the open link is threaded through both ends of the chain and is bent to a closed link. The contacting end surfaces of the new link will be welded together.

If the chain is already broken, the submerged end needs to be located by an ROV or diver and a lifting rope needs to be attached. After lifting the submerged end of the chain, the new link can be fitted in as described above.

If the mooring line needs to be replaced or removed completely for repair purposes, an Anchor Handling Vessel (AHV) is required for onsite repair action. AHVs are modified tug boats with very high power capacity (up to 18,000 kW). The high power capacity is required to pull the anchor out of the water. After performing the maintenance intervention, the mooring line and anchor needs to be laid back to the seabed. Then the anchor is fastened by pulling it with the full power of the AHV into the required direction of the tension force. Figure 4.2.2-6 shows a typical AHV. Bullard pull is a measure to classify AHVs.

Figure 4.2.2-6: Anchor Handling Vessel [82]

Multi-purpose vessels (MPV) for detaching of heavy devices and components:

MPVs in service of the offshore wind industry are partly converted to match the required specifications, partly hired for only a short period of time and therefore not directly adapted to wind farm installation requirements [152]. Figure 4.2.2-7 shows an MPV with a heavy load crane and some deck space area for deposition of MRE devices or large components.

Figure 4.2.2-7: Heavy lift vessel "Saipem 3000" [153]

For onsite interventions, which require the handling of heavy loads, MPVs will be used to detach large components from fixed founded devices or for lifting floating devices out of the water for further handling, i.e. transporting back to shore or performing maintenance actions on deck of a barge or transport vessel. The detachment of a nacelle unit, or even of the entire crossbeam with both nacelle units, from a piled tidal turbine like the SeaGen turbine can be taken as an example (see Figure 4.2.2-8).

Figure 4.2.2-8: SeaGen fixed foundation tidal turbine [122]

The demands to a MPV with respect to the handling of MRE array devices and its components are:

- Deck space to place the device / component;
- Crane capacity to lift the device / component;
- Operational limits due to wind, wave and tidal currents;
- DP abilities to allow smooth craning.

The required equipment for MPVs to be used for on-site interventions will be all craning staff (ropes, chains, shackles, etc.) and equipment / materials to fasten the load on deck for safe handling or transport.

It is clear that these high-cost MPVs should only be used for very heavy components which cannot be replaced by any other vessel mentioned above. Typically these heavy components will only be replaced when they are subject to accidental loads such as a ship overrun. A clever design of turbines, their support structure and foundations should avoid the use of these MPVs. This can be realized by early contractor involvement, i.e. EPCI contracts.

Rock Dump Vessels (RDV):

Any kind of offshore foundation (gravity based, piles, jackets, etc.) requires sufficient scour protection (this is not applicable when the seabed consists of rock). Monitoring of the scour protection is made by use of ROVs or divers as described in section 4.1.2 of this report.

In case the abrasion of the scour protection has reached a critical limit, an RDV will be used to dump gravel around the foundation to reinforce the scour protection. Dumping will be made by opening hatches beneath the gravel containers. As can be seen in figure 3.1.3-4, the RDV will be loaded with gravel of different grain sizes. This allows for building several layers to get a proper scour protection quality.

Depending on the foundation type, the RDV might need to come quite close to the structure of which the scour protection needs reinforcement. Therefore, a suitable DP system is required to avoid collisions of RDV and foundation. Selection criteria for the RDV will be the operational limits with respect to wind, sea state and current speed. It might be useful to reload the RDV on site using a large transport ship for the gravel to save travel time of the RDV. The transport ship should be equipped with its own loader crane.

Of course, other small generic vessels or transport equipment such as workboats, rigid inflatable boats RIB), multicast, tug boats, helicopters are expected to be used during O&M operations. Also, for large maintenance operations, large installation vessels may be required (especially in non-floating devices, see section 3).

4.2.2.3 LOAD OUT

Most O&M operations will be carried out by CTVs carrying personnel to the site, which does not require complex load out operations at port. However, for loading and unloading large components to be replaced on site there will be higher requirements.

Loading of large components into the vessels have similar requirements than the operations described in section 3 during the assembly and installation phase.

As described in section 3.4.2.1 all load-out operations shall be carried out during favourable environmental conditions. Although it is expected that most ports will provide adequate shelter to wave climate, some considerations have to be made with respect to the tidal range. In fact, tide variation is regarded as a critical parameter for load outs and should be carefully evaluated [124]. Wind load should also be taken into account especially if cranes employment is expected (depending on the type of component/equipment to be loaded, refer to section 3.4.2.1 for assembly and installation).

4.2.3 TRANSPORT/TRANSFER TO SITE

For transfer of personnel, CTVs as described in section 4.2.2 will be used in the first place. CTVs are fast (25-30 kn) and rather small vessels which transfer technicians and spare parts (1-2.5 t cargo capacity) to wind farms in order to carrying out minor repairs without the usage of heavy equipment (Figure 4.2.3-1). Apart from CTVs, personnel transfer can also be provided by helicopters which are commonly used by the O&G industry for fast access. Helicopters have certain operational limits with respect to wind speed and overall weather conditions. In addition, the procedures for winch down and up personnel also have operational limits. This is again the wind speed for all types of MRE array devices. In the case of floating devices, also the wave height is important to allow a safe winch procedure with respect to the movement of the device.

Figure 4.2.3-1: Example of a CTV (foreground) [154]

In the early days of offshore wind farm operations local charter vessels of conventional design were utilized as CTVs. Today these fast, light monohull vessels are still found in the service of offshore wind farm operating companies. Monohull CTVs are suitable for quick intervention during unplanned corrective maintenance. Catamarans are a two-hull design CTVs of medium size. They are more stable under rough sea conditions. Small Waterplane Area Twin Hull (SWATH) CTVs are more and more utilized for O&M purposes. These vessels have torpedo shaped floating bodies under each hull which minimize the contact area of water and hull and make them capable of withstanding even rougher sea conditions than catamaran designs. Typical characteristic of the CTV vessels are listed in Table 4.1.

Table 4.1: Typical characteristic of the CTV vessels

CTV	Speed [kn]	Passenger capacity	Cargo capacity [t]	Comfort	Hs [m] travel	Hs [m] for safe access to devices
Monohull	25-30	6 to 8	Limited	No	< 1	< 1
Catamaran	20-25	12 and more	2 to 3	Yes	< 1.8	< 1.8
SWATH	15-18	12 and more	Limited	Yes	< 2.5	> 1.5

There are three factors which should be taken into account regarding the utilization of O&M vessels:

- The weather conditions influence the operability of vessels, crew safety and accessibility of offshore structures.
- The travelling time due to the vessel's speed and the distance of working area to the O&M port.
- The water depth in the working area.

Slower vessels are not suitable for far offshore working areas because of the limited working time on site, unless the vessel is to stay on site overnight. Future offshore energy farms will consist of more devices and distances to shore are expected to increase. This will decrease the effective on-site working time which could be insufficient for some O&M activities. A solution to this problem could be higher vessel speeds or the utilization of O&M mother ships which stay on site and are able to deploy CTVs. There exist different O&M mother ship concept designs, some of these self-propelled and others non-self-propelled.

As explained in the previous Section 3, installation vessels may need to be used for the replacement of big components / systems and may stay on site during operations. Section 3 includes a description of the vessel requirements for transporting electrical components, anchors, moorings and foundations as well as MRE devices.

4.2.4 ACCESS TO DEVICE/SYSTEM

As mentioned above, the access to the component or system that needs to be maintained or repaired depends strongly on the type of energy converter. Floating devices can often be accessed directly from the water surface. Diving or ROV activities may only be needed for disconnecting the device from mooring and electrical connections. Due to the grade of automation, it is possible to totally avoid diving activities (see Pelamis P2 WEC [10]). Also the buoyancy of the floating device is promoting the maintenance procedure because no heavy crane vessels are needed and the device can be tugged if required. It is likely that only small vessels with light cranes or winches are necessary to hoist cables, tethers, etc. onto the vessel, where the personnel can safely work on them. In contrast, submerged devices mostly need diving or ROV activities or lifting to get access. Of course, many processes can be automated, too. Once the device is disconnected from its foundation, heavy vessels and cranes may be needed to recover it. This can be supported by buoyancy elements, but if it is necessary to lift up the device onto the vessel, again, heavy cranes may be needed.

4.2.5 MAINTENANCE/REPAIR ACTION AT SITE

The maintenance or repair action at site is described below using some examples from different technologies covered by the DTOcean project.

Alstom 1 MW tidal turbine: According to the Alstom website, the following actions need to be undertaken for the de-installation of a defect turbine unit after the disconnection from the electrical infrastructure (Figure 4.2.5-1):

- ROV submarine attaches upper guiding rope for buoyancy elements to top of nacelle;
- Buoyancy element is lowered and attached to nacelle;

- Defect turbine unit is disconnected from supporting structure and is moving towards sea surface, but is still connected with lower guiding rope;
- When defect turbine unit floats on sea surface, ROV detaches lower guiding rope from supporting structure;
- Defect turbine unit will be tied up to tug boat.

The de-installed turbine will be towed to port by the tugboat or will be loaded back to the transport vessel.

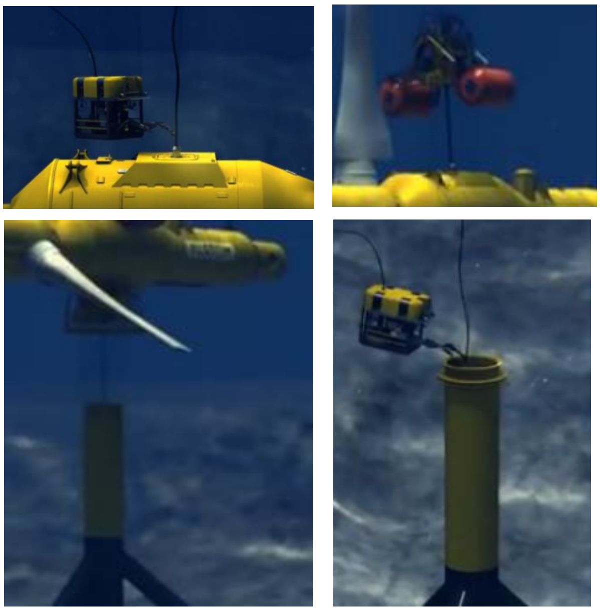


Figure 4.2.5-1: De-installation procedure of Alstom 1 MW tidal turbine [115]

The following actions need be completed in orderundertaken to re-install a (spare) turbine unit (Figure 4.2.5-2):

- ROV attaches lower guiding rope to the supporting structure;
- Spare turbine is lowered and connected to the supporting structure;
- Buoyancy element is detached from nacelle an returns to surface;
- Upper guiding rope is detached by the ROV.

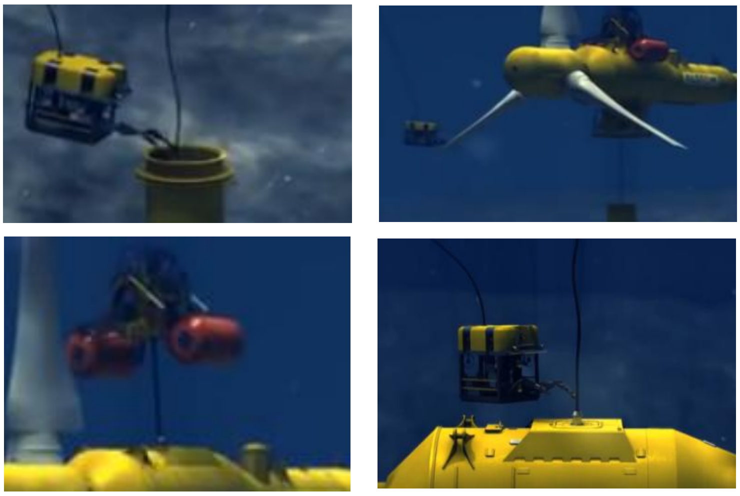


Figure 4.2.5-2: Installation procedure of Alstom 1 MW tidal turbine [115]

Pelamis P2:

Whilst onshore, a winch unit will be connected near the nose of the P2 and a winch line fed through the tip of the yoke. Once onsite, the buoy holding the TLA in place will be recovered to deck and removed and the line connecting the buoy to the TLA will be attached to the winch line and thrown overboard. The winch will now be remotely started to remove slack in the line. As winching continues the TLA will begin to rise and the yoke of the P2 will move from a horizontal position to a vertical one. As the TLA nears the winch it will self-align and the yoke will dock in the TLA. Power and communication links will be confirmed before latch arms and locking pins finalise the link between the yoke and the TLA. During this process, the winch on the P2 will remain connected to the installation vessel by tow line and will now be dragged from the P2 and back to deck. Thus, the connection of the P2 to mooring, electrical and communication lines can be completed without the need for personnel to land on the device, or dive, and with no offshore heavy lifting operations [45].

Figure 4.2.5-3: Vessel with integrated crane for maintenance purposes of Pelamis P2 [10]

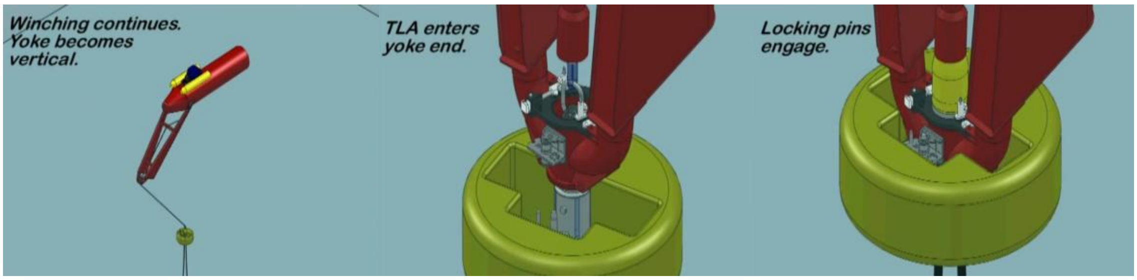


Figure 4.2.5-4: Installation procedure of Pelamis P2 [10]

Wave – Ocean Power Technologies (OPT) PB150 PowerBuoy – WestWave:

Each PB150 is to be fully assembled and commissioned onshore prior to transport to site. This includes the fixing of three bridle mooring connections to the spar module. OPT recommends transporting each device to site by towing in water using a standard tugboat. Towing requires that the device remains horizontal on the water surface so ballast tanks in the heave plate should be air filled.

Once on site, the PB150 must be attached to the mooring spread with each bridle connected to a different pre-placed mooring line. The exact procedure for making this connection is not defined, but each mooring line is to be recovered using the surface float attached during mooring installation, likely using a boat hook from the tugboat. Presumably bridle connections can also be recovered and the connections can be made on the deck of the tugboat.

The PB150 must next be flipped into its vertical operational position. This will be achieved by flooding the ballast tanks in the heave plate with seawater. An additional “trim tank” located in the spar module can be partially flooded to make minor corrections to alignment. The device will now be in its final position with the float module directly above the spar and heave plate modules and the whole device being held in station by the mooring spread.

The final stage of device installation requires the connection of electrical cabling. As mentioned above, an exact procedure for making these connections was not defined although “connections between the PowerBuoy low voltage cable assemblies and the Uninterruptible Power Supply (UPS) can be done above water”. A sensible approach may be for the installation vessel to keep hold of the connecting end of the cable emerging from the PB150 as the device is brought vertical. The pigtail cable from the UPS could then be retrieved to the deck, ideally from a storage surface buoy, and the connection between the two cables made on-deck. The cable could then be laid out to the water, attaching floats and weights at predetermined locations to maintain the required S shape [45].

As previously mentioned, the access to the device/component will depend from system to system. In other technologies, the full device will be lifted and towed special-purpose vessels (e.g. OpenHydro) or transported on deck using heavy lift or smaller vessels depending on its weight, size and water depth at which they are installed. Also fixed surface-piercing devices such as Seagen S will may have similar requirements as fixed offshore wind farms with the increased challenge of being located in high current and/or wave areas.

4.2.6 QUALITY CONTROL

After each onsite intervention, a revision of the entire process from the first request for the intervention (e.g. resulting from an alarm of a monitoring system) via the evaluation of the kind of problem, the mobilization of the required equipment, transport media and personnel, the vessel preparation and loading, the transfer of all required items (personnel, materials, spare parts, components / devices for replacement, etc.) to the site, the access to the device / component to be maintained /repaired and the performance of the intervention itself should be analyzed in detail. This allows the optimization of upcoming onsite interventions with respect to the suitability of equipment used, the identification of additional helpful equipment or such equipment which has no benefit for the intervention, etc. Also the reordering of sub-sequences of procedures might contribute to an overall optimization of the onsite intervention. Therefore, a detailed quality control of each conducted onsite intervention should be the last step in the process chain.

4.2.7 SUMMARY OF THE KEY LOGISTIC STEPS

To summarize the entire process, a flow chart of the sequences of the logistic operations for onsite intervention is depicted in Figure 4.2.7-1.

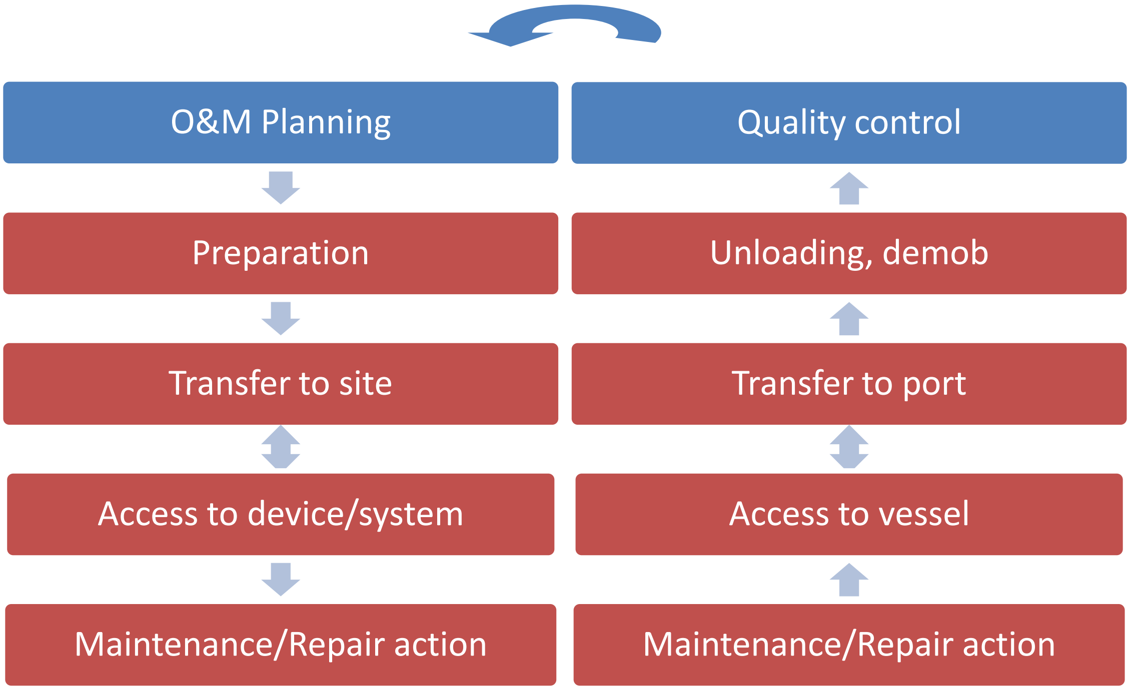


Figure 4.2.7-1: Flow-chart of the sequence of the logistic operations embedded in O&M activities

The logistic effort for onsite interventions is dependent on the maintenance type (i.e. Inspection/Repair/Replacement). The typical flow of the logistic effort embedded in maintenance activities can be distinguished in the following steps for an onsite intervention:

- O&M evaluation and mobilization including organization of spare parts, crew and vessels;
- Vessel preparation and loading;
- Transportation to site;
- Transfer of crew/equipment to port after the Repair/Replacement activities.

In Table 4.2, the most important relations between the inputs of the WP5 lifecycle logistics module and the selection of the suitable set of equipment, personnel and vessels are introduced. The selection procedure will be controlled by the descriptive parameters of the required equipment, personnel and vessels.

4.2.7. Parameters and related infrastructure for on-site interventions

Component / site data type	**Parameter(s)**	**Unit / Format**	**Related infrastructure characteristics**
Crew	Size and skills	Size in number, pre-defined classes ofskills (e.g. ROVoperator, diver, crane operator, etc.)	Suitable skills and number of crew; transport capacity of the CTV;
Spare parts	Weight	Weight in kg/tons	Type of transport or hoisting vessel with respect to crane and deck load capacity, draft; in case of use of jack-up platforms: operational depth;
	Dimensions	Dimension in m x m x m	
	Water depth	Depth in m	
Distance between array devices	Distance between array devices	Distance in m	vessel dimensions and maneuverability
Seabed conditions	Type of soil and layer thickness	Rock/mud/sand...	Type of vessel and equipment to be used for trenching, monitoring and protecting the cable
	Bathimetry	Depth (m)	Type of subsea equipment/personnel and vessel (e.g. jack-up)
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

Table 4.2.7-1: Interactions of on-site interventions with other activities

Sequence of the logistic phase	**Description of the interactions with other logistic activities**

What usually comes before?	Monitoring / Request of O&M operation
What usually comes after?	Plant operation
What can be done simultaneously?	Some O&M activities can be done simultaneously. Also some on-site interventions may be done while operating the plant.

4.3 ONSHORE INTERVENTIONS

4.3.1 O&M PLANNING

As with the on-site interventions, onshore interventions should start with a very careful planning in order to minimize costs, risks as well as the plant downtime. For a detailed description of this phase refer to section 4.2.1.

4.3.2 PREPARATION

Once the O&M operation has been carefully planned, the preparation of the onshore infrastructure can start. Onshore infrastructure plays an important role in the management of O&M procedures. Port-side activity and facilities include [155]:

- Warehouses and storage space;
- On-site offices;
- Vehicular access (including the capability to handle large lorries);
- Lifting equipment, cranes and special machines to undertake certain O&M interventions;
- Dry-dock capabilities;
- Berthing space;
- Vessel hire;
- Trained maintenance personnel;
- Vessel access.

In case of larger components (structural elements, rotor blades, frequency converters, etc.) the spare part lead time might cause a significant share of the overall maintenance intervention duration. Therefore, storage of at least a small number of spare parts might reduce O&M costs. In case of the example of the Alstom tidal turbine from section 4.2, a certain number of nacelle units could be held in stock to reduce reaction time for replacement and therefore reduce device downtimes during the operational phase of an MRE array. The optimum number of spare parts for a certain component is subject to an optimization process. Such optimization could be supported by performing an ABC analysis for the respective components.

Furthermore, repair of devices or large components may take place in land based facilities. Therefore, fabrication halls must be available at a site in or near the port with sufficiently large work space and access doors.

Mobilization of vessels and load-out (if required) will also be undertaken at this stage (see on-site interventions section for more details on O&M vessels).

In most cases, the vessel(s) will be mobilized to the site unloaded, in order to bring the device(s) back to harbor. For sites which are far from shore, crew transfer to site may be an important constraint (see section 4.2.3 for detailed description), but the most critical operation will be the transportation of the device to port and back to site(see section 0).

4.3.3 DISCONNECTION AND DETACHMENT

If required for maintenance, a device may have to be disconnected from its electrical umbilical and detached from its mooring system or foundation. In Bould [45], those procedures are described in detail for different kinds of fixed and floating MRE devices.

For fixed founded devices like the SeaGen tidal turbine (see section 4.2.2 and Figure 4.2.2-8) which can be lifted above the sea level, cable disconnection can be made in a more or less dry environment inside the foundation structure (tower, machine house). By unfastening flange bolts, the entire device can be detached from the foundation. A special case for disconnecting and detaching of a fixed founded but fully submerged tidal device (Alstom 1 MW tidal turbine) is described in section 4.2.5.

Floating devices are connected with a dynamic cable or umbilical. To disconnect the device, this cable needs to be unfastened from the connection point at the device and has to be marked with a buoy. In the same way, the mooring lines have to be disconnected and marked with buoys. Depending on the connection point of the cables and mooring lines, this procedure might require the assistance of ROVs or divers. Figure 4.3.4-1 shows a cable and mooring arrangement on the example of the PB150 device.

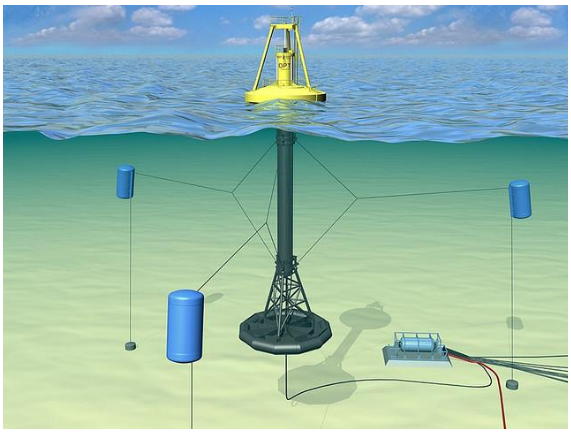


Figure 4.3.3-1: Cable and Mooring arrangement of a PB150 MRE device [125]

With respect to cost and working window aspects, the avoidance of subsea activities for disconnection and detachment of MRE devices is beneficial. In the case of the Pelamis P2, the procedures are strictly designed to avoid subsea interventions. The detachment procedure for the P2 device is described in section 4.2.5. The cable disconnection procedure is optimized by using floating cables as shown in Figure 4.3.4-2 below. The cable will be lifted above sea surface. With the interconnectors, the cable can be disconnected and the device can be taken out of the array.

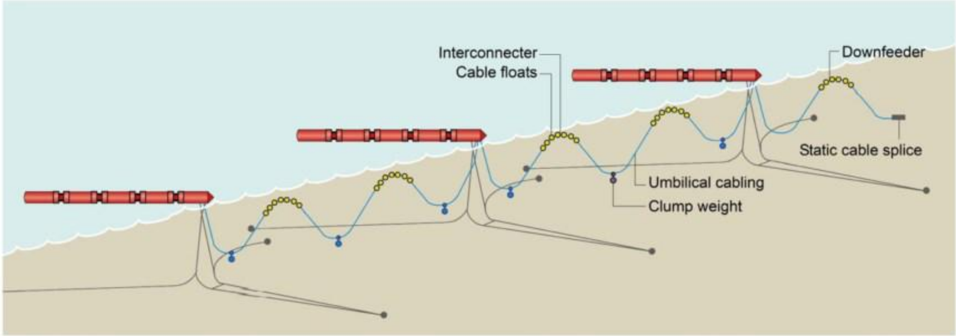


Figure 4.3.3-2 Cable arrangement in a Pelamis P2 array [114]

4.3.4 TRANSPORTATION TO PORT

Some devices of the types in scope of the DTOcean project will have outstanding dimensions as can be seen in Figure 4.3.3-1 and Figure 4.3.3-2 for the Pelamis P2 wave attenuator device. This will cause particular problems when maneuvering in the port basins or in dry docks. It may be required to work with several tug boats here to stabilize the device and to move it close to the quayside or into a dry dock without hitting the quayside or dock walls.

Figure 4.3.4-1: Pelamis P2 device [114]

Figure 4.3.4-2: Towing a Pelamis P2 device with several tugboats [114]

Some MRE devices might need to be transferred back to port for maintenance (see section 4.3.6 for details). Transportation of large component requires vessels with a corresponding load capacity. Transfer from the MRE array location to the port site can be done with an MPV or subsea support vessel as described in section 4.2.2 of this report. In fact, these vessels might have limited deck space and, therefore, could possibly transport only one device or only a few large components at a time.

In case of a far distance between the O&M port and the MRE array location, the transport of multiple devices or large components might be beneficial in an economic sense. Therefore, large transport ships or barges can be used to carry several MRE device units or large components. Figure 4.3.3-3 shows examples of barges with and without a crane.

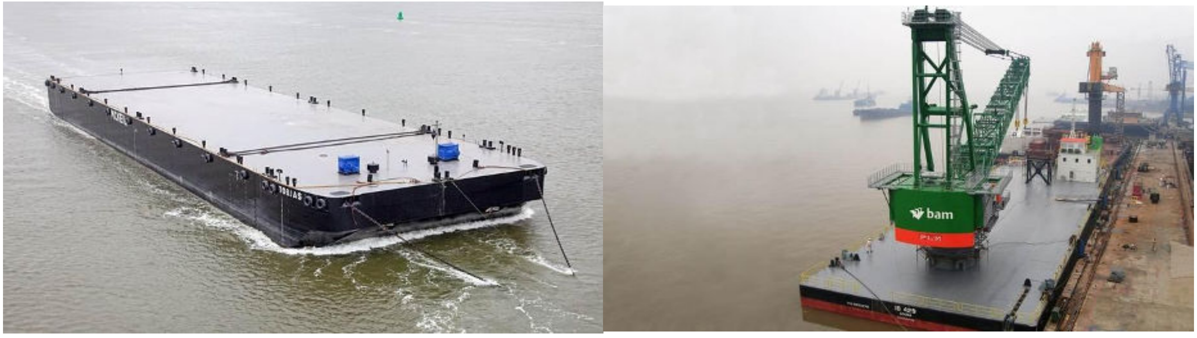


Figure 4.3.3-3: Barges [156]

4.3.5 PORT REPAIR ACTIONS

Most of the device types in MRE arrays need to be moved to dry land or into a dry dock by the transport ship or need to be lifted out of the water to do a full maintenance operation (when floating devices). In some cases of large and heavy devices, e.g. the Pelamis P2, repairs should be done in the port basin itself. For this purpose, the basin needs to be large enough and the quayside must have an appropriate length.

In general, the vessel preparation at the harbor quayside may require large enough dockside cranes with respect to lifting capacity and cantilever arm distance. Depending on the harbor infrastructure (or its absence), hiring of a mobile crane might be required. The surface load of the quayside must be able to carry the weight of the crane itself and the additional weight of the component or device to be loaded on a vessel or to be lowered in the water. Trained personnel at harbor are necessary for the operation of quayside cranes.

In the case of the example with the Alstom tidal turbine, a spare nacelle unit needs to be lowered into the water and tied to the tugboat as shown in figure 4.3.2-1 below.

Figure 4.3.5-1: Vessel preparation for replacement of an Alstom tidal turbine [115]

In the following the infrastructure of the ports and dry docks will be described.

4.3.5.1 TYPES OF O&M PORTS

There are different types of ports and facilities which have to satisfy different requirements during the pre-installation/O&M phase of an offshore renewables farm.

O&M ports should have the following properties:

- A quayside lifting capability to lift the device to shore;
- Local workshop facilities to allow strip down, refurbishment, re-assembly and testing of devices;
- A local skills base with mechanical and electrical technicians and familiarity with devices and necessary maintenance requirements.

Quick reaction and supply ports are two different classes of O&M ports:

Quick reaction port:

Quick reaction ports are utilized for spontaneous and short term maintenance operations. Therefore they need to be placed in short distances to the designated MRE array locations to keep personnel transfer times low and in consequence on-site working times high [157]. A port of this class does not need advanced facilities and infrastructure like reinforced quays, deep berths, huge cranes and extensive storage and assembly areas. Instead typical properties for an offshore wind quick reaction port are according to [158]:

- The designated wind farm must be reachable in 2 h maximum,
- Quay of at least 80 m length, suitable for docking and sheltering CTVs,
- Tide independent berth depth of at least 3.5 m,
- Unrestricted water access and 24 h work allowance for personnel,
- Bunkering capabilities,
- Sufficient storage area of 2,000 m² minimum for tools, small spare parts and components and general operating resources,
- Nearby store houses and office space of about 500 m² and max. loads of 5 t/m²,

- Appropriate accommodation and shelter for 15 to 20 personnel with supply of water and electricity,
- Good connection the public road network.

Supply port:

According to the maritime networking group the purpose of supply ports is the provision of remote quick reaction ports with required operating resources. Also such a port can directly function as an O&M base for wind farms if applicable. Supply ports are utilized for regular transports and performing planned routine maintenance so port properties for offshore wind supply ports are as follows [152]:

- Quay of 80 m to 100 m, suitable for docking CTVs and MPVs,
- Berth depth of at least 3.5 m,
- Permanent, tide independent access is not necessary due to planned transports,
- Appropriate facilities for loading and unloading medium wind turbine components (capable cranes, possibly reinforced quays),
- Bunkering capabilities as well as supply of water and electricity,
- Sufficient supplies storage area of at least 2,000 m² and store houses of at least 500 m² for tools, medium spare parts and components and general operating resources,
- Personnel-, office- and social facilities,
- Good connection the public road- and possibly rail network,
- Short distances to airports or helicopter landing pads,
- Availability of local component suppliers is of advantage.

4.3.5.2 TYPES OF DRY-DOCKS

There exist several basic types of dry-docks for O&M activities (Figure 4.3.6-1):

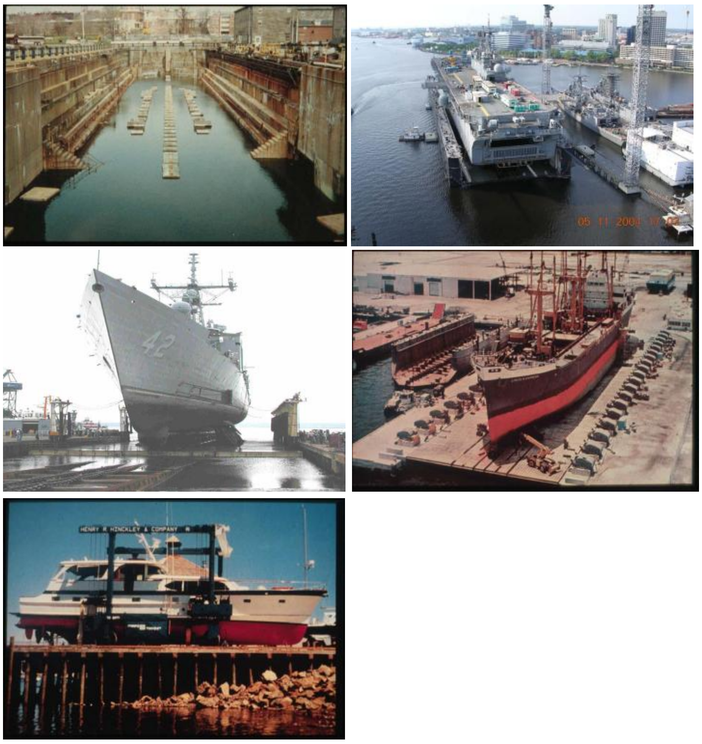


Figure 4.3.5-2 Different types of dry-docks for O&M activities [153]

Basin or Graving docks:

Basin or graving docks are large, fixed basins built into the ground at water's edge, separated from the water by a dock gate. Basin docks are capable of docking all sizes of vessels, with capacities of over 200,000 t. Its basic structure consists of a floor, sidewalls, head (front) wall and a dock gate. Alters (steps) may be incorporated into the side walls for structural stability (Figure 4.3.6-1, up left).

Advantages of a basin dock are:

- Long life expectancy of the basic structure;
- Low maintenance costs (dock floor and walls can be built of granite or concrete which last a very long time with little maintenance);
- There is no limit to the size of the basin dock;
- There is no need to worry about ship/dock stability, pumping plans or longitudinal deflection of the dock while docking ships (ship stability and block loading must still be addressed, however);
- The basin can be equipped with an intermediate gate that allows flooding of the aft half of the dock while the forward half remains dry.

Disadvantages of a basin dock are:

- High initial construction cost;
- The basin is a fixed structure, which cannot be moved. This makes it harder to re-sell thus harder to get financing;
- Routing of men and material is difficult since the floor is below grade;
- Ventilation and lighting;
- It is very difficult to enlarge a basin dock;
- Transfer;
- Usually slower to operate (power is inversely proportional to size).

Floating Dry Docks:

Floating dry docks are structures with sufficient dimensions, strength, displacement and stability to lift a vessel from the water using buoyancy. Floating docks range in lift capacities from a few hundred tons to over 100,000 t. In general the most economical range for floating docks is about 1,000 t to 100,000 t (Figure 4.3.6-1, up right).

Advantages of a floating dry dock are:

- It does not use valuable waterfront real estate;
- It can be built at the yard of low bidder and towed to the site; this keeps construction costs low by increasing competition;
- It can be sold on the world market, which keeps resale values high and makes it easier to get bank financing;
- Vessels can be transferred to and from shore relatively easily;
- The dock can be operated with a list or trim when docking vessels with a list or trim. This can reduce block loading and reduce or eliminate vessel stability problems when landing;
- Vessels longer than the dry dock can be docked by overhanging the bow and/or stern;
- The dock can be easily moved for dredging;
- Minimal landslide civil works are required which can result in easier permitting;
- The dock can be moved away from land to deeper water for docking and undocking operations. This can reduce or eliminate dredging and bulk-heading requirements;
- The dock can be lengthened relatively easily.

Disadvantages of a floating dry dock are:

- High maintenance is required on pumps, valves and steel structure;
- Routing of men and material is restricted to gangplank and/or crane service;
- Large tidal variations can complicate gangways, mooring, etc.

4.3.5.3 OTHER ONSHORE INFRASTRUCTURE

Marine Railways:

A marine railway is a mechanical means of hoisting a ship out of the water along an inclined plane. Lift capacities range from 100 t to 6,000 t. Theoretically, even larger sizes are possible, but generally the floating dock becomes a more economical alternative (Figure 4.3.6-1, middle left).

Advantages of a marine railway are:

- Low initial construction cost;
- Fast operating;
- The track slope can fit the natural slope of the shore in many cases. This eliminates or reduces dredging or bulk-heading requirements;
- Vessels can be transferred to and from the shore relatively easily;
- Vessels longer than the dock cradle can be docked by overhanging the bow and/or stern.

Disadvantages of a marine railway are:

- The track is a fixed structure and cannot be moved easily. This makes it harder to sell, thus harder to finance;
- It is a mechanical system that requires periodic replacement of some moving parts (hauling chains, rollers, etc.);
- Underwater maintenance is required;
- The vessels can damage the track.

Vertical Lifts:

A vertical lift is a mechanical means of hoisting a ship out of the water vertically (Figure 4.3.6-1, middle right).

The dock consists of a pplatform, a hoisting mechanism and a hoist support pier.

The platform is lowered into the water until sufficient water over the blocks is achieved. The ship is floated over the platform and centered. The platform is raised, grounding the vessel on the blocks. As the vessel is raised, all motors are synchronized to insure they each haul at the same rate no matter what the load on each of them is. This insures that no unit gets overloaded.

Advantages of a vertical lift are:

- Very fast operating;
- Easy to transfer;
- Can be trimmed to match vessel trim.

Disadvantages of a vertical lift are:

- Very high initial cost;
- High maintenance cost;

- High tech machinery requirements;
- Fixed structure – hard to relocate;
- Hard to dredge under platform.

Marine Travel Lifts:

A marine travel lift is a vertical lift on wheels. Instead of a structurally rigid platform to support the vessel, nylon straps are usually used. The slings are lowered into the water until sufficient water over the slings is achieved. The ship is floated over the slings and centered. The slings are raised to lift the vessel. Once the ship is at yard's elevation, the travel lift can be moved under its own power to place the ship on fixed blocks in a storage berth (Figure 4.3.6-1, down left).

The most popular type of travel lift is the "Marine travel lift" of Sturgeon Bay, Wisconsin. Capacities range from 7 t to 500 t.

The travel lift consists of:

- Structural frame on wheels;
- Wire rope hoists;
- Adjustable slings;
- Support pier.

Advantages of a travel lift are:

- Very fast operating;
- Many berths can utilize one lift;
- Can be trimmed to match vessel trim;
- Wire rope does not go into the water;
- Rubber tires can be driven on relatively rough surfaces;
- Lift can be relocated relatively easily (no support piers);
- Easy to dredge under;
- Machinery can be driven to a storage shed and stored away from the elements

Disadvantages of a travel lift are:

- High initial cost;
- High maintenance cost;
- Low capacity.

4.3.6 TRANSPORT BACK TO SITE

The transportation of equipment/personnel in terms of the procedures as described in section 0 can be considered to be identical because of the requirement of the same type of vessels, equipment, etc.

4.3.7 *RE-CONNECTION AND COMMISSIONING*

Re-connection and commissioning of MRE array devices can be considered as the reverse process of those that are described in section 4.3.3, as well as in the respective installation sections in Section 3.

4.3.8 *QUALITY CONTROL*

As described in section 4.2.6, again all the processes described above should be subject to an intensive revision and detailed analysis of what worked well and what worked not well.

4.3.9 *SUMMARY OF THE KEY LOGISTIC STEPS*

A flow-chart of the sequence of the logistic operations by onshore intervention is depicted in Figure 4.3.9-1. The logistic effort for the procedures described is dependent on the maintenance type (i.e. Inspection/Repair/Replacement). The typical steps of the logistic effort embedded in maintenance activities can be distinguished in the following steps for an on-site intervention:

- O&M evaluation and mobilization including organization of spare parts, crew and vessels;
- Vessel preparation and loading;
- Transportation to site;
- Disconnection of device/sub-system/component;
- Transfer of fault components to port in order to carry out the repair;
- Transfer back to site and re-connection of device/sub-system/component;
- Transfer of crew to port after the Repair/Replacement activities.

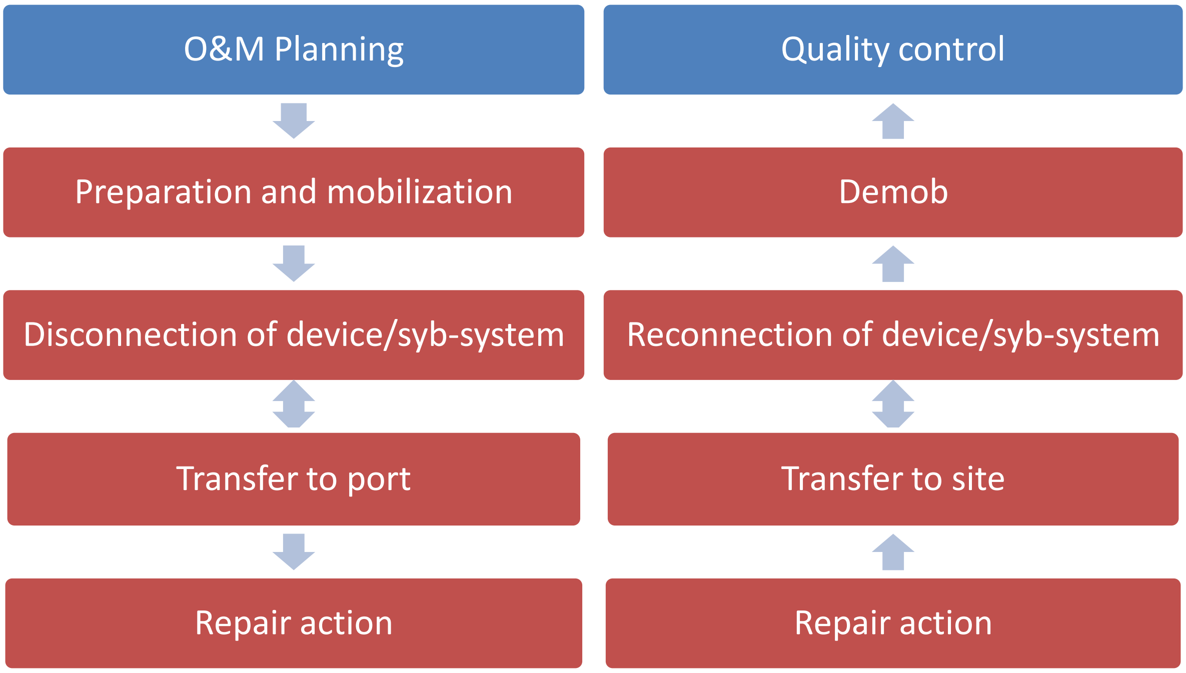


Figure 4.3.9-1: Flow-chart of the sequence of the logistic operations embedded in maintenance activities

The following Table 4.3 defines the parameters of the components and devices influencing the selection of ports and equipment for onshore interventions.

Table 4.3.9-1: Parameters influencing the selection of ports and equipment for onshore interventions

Component / site data type	**Parameter(s)**	**Unit / Format**	**Related infrastructure characteristics**
Onsite personnel (number and skills)	Number and skills	Personnel in number, pre-defined classes of skills (e.g. store manager, crane operator, cargo dispatcher, etc.)	Suitable skills and number of personnel; tugboats localized in port; capacity of storage facilities; capacity and suitability of work shop facilities (assembly halls).
Component(s) / Devices (s)	Weight	Weight in tons	Quayside or mobile crane capacity, surface load of the quayside and of connection roads (bridges); surface area load of workshops / assembly halls
	Dimensions	Dimension in m x m x m	Required area in storage facilities, required height and cantilever arm distance of crane, in/outlet distance of port gate; in/outlet size of assembly halls; required length of the quayside; maneuverability inside the port basins; required size of dry docks; required dimensions of workshops / assembly halls.
	Draft	Draft in m	Minimum water depth with directly at quayside, draft of transport ships.
Environmental conditions	Wave height, wind & current speed and tidal range	Time series (hs, s, m/s) or statistics (if not available) and max for tidal range (m)	Operational limit conditions of the vessels equipment and personnel to be used

As seen over the course of chapter 4, wave and tidal devices may be maintained on site, but generally because of the extreme environmental conditions that predominate at such locations they are more likely to be removed to a maintenance base for planned and breakdown maintenance. If a device is removed from site for maintenance, the mooring spread or gravity foundation may be left on site or also removed temporarily. Devices may be towed to and from site, or transported by vessels or dedicated maintenance barges depending on their design.

Table 4.3.9-2: Interactions of the onshore interventions with other activities

Sequence of the logistic phase	Description of the interactions with other logistic activities
What usually comes before?	Monitoring / Request of O&M operation
What usually comes after?	Plant operation
What can be done simultaneously?	Some O&M activities can be done simultaneously

5 DECOMMISSIONING

In principle, energy companies that operate offshore are obligated to remove all structures, clear the site and verify clearance upon lease termination [28]. All facilities, including foundations, mooring systems, MRE converters, electrical cables and equipment as well as any other obstructions due to the energy plant must be removed. This decommissioning operation is regulated at various levels: local, regional, national and international. Thus, the recovery of the exploited site must respect the legislation notably in terms of timing and environmental impact.

Decommissioning activities for arrays of wave and tidal energy devices may easily appear to be far future considerations since no commercial MRE array has been commissioned yet. One may conceive that new approaches to the decommissioning procedure for wave and tidal farms will spawn as the industry matures. To date, no array of MRE devices has been decommissioned and predicting how this task will be carried out is relatively unreliable. As for the Oil & Gas and offshore wind projects, endpoints for decommissioning are likely to be dictated by the lease instrument.

Each decommissioning project is unique in terms of the requirements of the operation, structure and site characteristics, equipment used, market conditions, contractual terms, time of operation and operator preferences [28]. Furthermore, assuming that the actual lifetime of the first commercial MRE arrays will be around 15-20 years, it can be easily realized how difficult it is to anticipate what the status of the equipment and vessel fleet by the end of this lifetime period will be.

However, when decommissioning programmes for MRE arrays will occur, they are likely to have many similarities to the Oil & Gas and offshore wind industry as well as singular peculiarities.

For wave and tidal arrays one can identify the following major steps toward the completion of the decommissioning phase (a stage under bracket is optional; the description below was adapted from [28], [159]):

- **Project management and engineering:** consists of a review of all contractual obligations and requirements from lease, operation, production, sales, or regulatory agreements. A management plan is constructed based on this review.
- **MRE device removal:** removal of an MRE unit is highly tied in with the type and design of the device. Generally the removal is the reversed operation to the installation method. However, special care regarding safety and structural integrity should be taken. Removal may involve specific disassembly and dismantling techniques such as cutting, unfastening and desoldering.
- **Umbilical and dynamic lines retrieval:** such components are expected to be disconnected and retrieved following the reverse process of their installation/connection method.
- **Foundations/anchors removal:** the removal method highly depends on the type of foundations and anchors. For pile and suction bucket foundations, a combination of dredging, cutting, pumping and lifting offshore operations can be enumerated.
- **(Offshore substation removal):** The offshore substation may stay after the decommissioning of the array. It’s decommission will largely depend on the type of foundation (see previous bullet point).

- **(Export and inter-array cables removal):** as with the substation, it may remain in place after the farm decommission (specially the export cable) while inter-array may remain or be removed probably using similar equipment as for its installation.
- **(Scour protection):** shall remain in place in many cases. Otherwise, mechanical dredging (for rock scour protection) or vessel crane lifting (for mattresses) is necessary.
- **Site clearance and verification:** can be conducted across the entire farm or on MRE device basis. Verification that the decommissioning was performed according to the lease instrument and other regulations is usually undertaken by an independent third-party.
- **Material disposal:** depending on the nature of the material, MRE farm components may be refurbished and reused, scrapped, disposed of in designated landfill or placed offshore as an artificial reef. Steel components can be recycled in many situations. On the opposite concrete structures and especially composites generally require alternative solutions for disposal.

As mentioned above, the electrical infrastructure as well as other seafloor-integrated structures may be left in place when they do not constitute a hazard to navigation, commercial fishing, or unduly interfere with other users.

The type of vessels involved in the decommissioning activities ranges from crane vessels, jack-up and cargo barges, and self-propelled installation vessel to AHVs and CLVs. Additionally, support vessels are assumed to be regionally available. Typically, the removal of MRE units will be carried out using the same vessel as for their installation. Disconnecting and detaching methods for MRE devices will require tailored techniques, though (as exemplified in Section 4.3.3).

In the case of pile foundation, removal of inner mud and internal cutting may be performed from a workboat. For scour protection or extraction of other buried structures, excavation by dredging or jetting may be required to overcome the frictional forces during lifting. Supply or cargo barges are useful for material transport.

The cable removal process involves divers and/or an ROV attaching the cable to a recovery winch. The cable end is retrieved via an engine to drive the cable up onto the recovery vessel. A hydraulic sheer is used to section the cable for storage and transport. Inner-array cables come in relatively short segments and can be recovered in one piece; if export cables are to be recovered in one piece, a large reel would be needed, or the cables can be cut into pieces as they are recovered [28].

Figure 5-1 illustrates the variety of vessels and equipment that can be involved in the decommissioning activities of an MRE array. In the future, one can expect the use of specialized vessels for removing MRE machines, as it shall be the case for their installation.

Figure 5-1: Example of offshore decommissioning activities: wind turbine sliced with cutting torch (top-left), MeyGen tidal turbine (hub+nacelle+blades) removal (top-right), DEME jack-up vessel with dredging capabilities (middle-left), Cable repair ship retrieving

Despite the relative infancy of the MRE sector, forecasting the magnitude of the decommissioning costs has attracted research interests [28], [39], [159]–[161]. The costs to remove each component (devices, mooring & foundations, electrical infrastructure) can be estimated based on expected work durations and vessel day-rates. Once ashore, the material is cut into appropriate sizes and transported to a scrap or disposal site. If the material can be sold, the operation receives income; if the material is disposed of, the operation records a cost. Disposal cost is calculated on a per ton basis.

In total, decommissioning costs for offshore wind farms have been roughly estimated to represent half of the total installation costs and up to 5 % of the capital costs [28].

As for the previous logistic phases, Figure 5-22 presents the summary flow chart of the main logistic operations leading to the decommissioning of an MRE project.

Figure 5-2 Summary flow chart of the key logistic steps occurring during the decommissioning phase of an MRE project

Table 5-1: Key logistic requirements associated with the decommissioning of an MRE project

Component / site data type	Parameter(s)	Unit / Format	Related infrastructure characteristics
Components and sub-assemblies	Number of units	See sections above for each specific component	Port access to receive the material and components
	Dimensions	See sections above for each specific component	Type and characteristics of vessels and equipment to be used
	Weight	See sections above for each specific component	
	Removal requirements	Full removal, partial removal or no-removal	
	Facilities close to port	Material disposal and recycling solutions (yes/no)	
Environmental conditions	Bathymetry	At port/at site	For accessibility and vessel and equipment water depth capabilities
	Wave height, wind & current speed and tidal range	Time series	water depth capabilities Operational limit conditions of vessels and equipment

Table 5-2: Interactions of the decommissioning stage with other major logistic phase over the course of a MRE development project

Sequence of the logistic phase	Description of the interactions with other logistic activities
What usually comes before?	O&M service life
What usually comes after?	none
What can be done simultaneously?	none

As mentioned in D5.1 [1], the DTOcean module on lifecycle logistics will adopt a simple approach for the decommissioning considerations. Following the review of the numerical techniques under development for the offshore wind to account for decommissioning costs, the DTOcean module will feature an algorithm computing an estimate of these costs based on the type of sub-array components, the environmental and physical conditions as well as a reduced number of regulatory variables.

6 CONCLUSIONS

In this document, a detailed review of the lifecycle logistic phases shaping the operational management of an MRE project was carried out. The chief goal of the review was to identify the most critical parameters influencing the selection of vessels, ports and equipment over the course of the lifetime of an MRE project. For this purpose, a systematic 5 steps methodology was applied for the logistic phases having been recognized of utmost importance in D5.1 [1].

Operational experience available from the Oil & Gas industry, the offshore wind sector and from the deployment of the first prototypes and pre-commercial wave and tidal machines has served as the main source of information nourishing this document. Ultimately, this work paves the way for the development of the algorithms for the characterization of logistic requirements that will be implemented in the lifecycle logistics module of the DTOcean suite of design tools.

At this stage, it is worth referring to the LEANWIND (Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments) EU FP7 project. Given the similarities between the offshore wind sector and the MRE sector, in particular in terms of lifecycle logistics, discussions between the LEANWIND and the DTOcean leaders have been initiated towards collaboration and information-sharing. Although not explicitly cited in the present report, the interested reader in offshore wind is warmly encouraged to consult the deliverables available from the LEANWIND project [162]–[165].

In this conclusion we provide an overview table, attached in Appendix A, summarizing the outcome of the report. Tables A.1-1 to A.1-4 are formatted around five columns that aim at compacting the information of the 5 steps methodology into a visually straightforward and friendly fashion.

In complement to Appendix A, an example Gantt chart is included in Appendix B. This Gantt chart sample conveys the inter-relations between logistic phases as examined in the interaction tables (5th step of the methodology) constructed throughout Chapters 3 and 4.

Together, Appendix A and B embody the essence of the content of the present document. These two additions outline and map the key logistic requirements associated with the lifecycle development of an MRE project.

Port facilities are critical for the offshore wind industry because they provide manufacturing facilities, marine vessels, and staging areas to fabricate, assemble, and load-out the blades, nacelles, towers, transition pieces, and foundations necessary for deployment. In the wave and tidal sector, port location relative to manufacturing sites, transportation networks as well as the staging area also determine the transport costs of components. In addition to the port features, an armada of vessels and specialized equipment bring an extra level of logistics and planning which is necessary when dealing with MRE farms.

This document has described that offshore work is equipment and labour intensive and costly. The amount of time and costs for performing certain activity offshore is significantly larger than the same activities done onshore, so planning plays a crucial role for minimizing time, costs and risks.

Throughout this report, several innovative projects striving to market the next generations of supporting logistic equipment tailored for the MRE sector were pointed out. For instance, the HF 4 vessel by MojoMaritme Ltd [104] or innovative connecting solutions as proposed by MacArtney [48] advocate that the future is likely to bear advanced and specialized techniques and maritime infrastructure that could significantly simplify the inherent complexity of offshore logistics, and hence, reduce their considerable costs.

This deliverable 5.2 will serve as the basis of work for the subsequent database of ports, vessels and equipment (Deliverable 5.3) and for the development of the lifecycle logistics functions (Deliverable 5.4) that will form the WP 5 module of the DTOcean suite of tools. The numerous relevant types of vessels and equipment along with their characteristics and the port features identified in this document shall feed the design process of the envelope of the database of maritime infrastructure.

Before programming the lifecycle logistics functions (Deliverable 5.4), an intermediate step will consist of translating the review of each logistic phase presented in this document into a decision-making tree.

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APPENDICES

APPENDIX A: SUMMARY TABLES

This appendix provides a set of four summary tables which attempt to bring together the most pertinent information analysed over the course of the present report. One table per subtask, as initially depicted in section 1.2, is included in this appendix to facilitate the reading. Below, a short explanation of the content under each column is given:

- Column 1 specifies the logistic phase under consideration. This column frames the size of each row.
- Column 2 restitutes the logistic operation breakdown as proposed for each logistic phase in the present report.
- Column 3 lists the key physical parameters influencing the selection of feasible ports, vessels and equipment.
- Column 4 indicates the corresponding characteristics of ports, vessels and equipment that should be verified in association with the array physical parameters of column 3.
- Column 5 is a preliminary list of the vessels most commonly involved in the execution of the corresponding logistic phase.
- Column 6 is a preliminary list of port features and equipment relevant to the execution of the corresponding logistic phase.

In the end, these tables aim to articulate the main findings of the above review in a friendly format.

Table A.1-1: Summary table of the key logistic requirements associated with the assembly and installation of the electrical infrastructure of an MRE project

Logistic phase	Logistic operation		Array physical parameters	Maritime infrastructure characteristics	Vessel types required	Key port features & equipment required
Static subsea cable	• Surveying pre-installation • Loading and preparing the vessel • Trenching the seafloor • Laying the cable • Cable landing • Protecting the cable • Surveying post-installation		Length of the cable	Size of the turntable	• Cable laying vessel (CLV) • Barge • Tug boats • Survey vessel	• Water jetting • Plough • Turntable/Reel • Coil tanks • Drum rails • Guiding arm • Linear cable engine • Tensioners • Subsea monitoring & handling equipment • Vessel DP system
			Weight of the cable	Deck loading of the vessel		
			Seabed conditions	Type of trenching, monitoring and protecting equipment		
			Bathymetry			
			Wave height, wind & current speed and tidal range	Operational limit conditions of the vessels and equipment to be used		
Dynamic offshore cable: (a) Surface-to-subsea (b) Subsea-to-surface	(a) • Prepare vessel and equipment load • Guide wire Connection • Cable installation • Wet-mate connection • Inspection and testing • Return connection equipment to vessel	(b) • Prepare vessel and equipment load • J-tube entrance inspection • Guide wire connection • Cable lay • Cable pull • Cable termination • Inspection and testing	Number of units	Deck space and size of winch system	• Cable laying vessel (CLV) • Workboat • Anchor Handling Vessel (AHV) • Barge • Tug boats	• Vessel DP system Plough • Guiding arm • Reel • Linear cable engine • Winches & Tensioners • Port lifting equipment • Vessel lifting equipment • Subsea monitoring & handling equipment
			Length			
			Weight	Deck loading of the CLV and lifting equipment		
			Minimum bending radius of cable	Type of winch system and cable handling equipment		
			Type of umbilical configuration (free hanging / Lazy / Lazy-s)	Affects number of components and thus deck area, loading and equipment		
			Installation strategy	Type and size of lifting equipment		
			Type of connector (Wet-mate / Dry-mate)	See offshore connection section		
			Wave height, wind & current speed and tidal range	Operational condition limits of the vessels equipment and personnel to be used		

Logistic phase	Logistic operation		Array physical parameters	Maritime infrastructure characteristics	Vessel types required	Key port features & equipment required
Offshore substation: (a) Top-side fixed platform (b) Seabed mounted	(a) • Foundation: - Surveying pre-installation - Loading and preparing the vessel - Foundation installation - Post installation activities • Top-side module: - Loading and preparing the vessel - Topside installation - Post installation activities	(b) • Prepare vessel and equipment load • Seabed preparation • Subsea unit installation • Subsea unit protection • Surveying post-installation	Foundation (a) / Support structure (b): Type	Sufficient deck space, large enough crane/A-frame/lifting equipment for loading and operations (vessel and port) for load, deck area, seafastening…	• Anchor Handling Vessel (AHV) • Jack-up vessel • Heavy lift vessel • Barge • Supply vessel	• Port storage facility • Port lifting equipment • Vessel lifting equipment • Drilling/hammering equipment
			Foundation (a) / Support structure (b): Number of units and subcomponents			
			Foundation (a) / Support structure (b): Weight & Dimensions			
			Subsea Substation (b) / Topside Module (a): Weight & Dimensions			
			Transportation location and method			
			Bathymetry	Type of subsea equipment/personnel		
			Wave height, wind & current speed and tidal range	Operational condition limits of the vessels equipment and personnel to be used		
Offshore electrical connections: (a) Dry-mate (b) Wet-mate	(a) • Prepare vessel and equipment load • Component protection removal • Connector lifting • Connection • Connector redeployment • Visual and electrical testing • Component protection	(b) • Prepare vessel and equipment load • Deploy connection equipment • Subsea connection • Visual and electrical testing • Surveying post-installation	Connector: Type (dry-mate, wet-mate)	Type of lifting and/or subsea equipment/personnel to connect cable	• Anchor Handling Vessel (AHV) • Multi-Purpose Vessel (MPV) • Supply vessel	• Port lifting equipment • Vessel lifting equipment • Wet-mate ROV tool • Subsea monitoring & handling equipment
			Connector: Number of units	Sufficient deck space, large enough crane/A-frame/lifting equipment for loading and operations		
			Connector: Dimensions			
			Connector: Weight	Deck loading of the vessel, crane/A-frame/lifting equipment		
			Static cable (see static cable section)	Requirements to connect connector to static cable (and umbilical) cable, cable protection to be removed, or re(applied), etc.		
			Type of soil	Type of vessel and equipment to be used for trenching, monitoring and protecting the cable		
			Bathymetry	Type of subsea equipment/personnel		
			Wave height, wind & current speed and tidal range	Operational condition limits of the vessels equipment and personnel to be used		

Table A.1-2: Summary table of the key logistic requirements associated with the assembly and installation of the moorings and foundations of an MRE project

Logistic phase	Logistic operation		Physical parameters	Maritime infrastructure characteristics	Vessel types required	Key port features & equipment required
Moorings	• Survey and determination of mooring location • Vessel preparation and loading • Installation of mooring lines and anchors • Pre-tensioning mooring lines and anchors • Pre-lay moorings or buoy off • Hooking up of MRE device		Number of anchors	Type and size of vessel, Vessel deck area & loading Vessel bollard pull Crane capabilities Winch capabilities Sea-fastening capabilities	• Anchor Handling Vessel (AHV) • Tug boats • Survey vessel	• Port storage facility • Port lifting capabilities • Water jetting or propeller/vibro-driven unit • Tensioners • Vessel DP system • Vessel winch • Working class ROV
			Size of anchors			
			Weight of anchors			
			Anchor installation load			
			Anchor penetration depth			
			Seabed conditions	Winch capabilities Type of subsea handling and monitoring equipment		
			Bathymetry			
			Met-ocean conditions	Operational condition limits of vessel and equipment		
Foundations	(a) Pile foundation • Vessel preparation and loading • Prepare seafloor and drilling equipment • Seafloor penetration • Foundation positioning • Surveying post-installation	(b) Gravity based foundation • Vessel preparation and loading • Prepare seafloor • Lower sub-structure to seafloor • Positioning of foundation over sub-structure • Surveying post-installation	Number of foundations	Quay loading capacity Type of vessel Vessel deck area & loading Vessel bollard pull Drilling capabilities Cranes capabilities Winches capabilities HC system capabilities	• Survey vessel • Jack-up vessel • Barge • Tug boats • Construction vessel	• Port storage facility • Port lifting capabilities • Maximum quay loading • Drilling/hammering or vibro-piling equipment • Vessel DP system • Vessel HC system • Vessel cranes • Water jetting
			Size of foundations			
			Weight of foundations			
			Pile foundation driving force (a)			
			Maximum foundation lowering rate			
			Seabed conditions	Vessel leg capabilities Type of subsea and handling equipment		
			Bathymetry			
			Met-ocean conditions	Operational condition limits of vessel and equipment		

Table A.1-3: Summary table of the key logistic requirements associated with the assembly and installation of the MRE devices

Logistic phase	Logistic operation	Physical parameters	Maritime infrastructure characteristics	Vessel types required (*)	Port features & equipment required (*)
Installation of Wave & Tidal Devices	• Port Infrastructure assessment • Assembly at port • Load out and transportation to site • Positioning and connection to moorings/foundations • Commissioning	Number of devices	Deck area (if transported on deck), storage at port, berths, etc., number of vessels	• Anchor Handling Vessel (AHV) • Multi-purpose vessel (MPV) • Barge • Tug boats	• Port storage facility • Port lifting equipment • Port berth & dry-dock • Vessel towing gear • Cranes & winches • Vessel DP & HC systems • Subsea handling & monitoring equipment
		Device dimensions			
		Mass of device	Lifting capacity at port and/or vessel, vessel propulsion		
		Array spacing	Vessel type and size		
		Umbilical characteristics	See umbilical section		
		Mooring system characteristics	See mooring section		
		Installation strategy (towing / on-deck)	Deck area, lifting capacity, bollard pull, etc.		
		Bathymetry	Type of subsea equipment/personnel		
		Wave height, wind & current speed and tidal range	Operational limit conditions of the vessels and equipment to be used		

Table A.1-4: Summary table of the key logistic requirements associated with the operation and maintenance activities over the course of a MRE project service life

Logistic phase	Logistic operation	Physical parameters	Maritime infrastructure characteristics	Vessel types required	Key port features & equipment required
Monitoring	• Installation/use of monitoring equipment • Data acquisition • Data processing • Request for O&M intervention	Number of monitoring equipment	Type of vessel Class of ROVs	• Survey vessel • Accommodation vessel	• Wave and strain gauges • Met-ocean data buoys • ADCP • ROVs/AUVs/divers • Transmission and communication system: SCADA/satellites • Control room
		Size of monitoring equipment			
		Weight of monitoring equipment			
		Location of use of monitoring equipment	Type of vessel and handling equipment for monitoring		
		Fixed or temporary monitoring equipment			
		Size of control room	Area availability onshore		
		Bathymetry	Operational condition limits of the monitoring equipment		
		Met-ocean conditions			
On-site O&M interventions	• O&M evaluation and mobilization • Vessel preparation and loading • Transportation to site • Access on-site location • Action on-site • Quality control	Number of parts	Type of vessel	• Personnel Transfer Vessel (PTV) • Anchor Handling Vessel (AHV) • Tug boat • Accommodation vessel • Barge • Workboat	• Repair toolbox • Vessel DP system • Vessel winch • Vessel crane • Subsea handling and monitoring equipment
		Size of parts	Vessel deck area and loading		
		Weight of parts			
		Crew size			
		Water depth of intervention	Operational limit conditions of vessel and equipment		
		Met-ocean conditions			
Onshore O&M interventions	• O&M evaluation and mobilization • Vessel preparation and loading • Transportation to site • Disconnection/detachment of device/component • Transfer to port • Action at port • Transfer back to site • Re-commissioning • Quality control	Number of parts	Port storage area Quay area and loading	• Personnel Transfer Vessel (PTV) • Anchor Handling Vessel (AHV) • Accommodation vessel • Barge • Heavy maintenance vessel • Multi-purpose vessel (MPV) • Tug boat	• Port storage facility • Port repairing facility • Dry-dock • Port cranes • Vessel DP system • Vessel winch • Vessel crane • Subsea handling and monitoring equipment
		Size of parts			
		Weight of parts			
		Size of device/component to be retrieved	Port berth and dry-dock capabilities Type of vessel Deck area and loading Vessel bollard pull Cranes capabilities Winches capabilities Quay area and loading Subsea handling and monitoring equipment capabilities		
		Weight of device/component to be retrieved			
		Type of connections system and disconnection strategy			
		Crew size			
		Bathymetry	Operational condition limits of vessel and equipment		
		Water depth of intervention			
		Met-ocean conditions			

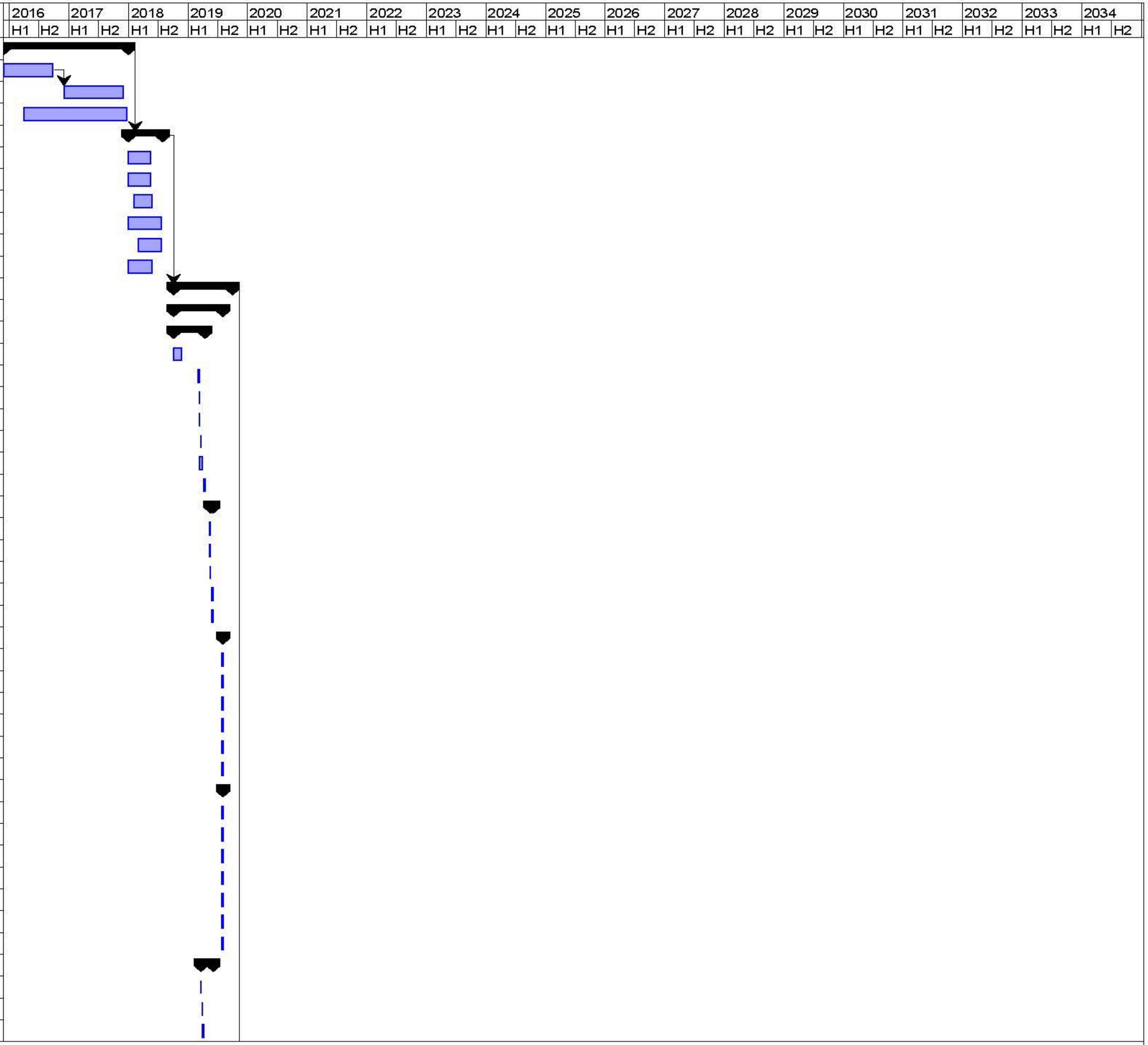
APPENDIX B: GANTT CHART

This appendix contains an example Gantt chart to illustrate how the different logistic phases, as reviewed throughout the present report, can interact. It is clear that such Gantt chart is very project specific and, hence, the one below only reflects one particular scenario.

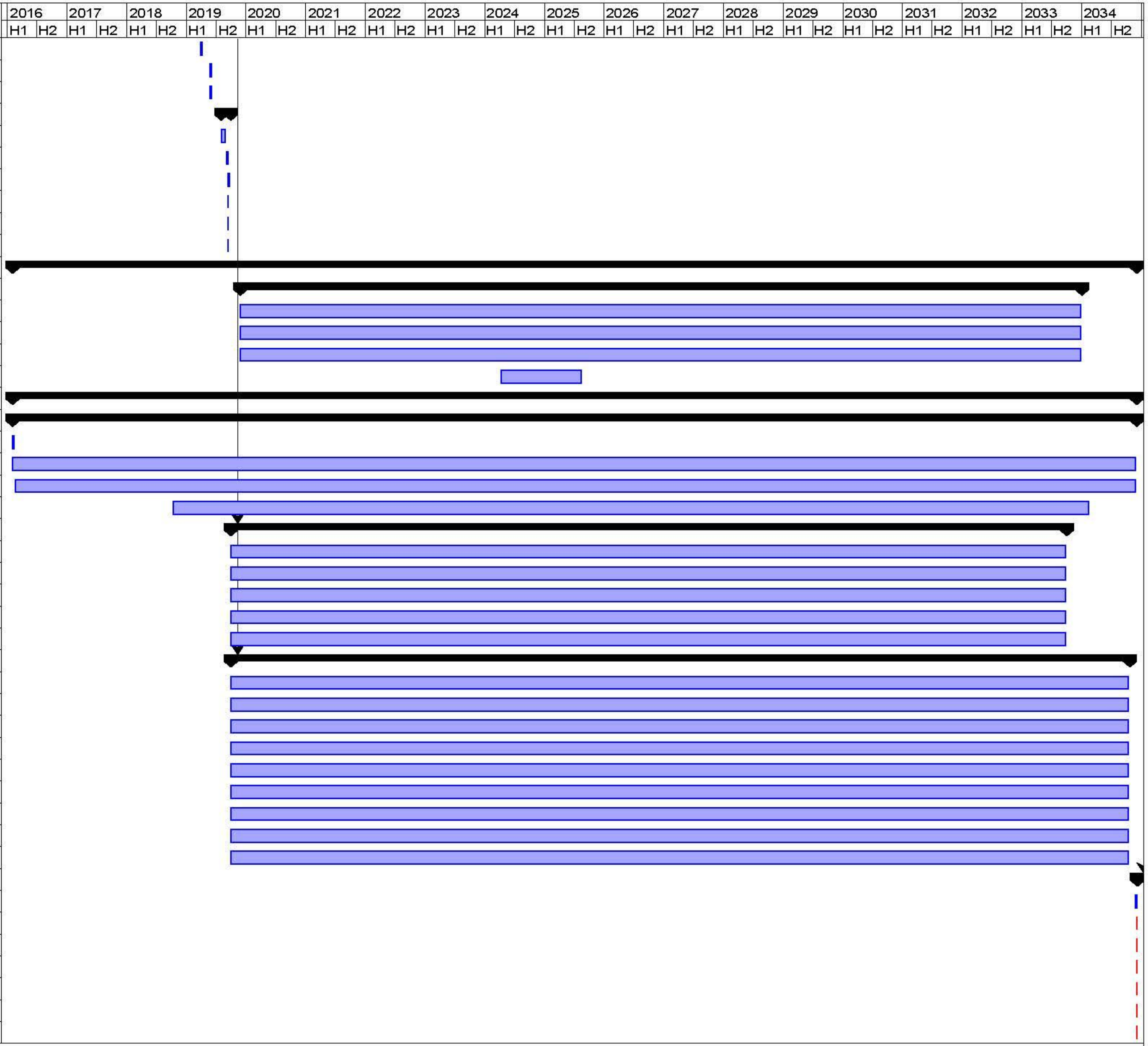
For this reason, we have considered one fictional scenario which can be defined as follows:

- 5 floating MRE devices
- Site where environmental and physical conditions are favourable for installation and commissioning activities
- Vessels and equipment for installation are readily available
- Grid connection is made through the use of a subsea mounted offshore substation
- Dry-mate connections are selected for the device-umbilical interfacing
- 3 drag-embedment anchors and catenary system configuration for each machine
- Operational lifetime is 15 years
- Mixed maintenance strategy including: regular onsite inspections, mid-life REFIT and condition monitoring with preventive replacement on one hand, and corrective actions in response of failures with a systematic onshore repair intervention mechanism.

	Name
1	**Planning & design**
2	Surveying
3	Permitting
4	Design and engineering work
46	**Procurement & manufacturing**
6	Steel manufacturing
7	Concrete manufacturing
8	omposite manufacturing
9	Other majorc component manufacturing
10	OEM procurement
11	Maritime infrastructure procurement
12	**Assembly & installation**
13	**Electrical infrastruture**
14	**Export and inter-array cables**
15	Survey and cable routing
16	Vessel prepartion and loading
17	Trenching of the seafloor
18	Laying of the cables
19	Cable landing
20	Protecting the cables
21	Post-installation survey
22	**Subsea mounted offshore substation**
23	Vessel preparation and loading
24	Seafloor preparation
25	Subsea unit installation
26	Subsea unit protection
27	Survey post-installation
28	**Umbilicals**
29	Vessel preparation and loading
30	J-tube entrance inspection
31	Guide wire connection
32	Laying and pulling the cable
33	Cable termination
34	Inspection and testing
35	**Dry-mate connections**
36	Vessel preparation and loading
37	Component protection removal
38	Connector lifting
39	Connection
40	Connector redeployment
41	Visual and electrical testing
42	Connector protection
43	**Moorings**
44	Vessel preparation and loading
45	Transportation to site
46	Anchor seafloor penetration



MRE project Gantt Chart - page1



	Name
47	Mooring lines deployment and tensioning
48	Post-anchor installation
49	Installation of other mooring system components
50	**Floating MRE devices**
51	Assembly at port
52	Vessel preparation
53	Device load out and transportation to site
54	Assembly at site
55	Device positioning and connection to moorings
56	Commissioning
57	**Operation & Maintenance**
58	**Calendar based maintenance**
59	Inspection of electrical infrastructure 1
60	Inspection of mooring system 1
61	Inspection of MRE devices 1
62	Mid-life REFIT
63	**Condition based maintenance**
64	**Monitoring**
65	Installation of continuous monitoring equipmen
66	Use of temporary monitoring equipment
67	Data acquisition and processing
68	Request for O&M intervention
69	**Preventive onsite replacement of parts**
70	Vessel preparation and loading
71	Transfer of personnel
72	Access to location
73	Replacement
74	Quality control
75	**Corrective onshore maintenance**
76	O&M evaluation and mobilization
77	Vessel preparation and loading
78	Transportation to site
79	Disconnection
80	Transfer to port
81	Repair action at port
82	Transfer back to site
83	Re-commissioning
84	Quality control
85	**Decommissioning**
86	Planning
87	Removal of floating MRE devices
88	Umbilicals and mooring lines retrieval
89	Anchors removal
90	Subsea mounted substation removal
91	Export and inter-array cable removal
92	Site clearance and verification

MRE project Gantt Chart - page2