Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments

Project acronym: **LEANWIND**
Grant agreement nº 614020
Collaborative project
Start date: 01st December 2013
Duration: 4 years

WP Framework/ Industry Challenges Report- supply chain and logistics
Work Package 5 - Deliverable number 5.1

Lead Beneficiary: EWEA
Due date: 30th June 2014
Delivery date: 7th July 2014
Dissemination level: PU

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No. 614020.

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Document Information

Version	Date	Description			
V0		Table of content with partners responsibilities			
		Name	**Prepared by**	**Reviewed by**	**Approved by**
			Ivan Pineda		
V1	14/05/14	Sections: 3.2.1, 3.2.2, 3.2.3, 3.3, 4.1.2,4.3,4.4			
V2	15/05/14	3.2.1	Federico D'Amico	Ivan Pineda	
V3	16/05/14	4.2.3	Dylan Jones	Ivan Pineda	
V4				Ivan Pineda	
V5	23/05/14	3.2.2, 4.2.1, 4.2.2	Elin E. Halvorsen-Weare	Ivan Pineda	
	27/06/14	3.2.1	Jan Goormachtigh & Hans Schroyen & Jeroen De Neve	Ivan Pineda	
V6	29/05/14	**4.5, 4.6**	Elena Reig	Ivan Pineda	
V7	06/006/14		Ivan Pineda	Ivan Pineda	
V8	13/06/14		Ivan Pineda	Jan Arthur Norbeck Paul Doherty Jesper Tang Kristensen	
V9	03/07/14		Manuela Conconi, Elin E. Halvorsen-	Jan Arthur Norbeck, UCC	Jan Arthur Norbeck, UCC

			Weare, Mar Rodriguez, Elena Reig Amoros		

Author(s) information (alphabetical):	
Name	**Organisation**
Manuela Conconi	EWEA
Giorgio Corbetta	EWEA
Federico D'Amico	UHULL
Jan Goormachtig	OWA
Rachelle Hajjar	EWEA
Elin E. Halvorsen-Weare	MARINTEK
Jacopo Moccia	EWEA
Inge Norstad	MARINTEK
Ivan Pineda	EWEA
Agathe Rialland	MARINTEK
Elena Reig	ACCIONA
Mar Rodriguez	Kaleido Logistics

Acknowledgements/Contribution	
Name	**Organisation**
Offshore Wind Industry Group	(EWEA)
Paul Doherty	GDG
Jesper Tang Kristensen	A2SEA

Definitions

CTV	Crew Transfer Vessel
O&M	Operation and Maintenance
MPV	Multi-Purpose Vessel
LCOE	Levelised Cost of Energy
GBF	Gravity Based Foundation
DP vessels	Dynamic Positioning Vessels
TLP	Tension Leg Platform
ROV	Remote Operated Vehicle
TTR	Time to Repair
OEM	Original Equipment Manufacturer
IMO	International Maritime Organisation
SES	Surface Effect Ship
US-CTV	Ultra Stable Crew Transfer Vessel
TAS	Turbine Access System
OHVS	Off Highway Vehicles
TTR	Time to Repair
PTV	Personnel Transfer Vessel

Support by:

Executive Summary

This report aims to provide a broad overview of the state of art of logistics in the offshore wind industry. In particular, it will give a detailed review of the current methods and transport techniques used, from a project life-cycle perspective.

The three phases of a project life-cycle are analysed: installation, operation and maintenance (O&M) and decommissioning.
The overreaching need for the offshore wind industry is to achieve cost reductions across the board in its supply chain. The sector is optimistic about the prospects of cost reductions in both, the medium and long term. In the near term, it is believed that pressures in the market will drive standardisation and some immediate need of logistics optimisation. These two factors are believed to drive future cost reductions especially in installation and construction phases. Operating costs derived from O&M activities are foreseen to decrease as well but more in the longer term.

a. Installation

The installation process of an offshore wind farm is highly dependent on the type of substructure chosen. The report provides a summary of installation activities with a strong focus on the foundation types. The following different technologies are taken into account. For each of them the main features, advantages, disadvantages and logistics needs are analysed:

- Monopiles
- Gravity Based Foundations
- Jacket foundations
- Tripods
- Tripiles
- New foundations concepts: Suction bucket and floating foundations

The reports looks briefly also into cabling activities (general onshore activities and laying down ones), without entering into specific details.

b. Operation and Maintenance

During the O&M phase of an offshore wind farm, the logistic system supports the maintenance activities that are needed to reduce the downtime of the system and thus increase the production from the wind turbines. The report presents a summary of features and main characteristics of both infrastructures.

A brief review on models, tools and software for logistics is also presented. Models for offshore wind farms that look at the logistic systems can be divided into two main groups:

- Decision support models that consider main parts of the logistic system;
- Operational models that consider more short-term and day-to-day logistic operations and strategies.

This analysis highlighted that tools considering the logistic system for offshore wind farms seem to be scarce.

c. Decommissioning

Similar resources needed for installation are then needed for decommissioning. Decommissioning logistics also depends to great extent on the foundation selection. The decommissioning procedures will be completely different according to the type of support structure used, the water depth and soil conditions. Currently, the lack of experience in decommissioning offshore wind installations increases the risk that developers are unable to provide a fair valuation of decommissioning costs.

The report also performed a mapping of existing infrastructure for the offshore sector and identifies major bottlenecks to the deployment of the offshore sector. Moreover, an overview of the current offshore wind industry is provided: 69 online offshore wind farms in 11 European countries, 2,080 turbines installed and grid connected in European waters, making up 6,562 MW.

The scale of growth of the industry is not the only driver of the logistic challenges. As offshore wind market moves forward, new opportunities appear which present some technical challenges to be faced. The trends for the upcoming years are oriented towards the construction of larger wind farms in terms of capacity. This may require turbines with greater rated capacity (associated with an increase of mass and dimensions of the components) and moving the installation sites further offshore, implying greater distances to shore, as well as increasing water depths.

Vessels and equipment challenges will be driven by present and future developments but also by present gaps. Therefore, optimization for present conditions and components, together with adaptation and upgrading to meet the requirements of new farm sites, components concepts, and dimensions must be considered. The report includes a review of the main challenges for the different types of installation vessels covering:

- Self-propelled vessels and towed Jack up vessels
- Heavy lift vessels
- Vessels equipment
- Transfer vessels
- New concepts and specialised vessels

The report provides a short summary of equipment used in inbound logistics and their associated challenges, identifying lack of standardisation of handling procedures as the biggest challenge to overcome. Moreover, it provides a future outlook from the whole logistic perspective on what is needed to adapt across the entire project life cycle.

A list of topics identified as possible cost-reduction measures has been provided by the industry and presented in the report in section 3.3.

A section dealing with uncertainties and constraints is included in the report. Many challenges are well known; however, there is room for unexpected ones that pushes costs and risk throughout the entire logistics. A detailed explanation of each component uncertainty is given with some gaps of knowledge already identified.
Finally new logistics and solutions for further offshore wind farms are provided through a graphical and analytical method considering LEAN principles, especially focused on foundation and wind turbine installation logistics.

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1. Introduction and background

The offshore wind industry is under governmental and financial pressure to become cost competitive with the conventional fossil fuel industry and reduce the need for subsidised energy prices. Today's logistics activities are often based on manual planning or quite simple models. Plans to build a large number of offshore wind farms have created a need for decision support in the planning process to choose the most cost-efficient alternatives.
It is expected that in-short term, improved logistics infrastructure for installing wind farms reduce costs. However, in the long run, the application of larger turbines and the improvement of efficient manufacturing and installation processes determine the trends.
The whole WP5 is dedicated to Integrated Logistics, and in particular it has targeted key areas where innovations will have a positive impact on the LCOE and has set out the tasks to achieve these cost savings. In this context, this report defines the design constraints and functional requirements related to optimising logistics over the life cycle of the wind farm.

The report:

- Identifies the challenges and opportunities in the field of logistics and supply chain interaction;
- Identifies the interactions between project schedule and logistics and the differing contracting strategies;
- Provides concrete recommendations for the future, focusing on optimization of the logistics strategies.

1.1 Project description

The primary LEANWIND objective is to provide cost reductions across the offshore wind farm lifecycle and supply chain through the application of lean principles and the development of state of the art technologies and tools.

The LEANWIND approach will ensure that unnecessarily complex or wasteful stages of the development process are removed, flow between the required stages is streamlined, quality is enhanced and thus overall cost and time efficiency improved to enable the industry to bridge the gap between current costs and industry cost aspirations. Properly applied, lean management will improve quality, reliability and H&S standards across the project supply chain and throughout the wind farm lifecycle.

Task 5.1, which this report refers to, aims at determining the key industry challenges and constraints necessary for optimising offshore wind farm logistics. The final cost of energy produced by off-shore wind farms can be reduced by rendering the whole logistics system more efficient throughout the wind farm supply chain lifecycle – from installation and O&M to the decommissioning phase. The use of lean principles will help in defining the key industry challenges, analysing the separate parts composing the offshore wind supply chain – such as on-land transport and ports- and optimising them.

1.2 Scope of work

This report examines and defines industry constraints and specifics that will have impact on logistics optimisation over the various stages in the life cycle of a wind farm. This will be achieved, among others, through the use of lean tools such as value chain mapping. It summarises the work performed by the following sub-tasks:

- Task 5.1.1: Identifying key industry challenges and opportunities through direct contact with relevant stakeholders and a targeted questionnaire. The findings will be validated through a workshop with key industry players.
- Task 5.1.2: Mapping all the elements of the logistics chain and describing the state of play in detail.

This report uses as an input the results from tasks 2.1, 3.1 and 4.1.

2. State-of-the-art

2.1 Role of the logistics in the offshore wind industry

Logistics aims to ensure efficient installation, Operation and Maintenance (O&M) and decommissioning of an offshore wind farm. Logistics are fundamental in planning and managing the offshore wind farm. It is necessary to adequately coordinate seabed ground conditions with cables and tower design and installation as well as to take into account access for maintenance in the design and manufacture of support structures.Numerous actors are involved in the planning of a logistics including the asset owner, logistics service providers, the power producer, manufacturers, shipping companies, port operators, banks and insurance companies. Logistics is an important competitive factor for the offshore wind industry; logistic expenses have a significant impact since they represent a share of up to 20% of wind farm total cost [1]. Current challenges in offshore wind logistics include facilitating the large scale deployment of wind turbines with growing capacity, further offshore in deeper waters. There is a significant potential for cost reductions in logistic expenses if interfaces are better organised, practised and if support structure manufacturers are involved early in the project.

Progress towards more efficient logistics and transport is essential for large scale deployment of larger turbines. Technology innovation in wind turbines has the potential to reduce the levelised cost of offshore wind by 25% for wind farms with financial investment decision in 2020, mainly due to the increase in average turbine size from 4MW to 6MW. Fewer turbines for a given wind farm rated power would allow significant savings in foundations, installation and operation and maintenance services. Increases in supply chain efficiency combined with technology acceleration are the main drivers for LCOE reductions by 2020 [2].

With the increase in turbine size, there will be also increasing pressure on vessel operators to provide sufficient capacity to meet market needs [3]. This pressure has been focused so far on a small group of leading contractors since only a few number of specialised installation vessels are in operation in European waters. Their capabilities are mainly adapted to turbines of less than 5 MW but vessels owned by A2SEA, MPI, Bard, HGO/GeoSea and Hochtief are currently capable of dealing with larger turbines and their foundations [4].

Constraints on the availability and capacity of vessels are an important issue for the supply chain and demand an increased competition in the market. New players are expected to offer different installation solutions, specialised vessels and crews in order to increase efficiency and to bring additional skills into the industry. As new entrants take part in the offshore logistics market, it is expected that increased choice will drive competitiveness and reduce installation costs by 5% by 2020.

Greater level of competition will also put pressure on the pool of skilled labour available. The industry believes that there is a significant scope for savings through information and asset sharing. Horizontal collaboration such as information and asset sharing, could lead to an additional 4% reduction in total installation costs by 2020.

2.2 Review of current methods, transport techniques used in the entire lifecycle

The work undertaken in the initial deliverables of LEANWIND project, D2.1, D3.1 and D4.1, provided a general overview of the way offshore wind farms are currently being installed and methods that have been developed so far. This section summarises the main aspects of the different stage of a project life-cycle. Please refer to the complete deliverables for further details.

2.2.1 Installation

a. Substructures

The installation process of an offshore wind farm is highly dependent on the type of substructure chosen. A summary of the key features, challenges and constraints of each foundation type is provided in this section. Please refer to D2.1 for challenges in design and construction and to D3.1 for the required improvements in equipment and vessels.

Monopiles

Design

Monopiles are the most common offshore wind support structure. Its design consists of a cylindrical foundation pile driven into the sea bed that provides lateral restraint to resist environmental loads by mobilising horizontal earth pressures in the near surface soils.

Features

Diameter: 4-6m with a transition piece of a larger diameter overlapping 10-12 m.

Monopiles are driven 20-30 m into the seabed at a water depth of 30-35 m. Due to the recent trends in increasing turbine size and weight, extra-large monopiles (diameter above 7.5-8m) are required.

Water depth: Monopile substructures are ideally suited to sites with water depths between 10m and 25m[1], but can be used up to around 35m of water depth[2].

Weight: A monopile typically weighs around 500 tonnes, making it one of the lightest support structures.

Construction and installation approach

Monopiles present some limitations in terms of water depth. Depending on the sea bed conditions, there are basically two ways for the foundation pile to be installed:

- If the seabed presents a rocky structure, pile installation may require prior drilling.
- Otherwise, the foundation pile can be driven and placed firmly in the seabed with the use of a vibrating hammer or a hydro hammer. In some cases, such as Barrow offshore wind farm, a combination of drilling and driving needs to be employed.

Advantages	Disadvantages
Simple and quick fabrication process	Limitations of fabrication and handling from certain sizes
Proven concept	Limitations due to heavy installation equipment (hammers)
No seabed preparation required	Large scour protection required
Low price per ton of steel	Flexible at water depths

[1] Seidel 2014

[2] Baltic 2 Monopile installation

High serial production	Limited to large water depth
Quick installation process	Noise level generated during installation
	Difficult to remove after design life

Table 1. Advantages and disadvantages of monopoles [5]

Transportation of monopiles

There are several options for transporting a monopile from the fabrication yard or marshalling harbor to the construction site. This choice depends on the installation equipment used, sailing distances and the infrastructure available at the port.

- Floating: the monopile (MP) is plugged on both sides with a hydraulic plug, so the MP stays afloat when put in the water. The MP is towed to the construction site by tugs. This method is only possible when the distance between fabrication yard/marshalling harbor is limited. Also some on shore space is required to prepare the MP for towing. Upon arrival at the construction site, the MP is upended and both plugs are removed.

Figure 1- Monopile floating transportation. Source: Dong Energy

- As cargo on the installation ship: when a big installation vessel is used or if the MPs are not too big, the MPs can be transported on board the installation vessel. This methodology requires an upending frame on board the vessel.

Figure 2 - Cargo transportation of monopiles. Source: Seaway heavy lifting from http://guide.offshorewind.biz/profiles/view/seaway_heavy_lifting

- With barge/offshore supply vessel: this method requires a very calm sea-state to transfer the piles from the supply vessel to the installation vessel.

Figure 3 - Monopile transportation on a barge/vessel. Source: Jumbo Shipping from www.maritimejournal.com

Gravity Based Foundations (GBFs)

Design approach:

Gravity bases are support structures which resist loads by their self-weight and ballast. GBFs rely on a low center of gravity combined with a large base to resist overturning. The base structures are made of steel reinforced concrete on which the tower is placed.

Features:

Water depth: to date, concrete GBFs have been installed mainly in shallow water (7 – 27 m)

Weight: Rodsand 2, is comprised of 90 structures weighting from 1,200 to 1,800t each excluding the ballast Thorton Bank I, included 6 GBFs weighing from 2,000 to 3,000 tonnes.

Construction and installation approach:

Generally, structures are transported on a barge to the location site. In other cases, the support structure is floated and towed to the installation site. This latter possibility produces an important reduction of costs. Some developers envisage auxiliary buoyancy GBF design which require special transport vessel for buoyancy support. This concept helps to reduce concrete volume. To date, these two concepts are not yet being used and small scale tests are scheduled.

Advantages	Disadvantages
Reduced fatigue sensitivity compared to other concepts	Limitations of transportation and installation due to the high weight
Low environmental impact due to the absence of piling during the installation	High production cost
No transition piece installation	Challenging and complex logistical requirements
Low levels of corrosion protection	Require seabed preparation (dredging, levelling) and scour protection
Fully removable (decommissioning)	Large "footprint" (environmental impact when installed)
Possibility to be internally J-tubed	Not suitable on soft seabed surfaces
The structure can be floated	Requires special operations on deep waters
Long lifetime	Difficult to handle above 50m water depth as size and weight increase
	Large port infrastructure (30-50 Ha for production of 50-80 GBS/year) required for construction site (storage area, quay capacity and bearing, water depth…)
	Requires a lot of harbour space
	Installation procedure requires intervention of large vessels, subject to weather risks

Table 2: Advantages and disadvantages of GBS. [5]

Jackets

Design approach

A jacket is a structure made up of three or four legs connected by slender braces. All the elements are tubular and they are joined by welding. Each of the joints has to be specially fabricated, taking a lot of time to complete the whole structure. To date, the wind farms that have been fully completed relying on jacket structures are all based on the OWEC Quattropod© design, proposed by the Norwegian company OWEC Tower.

Like monopiles, jackets need a transition piece to support the wind turbine tower. Melting the transition piece with the jacket substructure becomes one of the key activities during the jacket manufacturing.

Features of a jacket:

To date, only 5 offshore wind farms fully completed have used Jacket structures: Beatrice Demonstrator (2006 – UK; 2 units at 20-45m water depth), Alpha Ventus (2009 – Germany; 6 units), Ormonde (2011-12 – UK; 30 units) and Thornton bank II & III (2010-2013 – Belgium; 48 units).

Construction and installation approach:

Once the substructure is fully assembled, it is transported on a barge to the installation site where it meets with the installation vessel. There are two procedures when it comes to installation of a jacket: pre-pilling and post-pilling.

Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopoles	Large number of joints required compared to other latticed structures
Large variations in water depth can be covered through cantilevering piles or modifying the geometry	Logistical issues due to the templates (pre-piling case)
No scour protection required	Complex connection to transition pieces
Structural redundancy	High manufacturing lead-times
Low soil dependency	No standardized design that leads to long certification processes
Good response to wave loads. Little sensitivity to large waves and limited dynamic amplifications of loads due to high stiffness	
Limited storage area compared to GBF	
Faster fabrication compared to GBFs (serial production)	
Better quality control	
Easy decommissioning	

Table 3: Advantages and disadvantages of jackets [5] [6]

Tripod

Design approach:

A tripod is a standard three leg structure made of cylindrical steel tubes. These legs are connected to the main tubular, in the centre of the structure, making the transition to the wind turbine tower. The substructure is driven into the seabed using foundation piles through sleeves at the end of each leg. For deep water installations, the tripod foundation adapts the monopile design by expanding its footprint.

Features of a tripod:

Water depth: Alpha Ventus site (42 m depth)

Weight: Borkum West II Phase 1 wind park 40 wind turbines will be installed on tripods of approximately 700 tonnes of weight each. In Global Tech I wind park 80 tripods of 900 ton weight will be installed [7].

Construction and installation approach:

The tripod support structures are pre-assembled in a construction yard. The standard installation procedure is to load several tripods onto a barge and tow them to the offshore location site where the support structures are lifted by a crane and guided to the final position. It does not require any seabed preparation [5]. The support structure is slowly lowered onto the seabed, ensuring that the structure is entirely levelled.

Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopoles	Limitations of transportation due to the width
No seabed preparation required	Limitations of storage due to large

	sizes
No scour protection required	Slow fabrication process
Possibility to be internally J-tubed	Impractical in shallow waters
Easy to remove after design life	Main join susceptible to fatigue
	Difficulties for mass production

Table 4: Advantages and disadvantages of tripods. [5]

Tripile

Design approach:

A tripile is a structure formed by three individual tubular steel piles and a three-legged transition piece placed on top connecting with the turbine tower. The transition piece is welded from flat steel elements and weighs around 490 tonnes. The joints between the piles and the transition piece are grouted permanently. The tripile foundation is also a relatively new adaption of the traditional monopile foundation. Instead of a single beam, three piles are driven into the seabed, and are connected just above the water's surface to a transition piece using grouted joints.

Features:

The German wind turbine manufacturer Bard Engineering GmbH developed this unique patented Tripile design which was first tested in 2008 for the Hooksiel Offshore Wind Farm developed by Bard (one 5MW Bard turbine). Then these Bard Tripiles, weighting approximately 1.100 tonnes [3] were manufactured at a larger scale for the Bard Offshore I farm (80 Bard 5MW turbines).

Construction and installation approach:

During the installation the piles are first driven into the seabed. Afterwards, with the top of the piles rising above the water, the transition piece is placed on top, with each leg-end aimed into a pile.

One challenge during installation is to position the three piles accurately. With the assistance of a seabed template and the Global Positioning System, the piles are hammered down one by one. Afterwards, the tops of the piles rise above the sea, allowing subsequent operations to be performed above water. This contrasts with monopiles, where a large part of the transition piece is below the mean sea level.

Advantages	Disadvantages
No bolted or welded connection between piles and transition pieces	Complexity of transition piece manufacturing
Easily adjustable to water depths	Complexity of transition piece installation
Loads transferred by the grout alone	Only one test facility to date
Compact construction relatively cost-effective	Difficulty for mass production
All connections above the water surface	
Less dependency on weather conditions	

Table 5: Advantages and disadvantages of tripiles. [5]

Suction bucket

Design approach:

[3] http://www.lorc.dk/offshore-wind-farms-map/bard-offshore-1

Suction bucket is a large diameter cylinder, with a closed cap, resembling a gravity base foundation in shape and size. Once installed the bucket, vacuum pressure is removed. This type of structure has been used to assist levelling of a traditional GBF or as a support for a jacket or tripod structure. [D2.1]

Features:
Diameter: from 2 to 4m in diameter for water depths less than 5m, and up to 12 to 15m in deeper waters.
Weight: A prototype monopod suction bucket at the Aalborg University offshore test facility in Frederikshavn: approximately 150 tonnes. Second prototype in Wilhelmshaven, Germany, 450 tonnes.

Construction and installation approach:
The installation method and the load transfer mechanisms are different from the gravity base substructures. Suction bucket is placed on the sea-bed and a pump is activated subsequently to remove water from within its hollow section. This creates suction underneath the cap and drives the bucket into the sea-bed. Once the pressure is removed, the wall friction keeps the bucket in place. Suction buckets provide the possibility of integrating the transition piece, and hence the need for grouting the transition piece once the foundation is installed [D2.1].

Advantages	Disadvantages
Faster installation process with no dependency on jack-up vessels, no seabed preparation, no diving need	Since installation is reliant on the pressure difference a minimum water depth is required
Capability to accommodate a broad range of site conditions, loadings and operational performance requirements	Installation proved in limited range of materials. [8]
No pile driving eliminating the associated environmental concerns regarding noise and avoiding 'no pile driving' periods in the year	More expensive construction. [8]
Easy to remove by reversing the installation process	Installation and life time use is very site specific
Possibility of integrating the transition piece eliminating the need for a grouted connection	Complex equipment for pumping
Reduced or no need for scour protection	Time for pumping and checking of leveling
The foundation weighs less than traditional foundation structures	
Manufacturing easiness (less steel and more simple welded joint)	

Table 6 - Advantages and disadvantages of suction buckets [9] [5]

Floating structures

Design approach:
Floating support structures have appeared in the offshore wind market as a consequence of the tendency within this industry to move into deeper waters.
At the moment, three main types of floating foundations, can be identified:

- Spar buoyance monopile: Cylindrical hull submerged with a tank providing buoyancy and ballast in the lower part to lower the centre of gravity in order to reach stability (weight induced stability). Moored by catenaries [D2.1].
- Semi-submersible platform: Platform formed by 3 or 4 columns connected by bracings. The upper hull provides buoyancy and the lower ballast hull provides stability. Anchoring system: catenary/taut.
- Tension leg platform (TLP): Similar to semi-submersible but attached to seabed with tensioned anchors (metal or synthetic). It is formed by three or six legs interconnected horizontally and submerged.

Construction and installation approach:

- Spar: A possibility of installation of the spar floater is the one chosen for the Hywind Demo project, which was divided into several stages. During the first stage the support structure was towed horizontally from the coast. Secondly, the foundation was straightened up by pumping water to an end of the structure. Once the foundation was in a vertical position, more water was added to sink the foundation. Consequently, and with the help of a big barge used to reduce the differential motion from the tower, a crane lifted up the tower, the turbine and blades. Therefore all the different parts were assembled. Finally, three anchors were dropped out to sea and the turbine was connected to the cable line. [5]
- Semi-submersible platform: The demo project that develops this kind of foundation is *WindFloat.* Semi-submersible platforms can be assembled onshore, contributing to limit expensive offshore installation and maintenance procedures. Fabrication, installation, and commissioning of the floating support structure should be in line with other current fixed installations methods for deeper water sites. [5]
- Tension leg platform (TLP): The demo project Blue H started testing a prototype located off the coast. [5] The complete platform and turbine can be towed to the site, and then connected to the preinstalled tendons, but buoyancy elements are required. Major maintenance activities will be done onshore, by using the additional buoyancy elements. [D2.1]

Advantages	Disadvantages
Inexpensive manufacturing	High mooring and platform costs
Less sensitive to water depth	Excludes fishing, recreation and navigation from most areas of the farm
Lower sensitivity to wave loads	Increase in design complexity
Access to superior wind resources further offshore.	Lack of mass production
Ability to reduce visual effect	Little experience
Ability to locate further offshore	Complex major component replacement on-site
Simplified offshore installation procedures	

Table 7 Advantages and disadvantages of floating structures. [5]

b. Turbine installation

Turbines are installed after foundations and transition piece are in place. There are various options for turbine installation, depending on the number of lifts required (from 6 to 1 lift). Generally, turbines are delivered at port in seven key components: 3 blades, 2 tower sections, the nacelle and the hub. Some degree of quayside assembly is performed to reduce the number of offshore lifts and the degree of pre-assembly impacts vessel selection and installation time.
The turbine is then taken to the site in its main components and then it is erected on top of the foundation substructure using a jack-up vessel (barge or self-propelled) and/or crane barge.

For the turbine installation, the following vessels are the most commonly used and the pros and cons are set out as follows:

- Jack-up barge:
  - Limited storage capacity,
  - Sufficient lifting power and height,
  - Slow, hauler needed,
  - Less susceptible to waves.
- Jack-up crane vessel (self-propelled):
  - Large storage capacity,
  - Sufficient lifting power and height,
  - Fast, flexible and independent,
  - Less susceptible to waves.
- Heavy-lift crane vessel:
  - Very limited storage capacity,
  - Strong lifting power, low height,
  - Slow, hauler needed,
  - Susceptible to waves.

c. Cable installation

Cables are laid using the reel-lay method; cable is made up onshore and spooled onto a reel or carrousel on the lay vessel. On the installation site, the cable is progressively unwound, straightened and paid out in a J-curve through the vessel moon pool or over the stern and down to the seabed.

During cable installation, trenching and burial are the most costly and time consuming activities requiring a dedicated marine spread. There are several methodologies used, mainly depending on the soil characteristics:

- Pre-trenching: a trench is dredged/dragged prior to the cable laying. The cable is laid inside the trench and covered with material (fall-pipe vessel or similar)
- Post-trenching: the cable is laid onto the seabed. After cable laying, a trenching ROV is burying the cable. This is only possible in sandy areas, where the soil can be liquefied.

The timescale for inter-array cable installation depends on the number of turbines and layout, the seabed characteristics, the depth of burial, and scour protection requirements. Inter-array cables are generally transported and installed in lengths approximately equal to the distance between turbines (usually, less than 800 m), while export cables are at least as long as the distance to shore (3 to 60 km).

2.2.2 Operation and Maintenance

Activities in the O&M phase

The role of the logistic system in the O&M phase is to support maintenance activities that are needed to reduce the downtime of the system and this increases the production from the wind turbines. These activities can be divided into the following two types:

- Preventive maintenance – maintenance activities carried out to avoid component failures and hence reduce the downtime. These types of activities can be scheduled, condition based, or opportunity based.
- Corrective maintenance – maintenance activities executed due to unforeseen failures to system or components. These include both planned and unplanned activities, i.e. activities executed as failure is expected in near future, or executed after an unexpected failure.

Table 8 contains a list of some maintenance activities that may be necessary to execute at an offshore wind farm and the resources they demand from the logistic system. Some activities only require service engineers and thus the necessary resource will be personnel transfer vessel. Other activities will require several expensive resources that may not be available on short notice.

Activity type	Description	Resources needed
Preventive, scheduled	Routine inspection and change of consumables (filters, grease etc.) at wind turbine	Total about 100kg in spares and service engineers, personnel transfer boat
Preventive, scheduled	Change of gear oil, bolt torqueing at wind turbine	Gear oil and service engineers, personnel transfer vessel
Corrective, unplanned	Turbine blade failure	Crane at hub height, service engineers, crane vessel
Corrective, unplanned	Generator failure at wind turbine	Crane at hub height, service engineers, crane vessel
Corrective, unplanned	Gear box failure at wind turbine	Crane at hub height, service engineers, crane vessel
Corrective, unplanned	Transformer failure at wind turbine	Crane at hub height, service engineers, crane vessel
Corrective, unplanned	Main bearing failure at wind turbine	Crane at hub height, service engineers, crane vessel
Preventive, scheduled	Inspection of sub-sea structure, anodes etc.	Diving/ROV vessel, service engineers, personnel transfer vessel
Preventive, scheduled	Inspection of cable/j-tube/scouring protection etc.	Diving/ROV vessel, service engineers, personnel transfer vessel
Preventive, scheduled	Visual inspection of transforming stations (transformers, HVAC, fire, reactors onshore, breakers/relays, cranes etc.)	Service engineers, personnel transfer vessel
Preventive, scheduled	Functional inspection and test of transforming stations (transformers, HVAC, fire, reactors onshore, breakers/relays, cranes etc.)	Service engineers, personnel transfer vessel

Table 8: Maintenance activities and logistic needs that an offshore wind farm may face, Source: FAROFF project, MARINTEK, 2014

The cost of executing a maintenance activity consists of several main components, illustrated in Figure 4. Cost of spare parts includes all costs of spare parts and equipment (grease etc.) needed for the activity. Personnel cost include wages, social costs, overheads and all other relevant costs associated with the necessary personnel. Transportation cost are all cost involved with transportation of spare parts and personnel to the offshore wind farm site. Also on land transportation and any port cost are included. Downtime costs are the lost profit due to wind turbines not being operational, either due to failure, or due to shut-down while a maintenance activity is being executed.

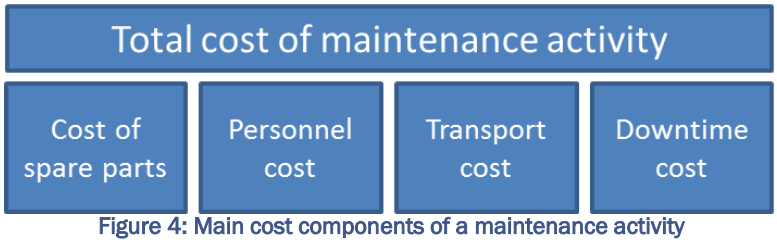

Figure 4: Main cost components of a maintenance activity

The transportation cost and downtime cost can vary to a great extent depending on the maintenance activity type, distance from the maintenance base to the offshore wind farm and the weather conditions at the offshore wind farm site.

The time to repair (TTR) is defined as the time it takes from a failure occur at the wind farm until it has been repaired and the system is again up and running [10]. It is illustrated in Figure 5. *Time in logistics* is the time it takes to retrieve the necessary resources: Spare parts, means of transportation, necessary personnel. Then, *wait for weather* involves waiting for suitable weather condition for travelling from the maintenance base to the wind farm and the execution of the maintenance activity. *Travel time* is the transfer time from maintenance base to the offshore wind farm. Finally, the *repair time* represent the time to execute the maintenance activity.

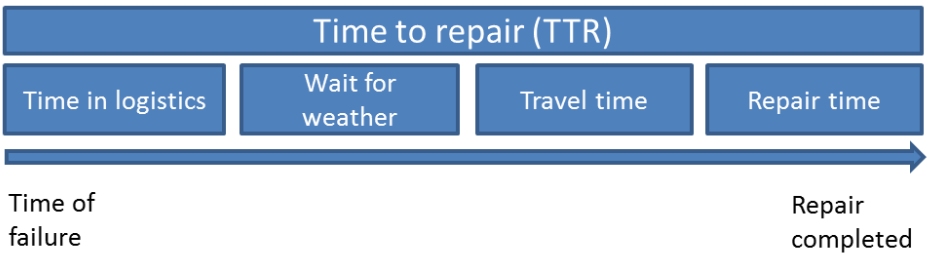

Figure 5: Time to repair, figure loosely based on [10]

TTR will be the total downtime for a corrective maintenance activity involving a failure resulting in a wind turbine shut-down. For a preventive maintenance activity, downtime cost will normally be limited to the shut-down of the wind turbines when activities are being executed.

Logistic system

The role of the logistic system in the O&M phase is to support the different maintenance activities described above. Figure 6 gives an overview of the O&M activities and the logistic system for offshore wind farms.

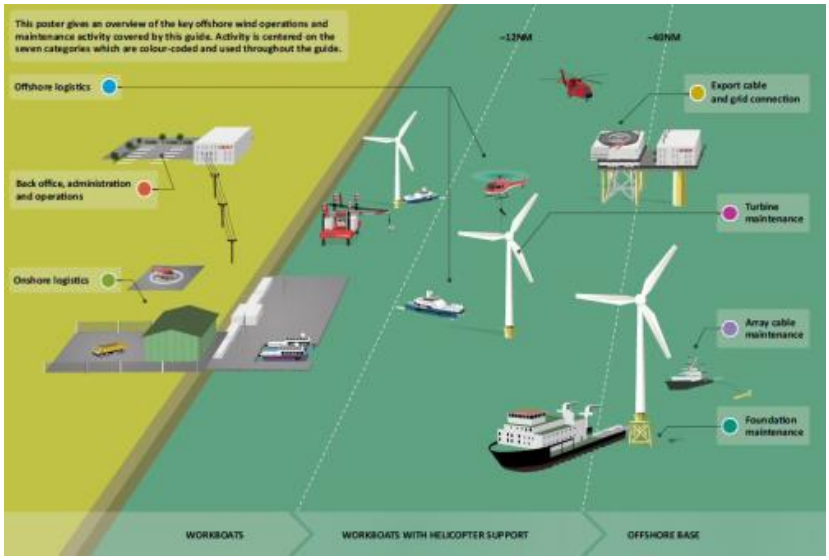

Figure 6: Overview of the O&M activities and logistic system for offshore wind farms. [11]

The following aspects have been identified as critical for the support organization (i.e. logistic system) for offshore wind farms [12]:

- Location of maintenance accommodation
- Number and type of personnel transfer vessels
- Use of helicopters
- Work shift organization
- Number of maintenance teams per work shift
- Spare part stock management
- Technical support
- Buy or contract of crane vessel

Operation and maintenance (O&M) costs account for 25 to 30% of the life cycle cost of an offshore wind farm project [11] [13]. Similarly, up to 25% of wind farms costs are related to logistics activities [13]. Offshore logistics are the most costly part; however, onshore and inbound logistics are critical activities for ensuring efficient and effective execution of maintenance activities, both preventive and corrective. Since time is an important cost factor for offshore logistics, proximity between the port and the wind farm, for shortest possible transfer of service personnel and equipment, is a key factor. Regarding replacement of parts, infrastructure to support the inbound transport, handling and storage of equipment is more critical, but also the proximity to the component factories [11].

<u>Onshore logistics</u>

Onshore logistics include *port-side activity*, *warehousing* [11] and *transportation to port*.

O&M ports: Roles and properties

Port operations for O&M include the deployment of crew transfer vessels (CTVs) and multi-purpose vessels (MPVs) to wind farms and providing spare parts, tools and components for maintenance and replacement [14].

Port infrastructure that is adapted to the specific needs of the wind farm and that is responsive in any situation is crucial for limiting logistics costs. Given the high costs of operations at sea, but also the risk and uncertainty related to environment conditions, it is important to retain as much activity onshore as possible [8]. During O&M, the onshore service park must ensure availability and quick loading of spare parts, as well as 24/7 transfer of personnel and equipment (work-boat based or heli-support).

There are two main types of O&M ports [14]:

- *Quick reaction ports* are used for spontaneous and short term maintenance operations. They have the following properties:
    - Offshore wind farm reachable in 2 hours 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 hours' work allowance for personnel
    - Bunkering capabilities
    - Storage area of 2,000 m² minimum for tools, small spare parts and components
    - Nearby indoor storage facilities and office space of about 500 m² and maximum loads of 5 t/m²
    - Appropriate accommodation and shelter for 15 to 20 personnel with supply of water and electricity
    - Good connection to the public road network
- *Supply ports* with the aim of providing remote quick reaction ports with necessary operating resources. They are used for preventive maintenance activities and have the following properties:
    - Quay of 80 to 100 m, suitable for docking of CTVs and MPVs
    - Berth depth of at least 3.5 m
    - Permanent, tide independent access is not necessary due to planned transport
    - 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
    - Storage area of at least 2,000 m² and indoor storage facilities of at least 500 m² for tools, medium spare parts and components and general operating resources
    - Personnel (mechanical and electrical technicians), office- and social facilities
    - Local workshop facilities
    - Good connection the public road- and possibly rail network
    - Short distances to airports or helicopter landing pads
    - Nearby accommodation possibilities for service personnel

Availability of local component suppliers is of advantage.

Business case: Port of Oostende

Port of Oostende provides a good example of port facilities dedicated to Offshore Wind, including facilities for assembly, storage, offices, and direct access to open sea, as illustrated in the map in Figure 7.

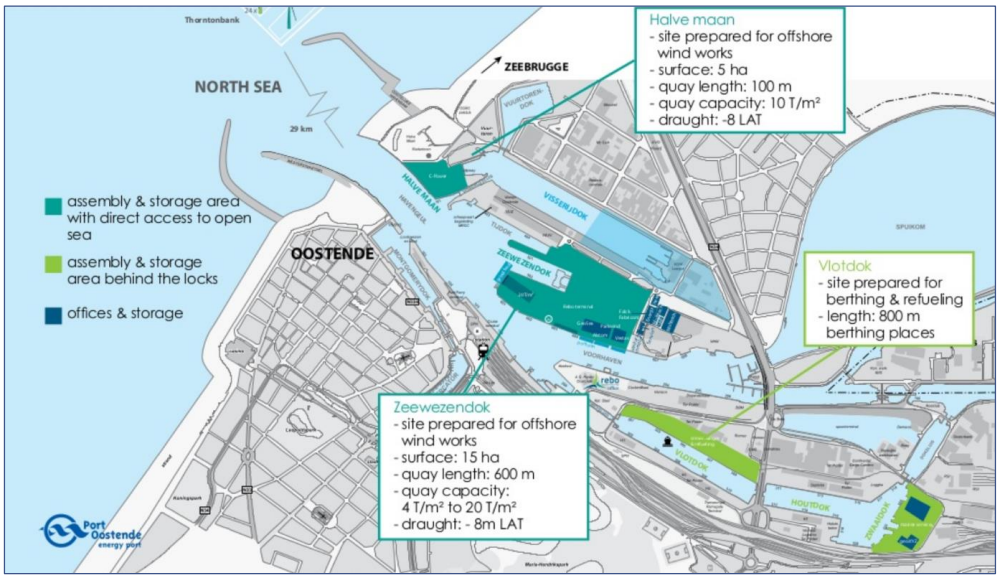

Figure 7: Port of Oostende [15]

Quay infrastructure and support services for offshore wind at the port of Oostende include the following:

- One heliport for helicopter transfer
- For service vessels: 3 pontoons and 2 fixed cranes, servicing about 3000 movements every year
- For O&M management activities: a maritime rescue and coordination center (MRRC) and an online booking system for pontoons (Ensor)

To allow close proximity to its network of suppliers, the port is expanding its infrastructure for offering office, warehousing and workshop facilities [15].

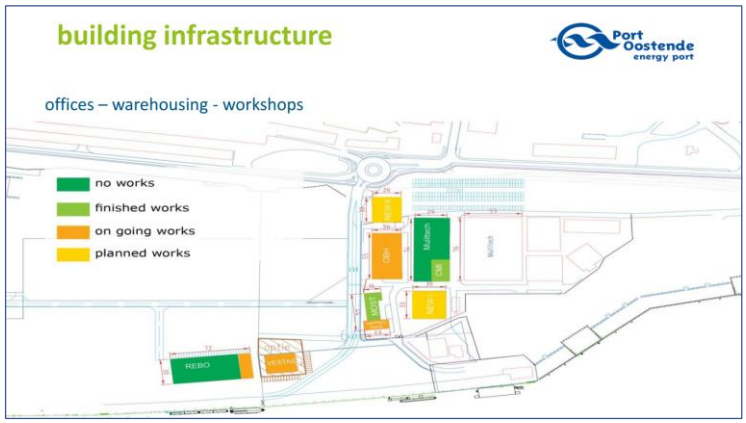

Figure 8: Building infrastructure in Port of Oostende [16]

Spare parts

Spare parts (repairable and consumable) are used to replace defective or worn out parts [17], and their availability and easy access is vital for efficient service operations [18]. Spare parts for offshore wind turbines are complex and expensive; hence spare part logistics is mainly characterized by high procurement costs and low inventory levels [17].

Planning maintenance activities is one of the most complex task of O&M, mainly due to high uncertainty related to the need and timing of the maintenance activity (weather condition and sea state affecting the risk of operation failure) [17]. In [17] a *spare parts planning model* is proposed, showing how restrictive factors influence O&M costs.

Wind turbines are equipped with advanced and complex systems and contain items delivered by distinct suppliers that require special skills and tools to repair. For maintenance and repair, these items can either be returned to the manufacturer, or stored on site at some large warehouses. Such use of multiple localizations of spare parts is called a *multi-echelon system* [18], as illustrated in Figure 9.

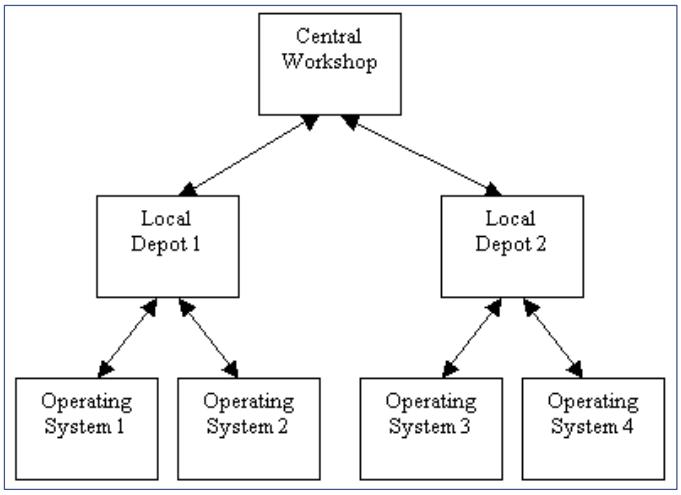

Figure 9: Multi-echelon system [18]

There are various strategies for spare part logistics [14]:

- *Pooling* or spare part pool: using a common stock for a number of sites, adequate when different operators have similar systems and spare parts. Pooling implies huge administration costs, and is therefore best suited for expensive items.
- *Mix of local and common depot*, using the latter for more expensive parts.
- *Consignment stocks*. Common during the first years of operation. The stock is owned by the supplier and provided when needed. This minimizes risks related to storage and transportation, but also limits the operator' freedom of action.

<u>Offshore logistics</u>

Offshore logistics for O&M consist of the transportation of personnel and spare parts from an onshore base to the offshore wind turbines.

The vessel types used for the O&M phase of an offshore wind farm are the following:

- <u>Crew transfer vessels</u> (also referred to as Personnel transfer vessels (PTVs), service crew vessels or offshore service craft). These vessels are designed to transport maintenance personnel comfortably between port and wind turbine. Typically, they are 15 – 25 meters, equipped with storage areas, small cranes and a transfer capacity of 12 people.
- <u>Jack-up vessels / barges</u> are used when major components need to be replaced. A jack-up vessel is a type of self-elevating platform capable of raising the hull above sea surface. The current generation of jack-ups is ship shaped self-propelled vessels with a

large working deck, storage space, DP technology and accommodation. Jack-ups designed for installation are normally too big and expensive for maintenance purposes.

- Specialized O&M vessels. As many offshore wind installations are placed further offshore, a key issue to overcome is to identify new and smarter concepts for vessels to support O&M activities. Offshore maintenance activities may include substantial repair work and turbine overhaul, both of which require larger, more capable vessels than CTVs. On the other hand, jack-ups (designed for installation) are too expensive for use in an O&M setting. The trend is therefore to design new vessels, tailor-made for the O&M phase of offshore wind farms.

A critical phase when transporting maintenance personnel is the safe and effective transfer of people between the vessel and the wind turbine. Today, there are two methods for transfer, where one of them still does not work as expected:

- Bump-and-jump is when the vessel pushes against the turbine with the force of the engines while maintenance personnel steps over from the vessel to a ladder on the turbine. Large waves make this transfer difficult and current vessels are limited to sea conditions of up to a maximum of 2 m significant wave heights.
- Motion compensating system is when the vessel is equipped with a damping system (either passive or active) that reduces the vessel motion, and hence allows for transferring people even when the significant wave heights are more than 2 m. The disadvantage of motion compensating systems (compared with bump-and-jump) is the large weight and the increased deck space requirement. Today's version of this system does not work as intended.

Models, tools and software for logistic operations in the O&M phase

Developing and maintaining a cost-effective logistic system is essential to reduce the O&M costs of an offshore wind farm, and cost-effectiveness in the O&M phase is an important factor for the offshore wind industry to be competitive.

Models for offshore wind farms that consider the logistic systems can be divided into two main groups: Decision support models that consider main parts of the logistic system, and operational models that consider more short-term and day-to-day logistic operations and strategies.

A review of decision support models for offshore wind farms is given in [19]. The review has a special emphasis on O&M strategies, and presents a total of 49 models. Most of these are simulation models, while some also includes optimization algorithms to part of the modelled system. Since the review in [19] was conducted, a number of new decision support models have been proposed. Two of these are presented in [13] and [20]. Some decision support models have been developed into commercially available software for actors in the offshore wind industry, some are in-house tools, and some are developed within research institutions primarily for research purposes and may be used to a limited extent by the offshore wind industry.

Most of the existing decision support models for the O&M phase analyze the cost of a given logistic system. Part of the system can be changed to see the cost effects, i.e. changing the number and type of vessels available for use. There has also been work on optimization models that analyses part of the logistic system, and where output will also consist of the cost-optimal

elements in the logistic system. For instance [20] proposes an optimization model that provides an optimal vessel fleet size-and-mix for an offshore wind farm.

Specialized short-term operational models for logistic operations seem to be limited for the offshore wind industry, although there are general tools and software for spare-part management. A recent academic contribution is [21] which propose a logistic model for managing the inventory of spare parts for O&M in the offshore wind industry.

There has been some academic work on the routing of vessels for maintenance operations, but models for this seem not to be applied in the offshore wind industry as of today.

In the models and tools listed above, the logistic operations and system is either a part of a larger system/analysis, or it is a smaller part of the logistic system that is modelled. Tools that mainly consider the logistic system for offshore wind farms seem to be scarce. One exemption is [22], a simulation tool for offshore logistics diagnostics, currently tested during the construction of an offshore wind farm, but that can also be used in the O&M phase.

2.2.3 Decommissioning

The design of an offshore wind farm is undertaken considering a design life time. However, some decisions should be made regarding the asset at the end of this life time. The first decision is whether to extending the life of the installation, or reusing the infrastructure in a beneficial way, which will often be preferred. However, when none of these solutions are possible a decommissioning programme should be carried out [23].

There are international obligations surrounding offshore decommissioning. In particular, decommissioning is takein into account by the United Nations Convention on the Law of the Sea[4] and by the OSPAR Commission[5].

Lack of experience in decommissioning offshore renewable installations increases the risk that developers are unable to provide a fair valuation of decommissioning costs. [24]

a. Superstructure decommissioning

The superstructure decommissioning process comprises removal of turbine components including blades, nacelle, tower and containerised transformer. It is assumed to be a reversal of the installation process, and will be the subject to the same constraints. [25]

[4] Article 60 of the United Nations Convention on the Law of the Sea. In this connection, the IMO adopted in 1989 "Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone". [57] The IMO standards specify the different solutions for disused installations or structures: leaving it in place or partially removing, entirely removing or reuse at existing location. Decisions will be made on a case-by-case basis, considering aspects such as costs, risk to personnel, risk to the marine environment, and safety of navigation and other uses of the sea.

[5] The OSPAR Commission adopted in 1998 a legally binding regulation for the disposal of disused offshore oil and gas installations (OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations [57]

Dismantling of the turbines will probably require a jack-up to ensure adequate control and to support the high lifts and high crane loads, especially if any turbine components are to be preserved in relatively good condition [25].

Decommissioning must be undertaken in a controlled manner so that safety will not be compromised in any of the decommissioning procedures. The level of care in this phase may not be necessary as the required during installation. [25]

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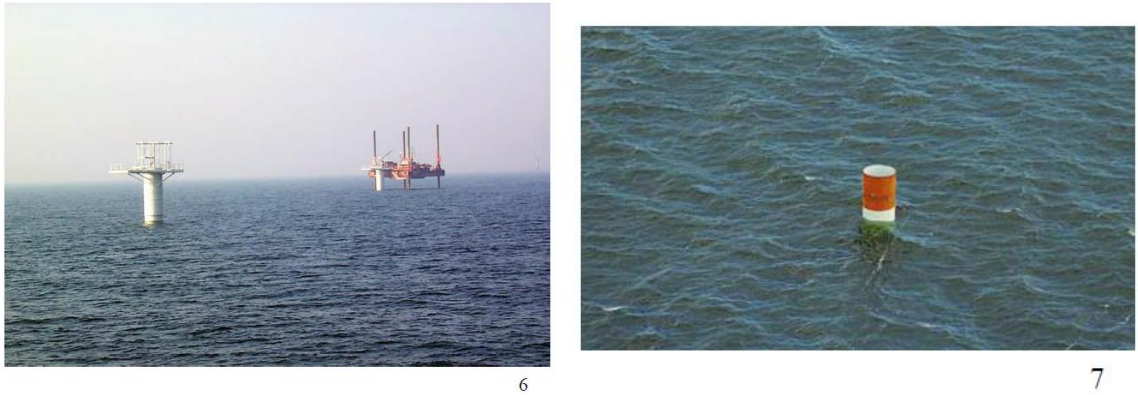

6 7

Figure 10: Decommissioning process [25]

b. Foundation decommissioning

The decommissioning procedures will be completely different according to the type of support structure used and also depending of the water depth and soil conditions. Suction buckets foundations could have advantages for decommissioning. [24]

GBF

According to IMO standards, installations or structures weighing more than 4000 tonnes in air (excluding any deck and superstructure) or standing in more than 100 m of water depth could be left wholly or partially in place without causing unjustifiable interference with other uses of the sea [23].

When the structure is to be removed, the most suitable procedure for GBF decommissioning would be refloating the structure. In some cases, a Heavy Lift Vessel would be required. After refloating, the platform bases could be towed inshore for further demolition and the demolition material transported for eventual disposal on land. [25]

Some uncertainties and constraints found in GBF decommissioning are [25]:

- Expensive heavy lift crane required even if filled with air.
- Unknown scour and build up could distort initial lift calculations due to considerable additional forces required to break suction under the bases.
- Possible solutions could be engineered into this however, would result in extra cost.
- Towing costs once refloated
- Disposal of concrete – Unlikely to have re-sale value, sinking of foundations in conflict with consenting.

Once refloated, demolition, fragmentation, crushing, disposal and recycling should all be possible in principle, though such extensive demolition work on offshore structures has never been attempted before. [26]

Steel structures

Monopiles and jacket piles can be decommissioned by cutting the piles using jet cutting technique or mechanical cutter:

- Underwater gas/oxygen torches: cutting is performed using a hydraulic operated internal pile cutting and lifting tool. A pile cutter robot will be lowered into the jacket pile or the monopile to cut it at any preferred depth.
- By means of an abrasive water jet. The internal jet should be connected to a containerized ultra-high pressure pump and lowered into the jacket pile or monopile. The frame of the cutting tool has the capacity to lift the pile on the deck.

Salvaged steel of approximately 18m could be relatively easy to handle with potentially high scrap value [25]. It is unlikely that the pile is pulled out entirely considering the overwhelming forces attaching it to the seabed. [25]

c. Other infrastructure decommissioning

Other infrastructure elements in an offshore wind farm to be considered identified for the decommissioning are:

- Scour protection: Decommissioning of scour protection will involve removal either by lifting or by dredging. Such removal may be questionable however at the end of the project life as it will minimise seabed disturbance and release of particulate matter and other contaminates that could have an impact on the ecology of the area. [25]

- Subsea cabling: Assuming that the subsea cable is buried and that full removal of the cable is required at decommissioning stage, costs could well be of a similar magnitude to installation costs. However, if cables were to be cut off at the same time as the foundation removal and the remaining length is allowed to stay in-situ, costs would be minimal.

2.3 Mapping infrastructure

As of January 2014, 2,080 turbines are installed and grid connected in European waters, making a cumulative total of 6,562 MW, in 69 wind farms in eleven European countries. Once completed, the 12 offshore projects currently under construction will increase installed capacity by a further 3 GW, bringing cumulative capacity in Europe to 9.4 GW. Moreover, EWEA has identified 22 GW of consented offshore wind farms in Europe and future plans for offshore wind farms totalling more than 133 GW. [27]

A minimum number of specially adapted ports are critical for supplying the offshore market and unless there are ports committed to working in the offshore wind sector (facilities, infrastructure and skills), the offshore wind industry will face major challenges between the land and sea parts of the operation. The lack of sufficient infrastructure in Europe could represent a major bottleneck for the offshore wind sector and better relationships with the ports should be developed in order to prepare and support the development of the industry. The latter seems to have realized this potential issue and is making plans to adapt to it. Recently, Siemens has invested nearly €200 million in wind turbine production and installation facilities in the UK and its partner Associated British Ports has invested a further £150 million in the Green Port Hull development [28].

Within the next 10 years, manufacturers will have moved close to or located outlets at port facilities. These facilities should possess deep water and reinforced quaysides to take the large weight of turbines, and large storage areas with market conformed rents and suitable space to move foundations and cranes.

New concepts, such as the Dutch 'harbour at sea' concept are researched for servicing the future large offshore arrays implemented far from shore. Such multi-purpose platforms could allow sailing times to be reduced for installation and maintenance. However, more commonly, work is being carried out on increasing vessels speed performance and on floating platforms.

Offshore wind ports mapping

Figure 11 shows ports potentially able to service offshore wind power developments in the North Sea with further investment[6].

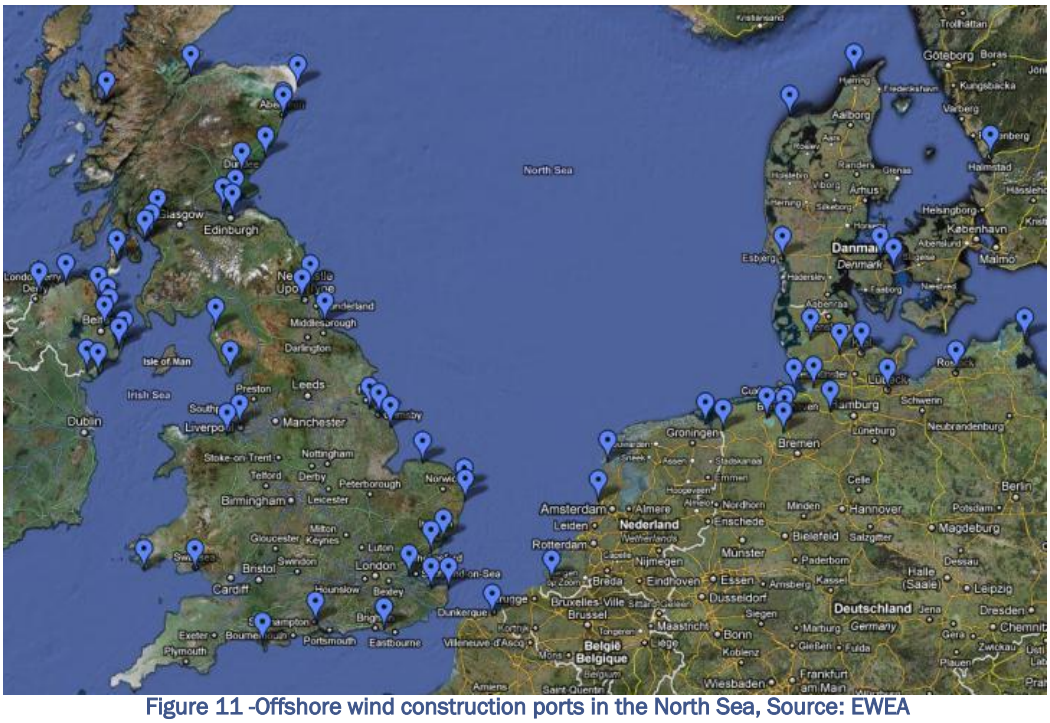

Figure 11 -Offshore wind construction ports in the North Sea, Source: EWEA

There are more than 70 harbours identified to potentially serve offshore wind projects, although the majority of them would require investments to be adapted to the specific needs of the offshore wind sector. Only a few would be suitable for the installation of substructures, and very few have a track record in offshore wind.

Germany and the UK, in particular, are very active in port development, which is considered as a way to diversify harbour activities, attract companies and create local employment. In the case of Bremerhaven in Germany, an integrated industrial approach was implemented, leading to promising successes. Such an approach bases the developments in port activities on strong local partnerships with wind turbine manufacturers, component suppliers, research institutes and developers. Different ports are being developed in Germany, such as Emden, Bremerhaven,

[6] Summary of the available literature to 2011.

Nordenham, Cuxhaven, Stade and Rostock [29]. Following the substantial success in northwest Germany of these North Sea ports, attention seems to be shifting towards the northeast region on the Baltic coastline.

Two more ports are noteworthy. Recently, the port of Wilhelmshaven hosted the construction and assembly of transformer platform for Alpha Ventus, including supply, service, diver-service and helicopter service. It also worked as basis for diving and vessel services for Bard Offshore 1. The Sea Terminal Sassnitz handled and stored additional components for EnBW Baltic 2, and the port terminal will be used for the staging and pre-assembly of components for Vikinger offshore wind farm, whose developers are presently waiting for consent.

In the UK several initiatives are underway to improve the "offshore readiness" of UK ports. Following the Department of Energy and Climate Change's 2009 report identifying the potential ports candidates for large-scale deployment of offshore wind [30], the government confirmed £60million (€71.4m) in funding to support the development of port infrastructure in England, Wales and Northern Ireland as well as £10 million awarded to various individual companies investing in UK facilities. These stimulation measures seem to have helped secure commitments to invest from some major supply chain players, most notably Siemens, GE, Mitsubishi, Gamesa, and Doosan which are all expected to create UK manufacturing facilities. Regions of high activity in England include Tyneside, Teesside, Humber and East Anglia.

Among major ports developments, Belfast Harbour is to fund and build a new £40m, 450m quay and 50-acre logistics space, which should be used by DONG to pre-assemble both the turbines and their foundations. Able Marine Energy Park is another port being developed and specifically designed for the offshore wind sector with 803 acres of land and 1500m of new deep water quays. According to the development plan, suppliers –blades, towers foundations as well as convertors, gearboxes, generators, and nacelle canopies- are supposed to be co-located in the port. The project was granted planning permission by the Department of Transport on 18 December 2013. Together with the port, also a land base facility is foreseen; the Able Logistics Park will in fact offer a further 667 acres of warehousing and external storage along with a purpose built Business Park providing office facilities.

A new fund of £70 million was also announced by the Scottish government to strengthen port facilities, testing sites and manufacturing for offshore wind. The National Renewable Infrastructure Plan (N-RIP) developed by Scotland's economic development agencies identified three potential clusters in Scotland, Forth/Tay, Moray Firth and West Coast in addition to existing expertise focused around Aberdeen and Peterhead.
Finally, as already mentioned, Siemens decided to invest in UK ports for its offshore wind activities [31].

Ports in Denmark have also been active in seeking opportunities in the offshore wind sector. Lindø Industrial Park is an ongoing conversion of a 1 million square metre area set up on the closing shipbuilding facilities of Odense shipyard. Smulders Group foundation manufacturer has entered a conditional agreement to set up extra production capacity at Lindø [32]. Meanwhile the port of Esbjerg has announced plans for significant expansion citing the forthcoming offshore wind market as a primary driver. In preparation of its use for DONG Energy's Anholt Offshore

Wind Farm, storage facilities at the Port of Grenaa were rebuilt. The port of Thyboron has provided vessel support for DP vessel engaged in seabed preparation work for Horns Rev3 offhsore wind farm. The port is also the site of the Envision Test Turbine (3.6 MW two-bladed turbine) commissioned in 2012.

France is similarly keen to exploit port development opportunities from its recent offshore wind tender and future installation programme of 6 GW by 2020. Saint Nazaire, Le Havre, Brest, Cherbourg, Cherbourg and Dunkirk are at the forefront of current interest to serve as platforms for the first phase of the projects (2 GW) and La Rochelle could also be identified for the second phase (1GW). Alstom has started to build a facility in St Nazaire (nacelles, generators) and in Cherbourg (blades, tower) whereas Areva Wind is developing a facility in Le Havre (nacelles).

While no significant capacity is expected to come online in Eastern European waters prior to 2020, Poland and the Baltic countries of Estonia, Latvia and Lithuania have identified opportunities for supply chain involvement of their ports. Significant labour cost savings in this region present a distinct advantage.

In the Netherlands, several facilities have been identified, including the extended Vlissingen area, Ijmuiden, den Helder (O&M) and Eemshaven.

For Finland, as most of the projects are located either in the northern part of Gulf of Bothnia or off the coast, between Pöri and Vaasa ports, the ports located in these areas are those expected to support the development of the sector. In particular, the ports of Pori, Vaase and Kristinestad. In the northern part of the Bothnia Gulf, the ports of Oulu, Kemi and Raahe should be mentioned.

Similarly in Sweden Halmstad, Uddevalla and Karlshamn could be suitable as installation base for offshore wind farms.
In Belgium, Oostende and Zeebrugge ports authorities have being undertaking major developments to service Belwind and Thornton Bank offshore wind farm projects.
In Spain, several ports along its north and northwestern Atlantic coast such as Vigo, Santander, Bilbao, have considerable industrial capabilities which would be well suited to serve any future developments of offshore wind in the area.

2.4 Mapping of offshore wind farms

Offshore wind installations have been ramping in Europe since the beginning of the years 2000. Since 2000 the MW installed has increased of almost 200 times to reach the record figure of 1,567 MW installed in 2013.

There are currently [27][7] 69 online offshore wind farms in 11European countries. 2,080 turbines are installed and grid connected in European waters, making up 6,562 MW.

[7] As of January 2014

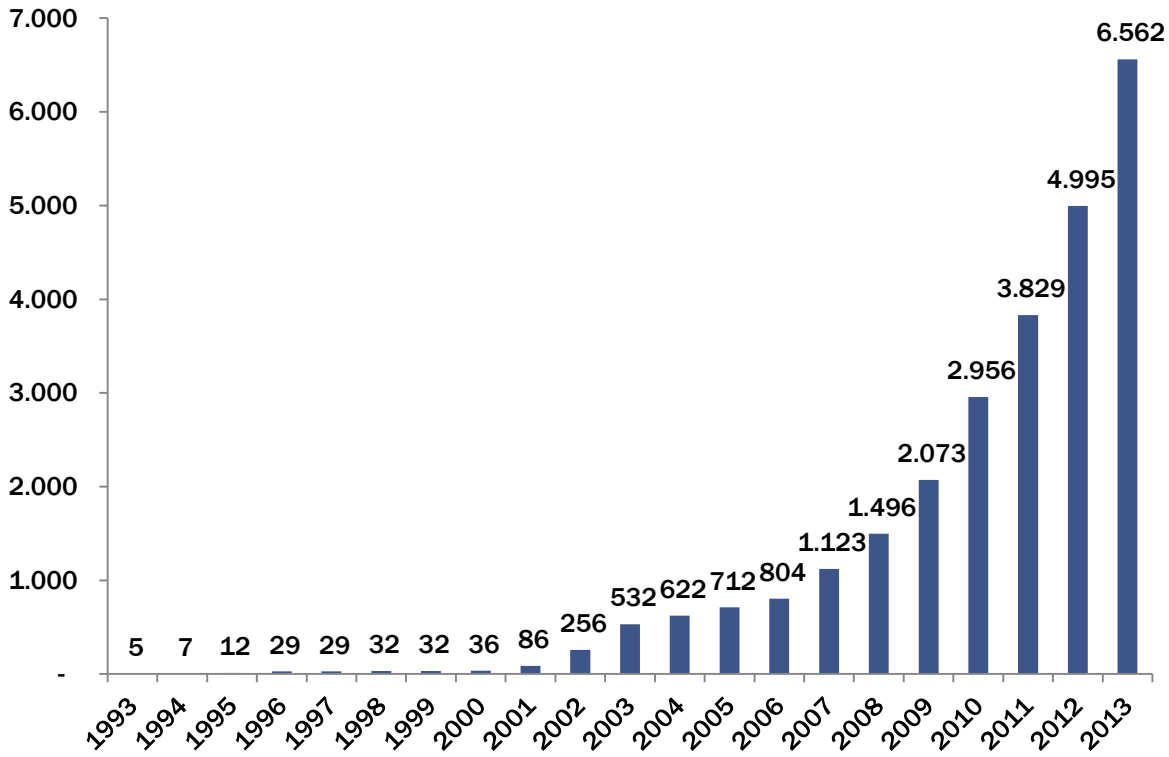

Figure 12 -Offshore wind installations, 1993 – 2013 (MW). Source: EWEA

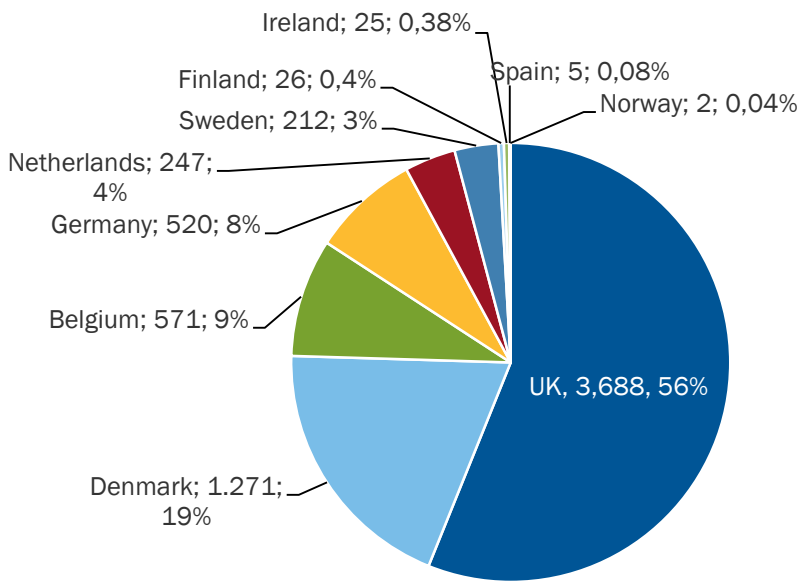

Figure 13 - Cumulative offshore wind installations per country (MW). Source: EWEA

The bulk of installations are in the UK which hosts more than half of all installations (56%), followed by Denmark (19%) and Belgium (9%).

Sea Basins

The majority of the wind farms are located in the North Sea (4.4GW) while the Baltic Sea (1.1GW) and the Atlantic Ocean (1GW) make up together a little more than 30% of all installations.

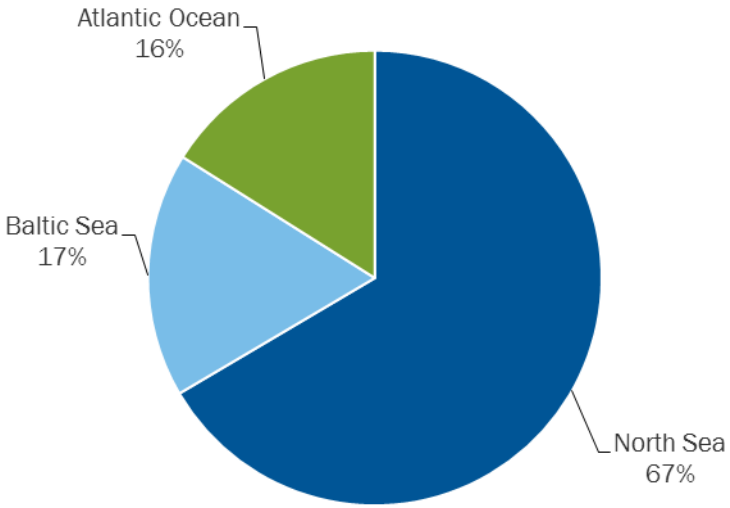

Figure 14 -Cumulative offshore wind installations per sea basin (MW). Source: EWEA

Market outlook for 2014 and 2015

With the completion of the wind farms that are currently under construction, some 3 GW of new capacity will come online in the coming years, which suggests that annual installations will remain stable in 2014 and 2015. EWEA has also identified 22 GW of consented offshore wind farms in Europe and future plans for offshore wind farms totaling more than 133 GW.

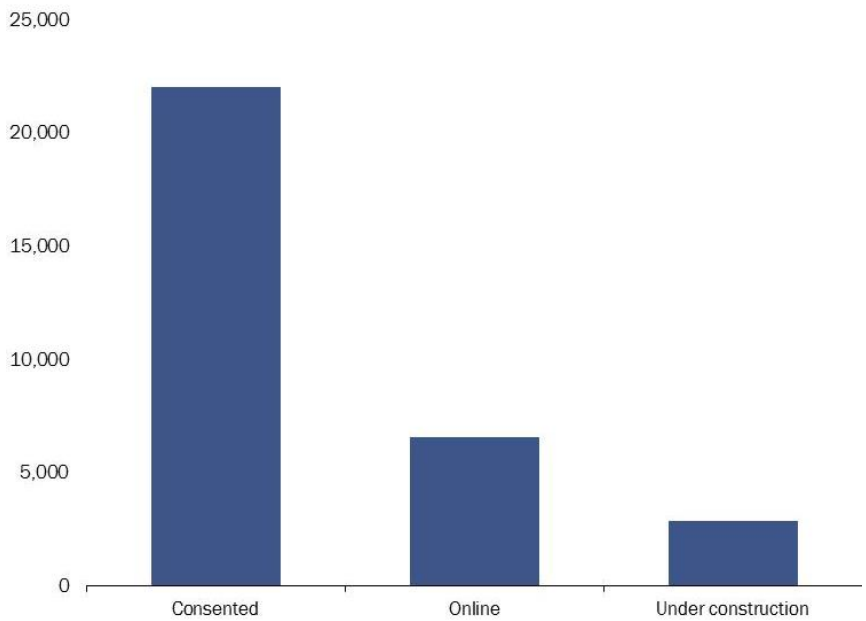

Figure 15 -Projects online, under construction and consented (MW). Source: EWEA

Consented wind farms

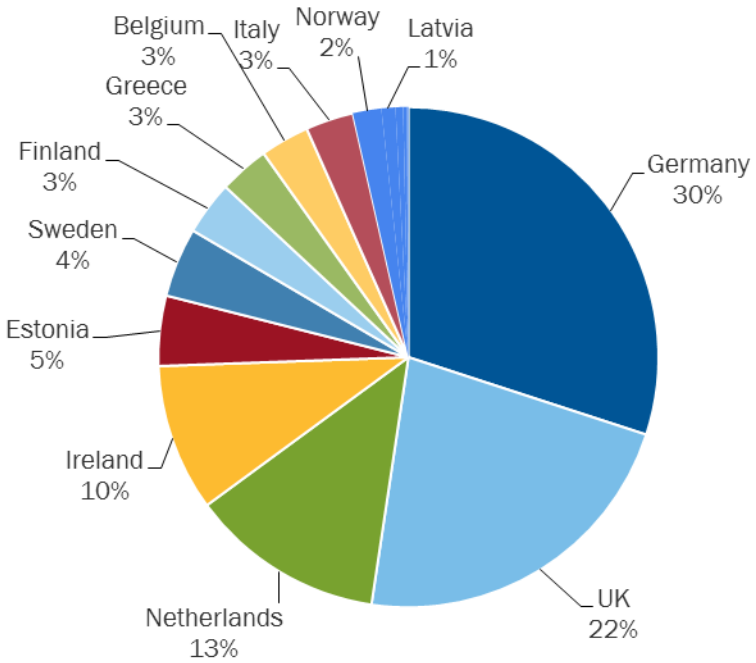

Figure 16 -Projects consented per country (MW). Source: EWEA

The majority of consented offshore wind farms is located in Germany (6.6GW); another 5GW is in the UK and around 10GW are split in other 13 countries.

Outlook for sea basin

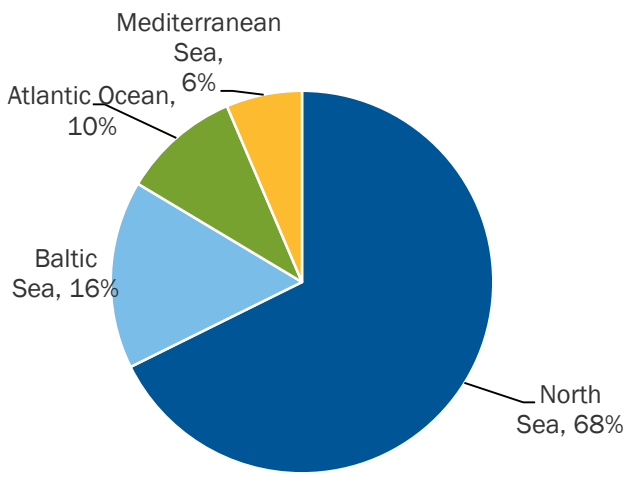

Figure 17 - Projects consented per sea basin (MW). Source: EWEA

The majority of the wind farms are planned (up to 2021) to be placed in the North Sea, but the Baltic sea and the Atlantic Ocean are going to be interested by offshore wind constructions as well. Finally, around 1.5GW of offshore wind are planned to be built in the Mediterranean Sea.

3. Industry challenges

The whole WP5 is dedicated to Integrated Logistics, and in particular it has targeted key areas where innovations will have a positive impact on the LCOE and has set out the tasks to achieve these cost savings. In this context, this reports defines the design constraints and functional requirements related to optimising logistics over the life cycle of the wind farm.

3.1 Future outlook from a components and concepts level

As offshore wind market moves forward, new opportunities appear that present some technical challenges that need to be faced. The trends for the upcoming years are oriented towards the construction of larger wind farms in terms of capacity, that may require turbines with greater rated capacity (associated with an increase of mass and dimensions of the components) and moving the installation sites further offshore, which implies greater distances to shore, as well as increasing water depths. Thus, the means of resolving these challenges will be through the assessment optimal transport systems and foundation and substructure designs.

3.1.1 New, bigger turbines

The current trend in offshore wind turbine design is the development of multi MW (6 to 8MW) capacity machines and this range will be commercialised soon (2015 and after). 10MW turbines are also currently being studied but they are unlikely to be commercialised before 2020. This increase in capacity leads to heavier nacelles (200 to 400 tonnes) but also to longer and heavier blades (60m to 85m weighting 20 to 45 tonnes).

The rated capacity of wind turbines has increased constantly since the first 450 kW offshore wind turbines were grid connected in 1991. In 2013, the average capacity rating of offshore wind turbines connected to the grid was 4 MW, almost ten times larger than in 1991, with various offshore wind projects using 5 MW and 6 MW turbines. The trend is expected to continue with the deployment of 8 MW turbines in the very near future and development of 10 MW turbines going forward. Turbine components are, therefore, also increasing in size and becoming more complex.

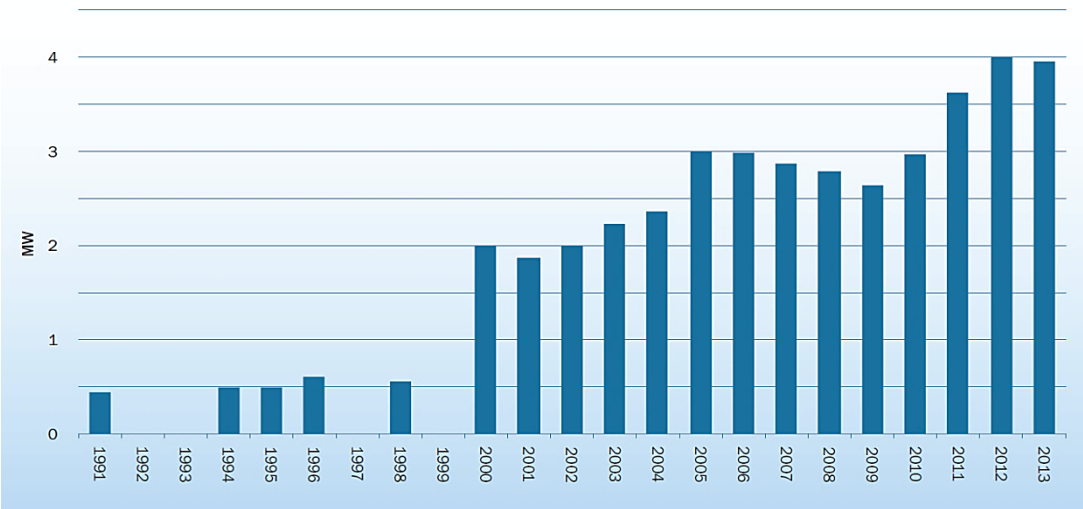

Figure 18 -Average Offshore Wind Turbine Rated Capacity. Source: EWEA, 2014

In order to harvest less windy sites, turbines manufacturers develop 2 rotor size models (eg. Siemens SWT 6.0 120m and 154m or Senvion 6.2M 126m and 152m).

Drive train technologies can be split into 3 main concepts:

- Geared Doubly-Fed Induction Generator (e.g. Vestas V90 3MW)
- Geared Permanent Magnet Synchronous Generators or also called "Hybrid" Medium Speed Gearbox (e.g. Areva M5000)
- Permanent Magnet Synchronous Generators – Direct Drive (e.g. Alsom Haliade 6MW 150)

To date only Mitsubishi Power Asystem Europe is developing a hydraulic drive-train for its Sea Titan 7MW turbine, currently being installed at Hunterstone demonstration site (Scotland).
Other innovative drive train concepts include High-Temperature Superconducting (HTS) generators (e.g. American Superconductor Corp), magnetic transmission systems (e.g. Magnomatics), axial flux permanent magnet machine (e.g. Smart Motor).
Innovations in the turbine nacelle are mainly focused on the drive train and power take-off arrangements (e.g. DC).

Regarding the installation of the nacelle and blades, the industry has to face the following challenges:

- Suitable ports for the assembly and the storage (large areas required, up to 50Ha for assembly), including water depth (>10m), quayside length (>300m), quay bearing capacity (10-20T/m^2), waterway for large rotors.
- Dedicated vessels for the transport, handling and erection
- Supply chain: avoid any bottleneck in terms of nacelle and blade supply

3.1.2 Foundation structures, blade innovations, nacelle design and implication

New scenarios of deployment may require novel foundation designs since monopiles will no longer be feasible at greater water depths, and for higher heavier wind turbines, therefore, some improvements need to be introduced to the current designs. Apart from monopiles, other solutions regarding steel structures that have been used in the offshore wind industry as support bases are four-leg jackets or the alternative solution such as tripods or tripiles. Furthermore, other steel designs have been proposed, such as braced monopiles, monopods that use suction buckets to provide the seabed connection, and jacket variants with designs of three or six legs or twisted structures [33].

The use of concrete foundations is also potentially a cost-effective solution. Basic concrete gravity base foundations have been used extensively in shallow-water sites in the Baltic Sea, but do not scale cost effectively for deeper-water conditions. In order to address this issue, "next-generation" concrete designs have been developed. Some self-buoyant structures have been proposed so that eliminate the need for the costly heavy-lift crane vessels, and some have also been proposed to allow the complete installation of the turbine on the foundation at the quayside before it is delivered to site.

Blade innovations

The key limiting factor in blade scale up is weight, and the solutions lie in new technology coming from studies of aerodynamics, load control and integrated design. Managing loads on blades

can maximise the rotor swept area and increase energy yield. Design is the key issue in blade scale up. A prototype glass fibre-polyester blade takes around 9 months to develop and testing takes a further 6-12 months.

Transportation of long blades could be also an issue, not only from the manufacturing facility to the assembly port but also on board of vessels, in particular when manoeuvring in the port (waterway).

Blade Dynamics is currently developing (Energy Technologies Institute "Very Long Blade" project) a new design of very long blades (up to 100m), in order to reduce the weight, increase the quality (manufacturing process) and reliability and improve the transportability.

Nacelle design

Similar as blades, weight is a key parameter for the installation of nacelles. There has been significant improvement in drive train design focusing on reduction of weight. In particular direct drive turbines are now as heavy as geared drive-train, mainly because converters and transformer are installed within the tower instead of the nacelle (e.g. Alstom Haliade 150).

It should be beard in mind that the installation of electrical equipment inside the tower leads to constraints in terms of installation: the tower must be handled vertically and not horizontally which requires specific process and transportation equipment.

3.1.3 Vessel and equipment

Vessels and equipment challenges will be driven by present and future developments but also by present gaps. Therefore, optimization for present conditions and components, together with the adaptation and upgrading to new farm sites and components concepts and dimensions must be considered.

Development of new installation vessels must be aligned with developments of new foundations, increase of weight and dimensions of present concepts of foundations and turbine component, and optimization or new development of installation strategies that will need to adapt to the new range of working conditions: further distance, deeper waters, increase in Hs and wind speed.

The following challenges can be outlined for the different types of installation vessels:

Self-propelled and towed Jack-up vessels:

Challenges for SP jack-up vessels face the increase of operational capacities above current specifications in order to increase weather windows for transport and installation phases, loading and lifting capacity and faster access to sites:

- Increase of transit speeds (current 8-12knots for SP).
- Limit significant wave height in transit (current 2.5-3m for SP and 2.5-3 for towed).
- Improve DP and manoeuvring performance in order to reduce positioning time.
- Limit significant wave height for jacking-up (current 1.5-2.5m for SP and 1.5-1.8m for towed).
- Maximization of deck space and optimal arrangement of jackets on deck.
- Increase of deck capacity.

- Increase of operating water depth/increase of leg length.
- Increase jack up speed (current 1m/min).
- Higher accommodation capacity (current up to 200 people).
- Increase of limit wind speed for crane lifts.

Heavy Lift Vessels:

- Increase of transit speeds (current 8-17knots).
- Limit significant wave height in transit (current 3-4m).
- Improve DP and manoeuvring performance in order to reduce positioning time and increase accessibility.
- Limit significant wave height for lifting (1-2m).
- Maximization of deck space and optimal arrangement of jackets on deck.
- Increase of deck capacity.
- Include solutions to reduce relative motion between crane and turbine during installation.

New concepts that are being developed for foundation solutions and for increasing weight and dimensions of foundation and wind turbine will raise both opportunities and needs for specific vessels to be designed. Examples of this are the BMT Nigel Gee purposed-design Transportation and Installation Barge for preassembled GBS and Wind Turbines, or the WindFlip Concept for transport and installation of Floating Wind Turbines.

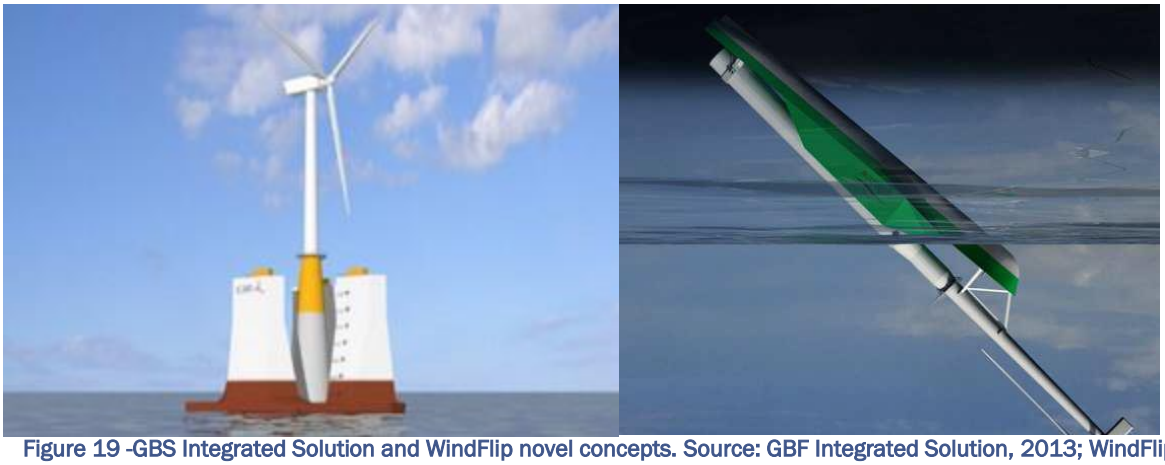

Figure 19 -GBS Integrated Solution and WindFlip novel concepts. Source: GBF Integrated Solution, 2013; WindFlip, 2011

Vessels equipment:

Increasing requirements for vessels and new transportation and installation strategies also have a direct impact in vessel equipment for handling, lifting transport and lashing operations. Nowadays, design of each of these systems or solutions are developed in a one-by-one approach for each project, vessel or wind farm component. Therefore, a change from the one-by-one to an integrated logistics and standardized approach presents high potential for cost reductions.

Several examples showing the high variety of transportation and installation equipment are included below.

- Handling equipment: handling and lifting equipment for monopiles is highly dependent on the installation strategy, but also in the individual designs for installation vessels:
    - Pile guiding tool designs for monopile installation from vessel;
    - Tooling designs for monopile installation with cranes.

Figure 20 -Pile-guiding tool installed onboard Seajacks' new jack-up vessel, Zaratan and in VeoSea's Jack-up Barge, Neptune

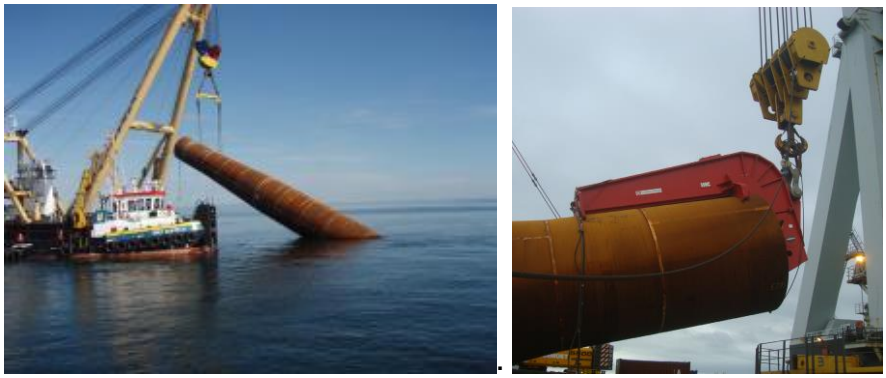

Figure 21 -Tooling solution for installation of a floating transported monopile. Source: Dong Energy 2010; Ballast Nedam, 2013

- Transportation tooling and sea fastenings

Transportation tooling and sea fastening are required to secure transportation when the ship is in transit. Again, tooling is designed in one-by-one basis. Cost reductions by applying a standardised approach is of special interest when considering large weight / heavy components such as monopiles.

Figure 22 - Monopile transportation frames examples. Sources: Fyns Kran Udstyr, 2014; Bilfinger, 2012

O&M vessels and transfer systems

During the O&M phase of an offshore wind farm the main challenge for the vessels are to ensure access to the wind turbines. Future wind farms are expected to be located further offshore and are expected to face a rougher environment where weather conditions periodically will be harsh. Two main factors future O&M vessels for offshore wind farms will need to compensate for is the distance from shore to the wind farm site, and to transfer personnel and equipment from the vessels to the wind turbine also during harsh weather conditions.

To accommodate for future needs for O&M vessels at offshore wind farms, several new concepts for future design has been proposed. This includes new specialized offshore wind service vessels, new solutions for transfer systems, and mother vessel concepts. In the following, some main features of these concepts are introduced.

<u>Offshore wind service vessels</u>

The main focus of the new generation of offshore wind service vessels is to minimize motion to ensure safe transfer of personnel from the service vessel to the wind turbines, and to minimize the time in transit. Vessel concepts with systems to minimize motion (both when transferring personnel and during transits) are:

- Nauti-Craft – Hydraulic suspension system for multihulled vessels [34]
- WindServer from Fjellstrand – Small Waterplane Area Twin Hull (SWATH) and trimaran concepts [35]
- Wave Craft from Umoe Mandal – Surface Effect Ship (SES) technology, also provides high vessel speeds [36]

Figure 23: Vessel concepts aiming at minimizing motion. Top: Nauti-craft. Left: Wave craft, Umoe Mandal. Right: WindServer, Fjellstrand. Sources: [34], [36], [35]

Other new vessel concepts include

- TranSPAR Craft from ExtremOcean Innovation – Ultra Stable Crew transfer vessel, suitable for in-field operations [37]
- Pivot Deck Vessel by North Sea Logistics – Incorporates a deck into the vessel that is linked with the turbine foundation [38]

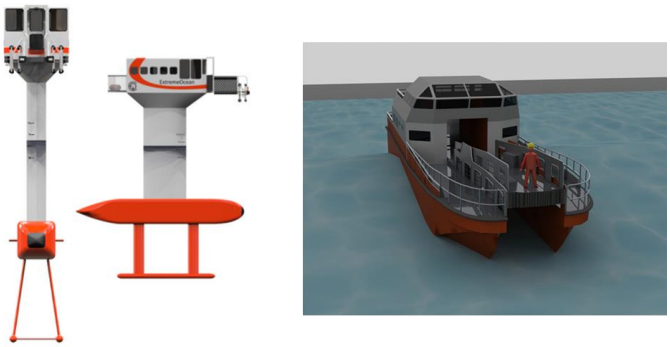

Figure 24: TranSPAR Craft and Pivot Deck Vessel. Sources: [37] [38]

<u>Transfer systems</u>

For safe and secure transfer of personnel and equipment from a vessel and to the wind turbine, there have been developments and ideas for future access systems that can be incorporated with an offshore wind farm service vessel. These include:

- Autobrow system by Otso Ltd (concept design by Ad Hoc Marine Designs) – Low cost, low weight, modular system [39]
- Momac offshore access systems – Lift cage for CTVs and a gangway for larger vessels [40]
- Zstep, Zcatch and Zbridge from Ztechnologies – Step up platform, mooring arm and motion compensated gangway system [41]
- Turbine Access System (TAS)™ by Houlder and BMT Nigel Gee - Lightweight, heave compensated gangway system [42].

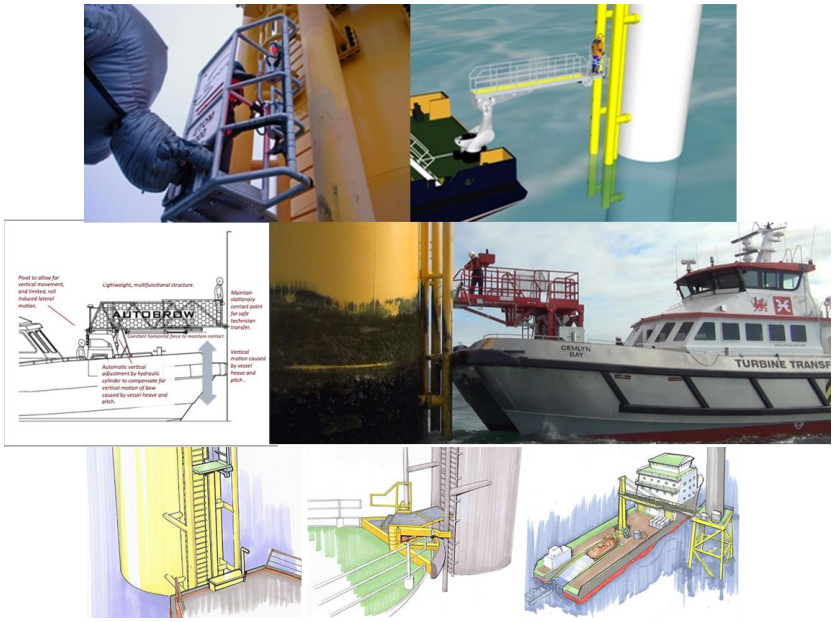

Figure 25: Access systems. Top: Momac offshore access systems, lift cage and gangway. Middle, left: Autobrow. Middle, right: TAS. Bottom: Zstep, Zcatch and Zbridge. Sources: [40], [39], [42], [41]

Mother vessel concepts

Mother vessel concepts consist of larger, tailor-made mother vessels that function as an accommodation vessel, maintenance base for equipment and smaller daughter crafts for personnel transfer from mother vessel to wind turbines, and on board crane for lifting activities. Helipads render possible the use of helicopters to transfer personnel from land and out to the mother vessels, and also from mother vessel to wind turbines.

Figure 26: Mother vessel concepts. Top, left: Seawind. Top, right: SeaEnergy. Bottom, left: Ztechnologies. Bottom, right: Offshore Kinetics. Sources: [43], [44], [41], [45]

Several mother vessel concepts have been proposed, and includes: The SeaWind by Offshore Ship Designers [43], the SeaEnergy mother vessel designed by Ulstein using their X-bow [44], the Zport by Ztechnologies [41] and the mother vessel concept proposed by Offshore Kinetics [45]. All concepts provide a safe harbor for smaller daughter crafts.

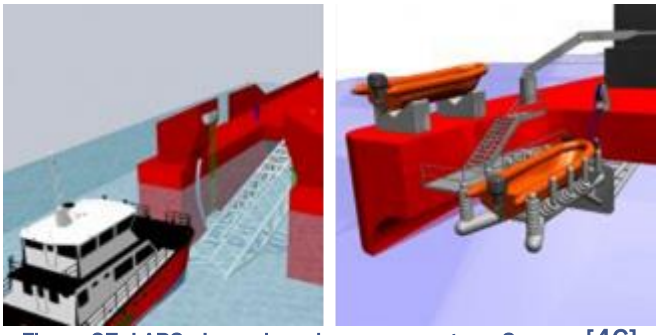

Figure 27: LARS - Launch and recovery system. Source: [46]

Solutions for recovering smaller daughter crafts are proposed. One is the Divex daughter craft launch and recovery system (LARS) using either a ramp or a floating dock principle to be able to cater both smaller and larger daughter crafts [46].

An overview of the main challenges for offshore wind vessels and proposed future solutions in the O&M phase is shown in Table 9.

Challenge	Description	Proposed solutions
Distance to shore/maintenance base	Further offshore wind farms makes transit time from shore to wind farm long, and reduce the access to the wind farm for O&M activities	- Specialized offshore wind service vessels that are stable and have high transfer speed - Mother vessel concepts reduce the distance to maintenance base
Transfer from vessel to turbine	Harsh weather conditions will make safe and secure transfer of personnel and equipment from vessel to wind turbine challenging	- Specialized offshore wind service vessels that are stable when stationary also in high waves - New transfer systems that compensates for the movement of the vessels
Recovery of vessels	Smaller offshore wind service vessels need to return to a safe harbour when weather conditions gets harsh	Mother vessel concepts that offers a safe harbour with a recovery system for daughter crafts

Table 9: Challenges and proposed solutions for vessels in the O&M phase

Port operation equipment

This section includes specialized equipment and tooling that is essential for correct handling of components from reception or final stage of manufacturing in construction ports to in-port transportation manoeuvres and offloading operations to final deliver to wind-farm sites.

Due to the lack of standardization of transportation and handling procedures which vary not only with the different component, but also with component manufacturer and logistic operator, a wide variety of handling and lifting equipment and tooling is nowadays applied in port operation.

Even using a wind-ready port or offshore wind cluster with high local manufacturing and assembly facilities, many large components will need to be received in the port and transported and handled within port facilities. The main challenge to be faced by these systems will be the increase of components and assembly dimensions and weight but also, the increase of number of turbines for a specific site, or even the simultaneous construction of different wind farms. This

fact will impact, not only the technical capacities of the equipment and tooling, but also an increase of availability in port facilities or cautious planning of its use during a wind farm project lifecycle.

Examples of tooling that is currently used for inbound logistics and port operations show challenges for new projects to be developed, related to present lack of standardization concerning equipment design. Also, is common that the decision for the type of equipment or tools to be used in a particular operation is fixed by transport and handling instructions provided by the component manufactures. Lack of standardization in these instructions is also present drawback for optimizing port logistics, as these instructions vary depending on manufacturers or components suppliers.

Equipment for inbound logistics:

- Specialized receiving, handling and lifting tooling. Standardized and versatile dedicated tooling will decrease time for operation and increase safety and security of lifting and handling operations.
  Instead of specific tooling for each phase of transportation and staging, new solutions must be focused on the development of versatile tools that can be used over several stages of transportation, port operation or installation, for example supporting frames that allows for handling a particular component from manufacturing site to installation in farm. This will reduce time for tooling change but also implies a low utilization factor considering the whole logistic cycle. Therefore, new solutions must be combined with an integrated tool if construction projects are not carefully planned.
    - Spreaders for monopile loading. Present solutions must be designed and approved for specific dimensions and weight of particular monopile design.

Figure 28 - Spreader for monopile lifting. Source: Fyns Kran Udstyr, 2014

    - Hydraulic yoke for nacelle loading and unloading on carriers and trucks.

Figure 29 -Hydraulic yoke for nacelle Hydraulic yoke for nacelle, Fyns Kran Udstyr, 2014

- Cranes, HL cranes, crawler cranes, etc
- Forklifts/reachstackers
- Conventional and special vehicles. Wide variety of vehicles is currently applied for transportation of WTG components. Sometimes, the type of selected equipment imposes additional loading conditions for the component. For example, in dolly platform transportation, the blade must support loading during transport phase.

Figure 30 - Telescopic platform and dolly platform for blade transportation, Source: Gamesa 2013

<u>Port Side Operation Equipment</u>:

Challenges derived from new assembly or installation strategies will derive new requirements for equipment used for port side operations such as staging, assembling or in-port transportation (in and out of lay down area, assembly area and dockside):

- Cranes: Lifting for offloading inbound cargo and out loading outbound cargo.

- Self-Propelled Modular Transporters. Land and sea SPMTs constitute an alternative to cranes for loading and offloading.

Figure 31 -SPMT for monopiles transportation : SPMT for monopiles transportation EWW, 2013; Multilift Gruppe 2013

- Staging solutions.
  Most common solutions consist of inshore staging. Components and assemblies are kept in staging structures to increase staging capabilities and ensuring correct load transfer to port ground. These structures will have to increase their loading capacity due to the increasing weights of WT and foundations.
  Inshore staging, can be combined with sea storage solutions. Projects such as Kentish Flat Extension consider only sea storage on barges for foundations and in vessels for WTGs [47] [27]. Best strategy should be planned taking in to consideration full transportation and construction schedule and available storage resources.

Challenge	Description	Proposed solutions
Increase in components and assemblies dimension and weight	Increasing capacity of wind turbines will lead to increase in component and assembly dimensions and weight for foundations and wind turbines (6+ MW WTG)	- Dedicated tooling and equipment development, optimized for the characteristics of new component design. - Development of new solutions for increasing staging and transport capacity (i.e.: specialized tooling design for better loading distribution to supporting surface: deck or ground)
Increase in number of turbines/wind farm	Increase in the total number of component to be received, transported and handled	- Development of new solutions for increasing staging and transport capacity (i.e: stacking frames) - Integrated logistic approach to assure availability of resources. - Standardization of equipment and tooling to decrease time required to certification and manufacturing
Reduce operation time	Bigger farms will need a quicker response from the supply chain, and therefore and optimization of inbound and outbound logistics	- Design of versatile tooling that could be used for all phases of transportation and port operations, to decrease change tool time.

		- Design of tooling together with operation definition
Standardisation of lashing procedures	No current standardization of sea fastening procedures	- Standarisation of lashing and fastening procedures to ensure safe and safety of transport, handling and lifting port and maritime operations

Table 10: Challenges and proposed solutions for equipment in transport and port operation phases

3.2 Future outlook from a system logistic perspective

Future components and concepts for offshore wind farms, described in Chapter 2, together with offshore wind farms being located further away from shore, creates new challenges for the logistic system supporting activities during all three life phases of an offshore wind farm. In the following, the future challenges and new concepts for the logistic system will be described.

3.2.1 Ports and infrastructure

The role of ports and infrastructure for an offshore wind farm is to support the logistic activities. The demand of the infrastructure is somewhat different for the three phases of an offshore wind farm, although similar activities need to be supported during all three phases. The main difference is the need to support more activities and handle larger components during the installation and dismantling phase compared with the O&M phase. The main focus in this chapter will be to describe new challenges for port and infrastructure during the O&M phase, but these will also be relevant for the two other phases.

The three main offshore logistics operations setups [11] [48] for optimizing access and minimizing O&M costs are (1) onshore, (2) airborne and (3) offshore. Suitability of each set-up is a function of the distance of the wind park from the shore, as illustrated in the graph in Figure 32.

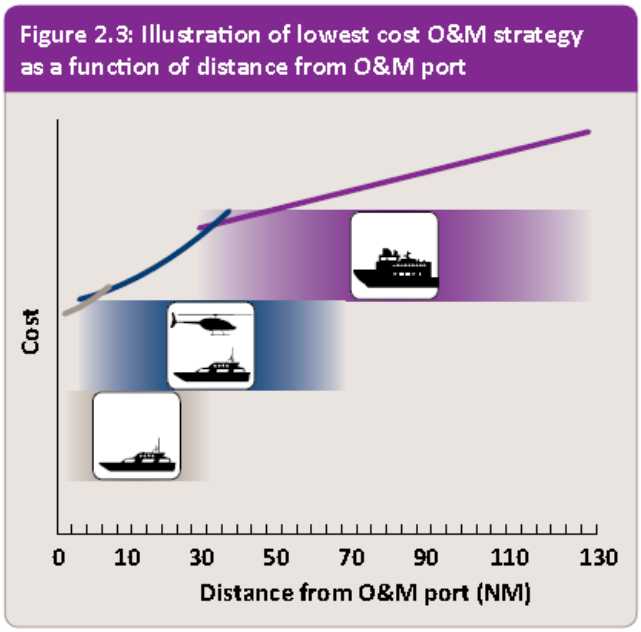

Figure 32: Three main offshore logistics operations setup [11]

Characteristics, as well as strength and weaknesses, of each setup are summarized in Table 11.

Setup	Description	Strengths	Weaknesses	Suitability
Onshore setup, workboat-based	Working/service vessels operating from a port base	• Reduced daily and start-up costs • Well-known transfer routine • Limited draft restrictions	• Travel time harbour-wind farm • No advantage taken of small good weather windows • Congestion at port • Dependent on tide	Until 12 NM from shore
Airborne setup, Heli-support	Workboat with support from helicopter	• High availability • Minimal transfer time • Possibly shorter production stops • Flexible location for the base • Small crew • Limited harbour restrictions • No rough sea exposure	• Not yet tailored for offshore wind • Fog, cloud, strong wind • Noise restrictions • High safety risk • Costly (operation, training, etc.) • Limited geographic area of activity • Limited number of helicopters • Low winching capabilities • Longer permit times	From 12 to 40 NM from shore Suitable when only personnel is needed Can also transport smaller components
Offshore base	Floating or fixed offshore accommodation A hotel/mother vessel + fast rescue crafts available at any time	• Office located at port of choice • Fast turnaround at port • Smaller weather window can be utilized • Less fatigue • Higher maintenance capabilities (resource available close to wind farm) • Fast response	• Costly to build • Requirements • 20- 35 technicians • Two-week rotation • 10-12 hour working day • Senior authorized person recommended	Over 40 NM from shore The larger and further away a wind farm is, the more relevant the concept of offshore accommodation The installation is located close to the wind farm, can accommodate different types of working vessels and host personnel

Table 11: Characteristics, strengths and weaknesses of offshore logistics operations setups, Source: LEANWIND consortium

Although most of active offshore wind farms are located close to shore, the main part of the current projects are moving further away, to deeper water and rougher weather locations in order to exploit a higher potential for wind energy, but also to avoid disturbance to ship traffic. Not only the number of wind farms is increasing, but also the density at sea, which represents a big opportunity for sharing – or *pooling* - of vessel capacity between several farm owners. This allows for economies of scales and O&M costs per turbine to be reduced. [11]

As a consequence of wind farms being located further away from shore, accessibility, quick response time and availability of spare parts will become even more challenging. Main challenges when "going further offshore" include [48]:

- Distance from shore to wind turbine offshore
- Transfer time in conventional crew transfer vessels
- Fuel consumption
- Working hours on site
- Sea conditions
- Communications, mobile telephone, internet, etc.
- Health & safety
- Emergency evacuations from site
- Accommodation for the crew on the farm

New concepts for offshore logistics infrastructure

Offshore accommodation are more likely to become common when of organizing offshore logistics in the future, with personnel located on a large accommodation platform, similar to the oil and gas sector [11]. Also larger vessels may be used as accommodation. This represents a great business opportunity for service suppliers specialized in this type of accommodation.

Future more remote offshore wind farms will require a slightly different set-up [48]:

- The size of these wind farms will, from an H&S perspective, require a daughter craft which can be placed in one sector of the wind farm, whilst the hotel vessel is in another sector, in order to ensure fast response in case of emergency
- Larger vessels are also needed to get sufficient space for cabins, welfare facilities, storage area and even more stability for the comfort of the service engineers

To compensate for the higher costs due to longer transfer time and longer cables for the electric connection, the concept of *offshore ports on artificial islands*, has been introduced in the Netherlands: the Dutch “Harbour at Sea” [49]. The island is 1000 m in diameter and provides sites for landing, berthing, storage, assembly and commissioning, hotel, substation, etc.

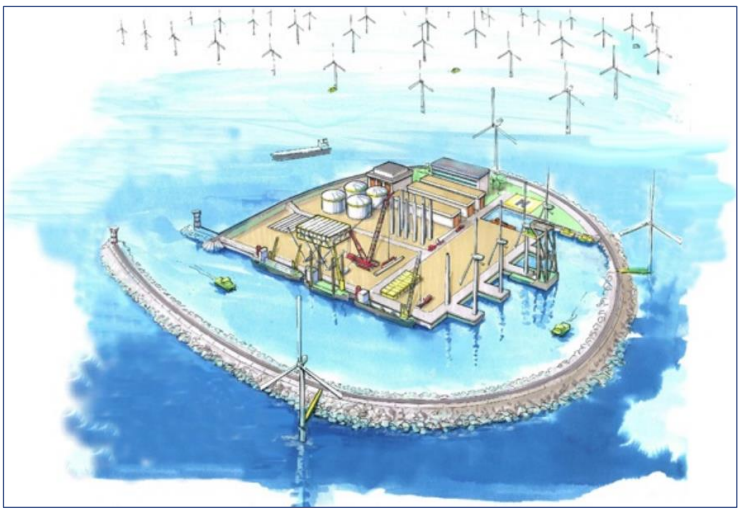

Figure 33: Dutch Harbour at Sea [49]

"Harbour at Sea" represents a safe location at sea for people and materials, and enables easier and quicker transfer of spare parts, tools and personnel, thus more efficient installation and maintenance activities. [49]

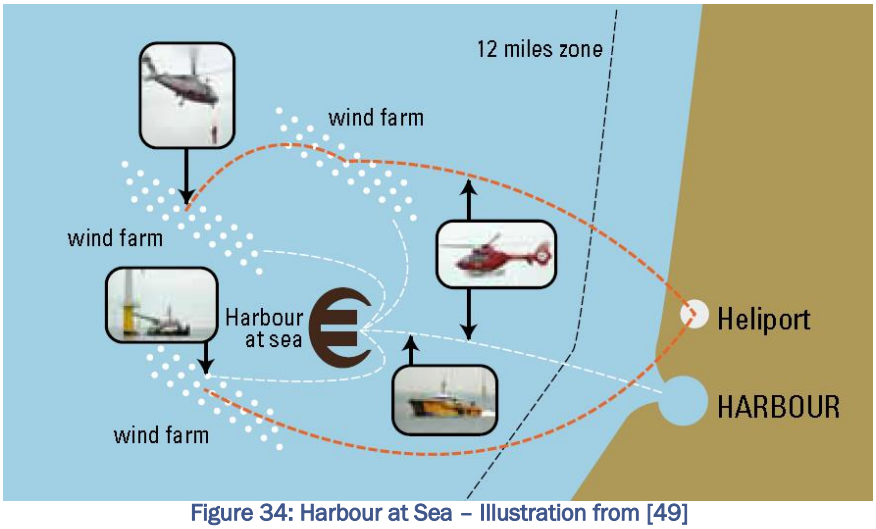

Figure 34: Harbour at Sea – Illustration from [49]

The following functions are suggested for a "Harbour at Sea" dedicated to offshore wind [49]:

- A station for transportation, assembly and maintenance for wind farms at sea
- Accommodation for personnel
- Storage for spare parts
- Workshops
- Foundations for commissioning assembled complete wind turbines
- Test site for new offshore wind turbines
- Transformer station,
- Electrical substation for connections on land

A similar concept to the "Harbour at Sea" for offshore wind is the artificial island, "Alpha", which is to be located approximately 45kms offshore from the port of Zeebrugge. This island shall primarily serve as a permanent and sustainable sub-structure for the offshore high-voltage station and a hub for connecting the offshore wind farms to the coast [49] [50].

The functional requirements for the island include [50]:

- Equipped with all infrastructure and installations necessary for the construction, foundation and maintenance of and access to the OHVS
- Helicopter landing pad
- Protected embankment

Figure 35: Illustration of artificial island – Alpha [50]

Another innovative concept to enable short response time for repair operation while exploiting the infrastructures offered is the "Offshore Wind Loft" [51]. "Wind Turbine Loft" proposes the installation of a residential unit at the top of the nacelle for hosting a group of technicians taking care of the functional integrity of the turbine.

Figure 36: Offshore Wind Loft [51]

Other O&M concepts for coping with wind farms further away include remote monitoring, new turbine design with onboard crane and new O&M vessel.

Ports and infrastructure supporting future offshore wind activity

In order to better exploit the resources, capabilities, skills, technologies available for the sector, industry actors can cooperate in order to establish "Port Super Clusters", a concept already adopted at the Port of Hull, UK. [52]

A SuperCluster [52] is "a geographic region based around a relevant and credible Port location, which incorporates most if not all of the offshore wind energy value chain including:

- Supply chain manufacture and assembly of products
- Provision of services which support the sector
- Academic links to support the research and development
- Training and skills provision"

The motivation for wind port super-clusters are [52]:

- Storage space maximization: A cluster can offer more storage capacity while sharing the costs. This gives the possibility to create a buffer to produce, transport and unload equipment.
- Exclusivity for port partners: To avoid competing against other port customers for space, services etc.
- Transportation risk minimization: More integration in operations for higher safety of components and material.

An analysis of the requirements toward wind port super-cluster, with regards to access by sea, access by land, quayside requirements, and manufacture and storage, has been performed by [53] and is summarized in Table 12.

Parameters		Manufacture & storage & installation		
		Min.	Desirable	Ideal
Access by Sea	Vessel Laden Draft (m)	14,6		
	Vessel Length (m)	250		
	Lateral Clearance (m)	107	150	200
	Vertical Clearance (m)	NVO		
Hinterland Access	Dedicated Rail Access	Yes		
	Suitable road Access	Yes		
Quay Side	Multiple Docks (m)	380	490	820
	Distance Between Docks (m)	100		
	Single Berth (m)	430	540	870
	Load Bearing Capacity (t/sqm)	16	20	25
	Berth Width	60		
	Haul Routes Suitable Between Quay and Store (t/sqm)	16	20	25
	Reinforce Seabed	Yes		
	Ro-Ro Berth	Yes		
	Sufficient Cranes Availability	Yes		
Facilities	Manufacturing area (ha)	30.638	53.635	112.82
	Storage area (ha)	2,8		
	Workshop	3		
	Car park, Offices, Accommodation, R&D (ha)	50.463	73.46	132.645
	Total	Yes		
Miscellaneous	24/7 fenced Access and Security	Yes		
	No working hour restriction	Yes		
	No exclusive Labour Agreement Restricting Load/Unloading Activities	Yes		
	Availability of Potable Water	Yes		
	Availability of Electrical Connection	Yes		

	Channels dredged	Yes
	Helipad	Yes

Table 12: Requiremenhts for wind port super-cluster [53]

A different concept that may be worth exploring to take best advantage of ports characteristics (location and capacities offered), is multi-ports. On the other side, with the development of offshore bases and mother ships to support wind farms located further away from the shore, distance is likely to become less critical. [11]

3.2.2 Assembly and inventory

Assembly activities are mostly related to the installation phase, although it is still partly relevant for the O&M phase when larger components need to be replaced. Inventory is related to spare part management, which is relevant for the O&M phase. For the dismantling activities during the dismantling phase, the strategies and ideas for assembly can be reversed.

<u>Assembly</u>

Assembly activities can be executed onshore, or partly completed offshore. An overview of existing practices for assembly activities is shown in Figure 37.

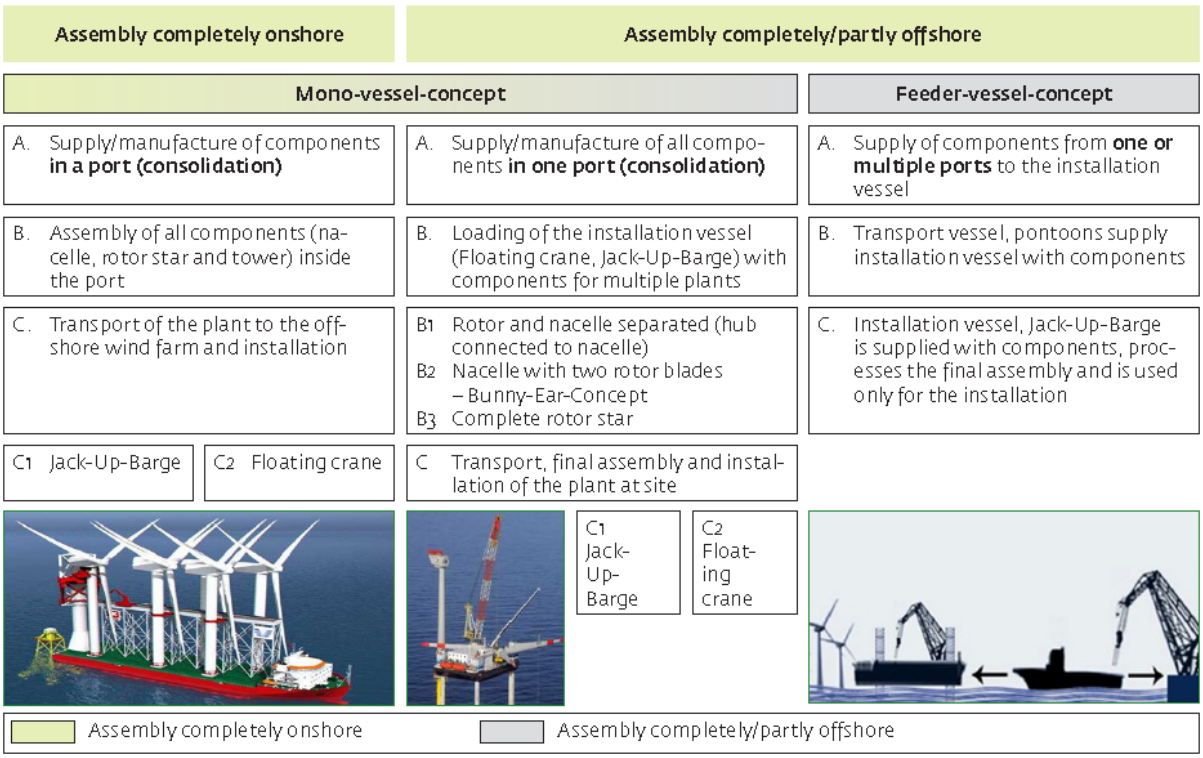

Figure 37: Existing practices for assembly activities [48]

Figure 38 shows the significance of distance to the wind farm for different assembly practices.

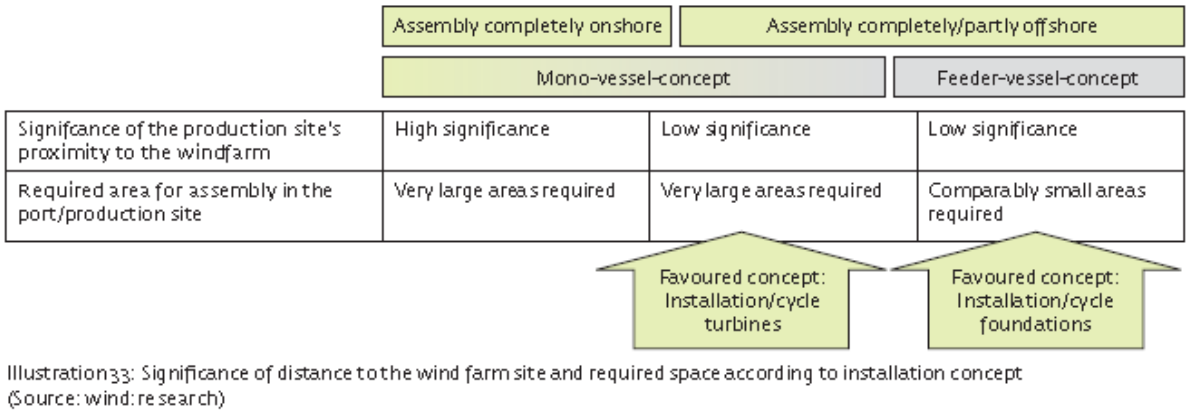

Figure 38: Assembly practices and significance of distance to wind farm [48]

Future challenges for assembly is mainly related to distance to shore, and larger turbines and other components. When a wind farm is located far away from shore, there will be larger uncertainties related to weather conditions during transportation. A summary of strengths and weaknesses related to assembly strategies is provided in Table 13.

Assembly strategy	Strengths	Weaknesses
Onshore	Short time to install component upon arrival at wind farm	Difficult to transport large assembled components Long distance to shore will require a large weather window
Partly offshore	Reduce time to install component upon arrival at wind farm Reduce risk of transporting very large components when part of assembly is done offshore Reduce number of vessels visit to the wind farm for component transportation	Need some time offshore for assembly Will require good weather conditions on the wind farm site
Offshore	Reduce risk of transporting very large components	Need time offshore for assembly Require good weather conditions on the wind farm site for a longer period of time

Table 13: Strengths and weaknesses related to assembly strategy

An introduction of new infrastructure concepts, like artificial islands and harbours at sea, can create new feasible strategies for assembly.

<u>Spare part management</u>

Future challenges for spare part management is related to wind farms getting larger and further away from shore. “Where” and “how many available” are questions that need to be asked and that need to be related to the rest of the logistic system. Easy and quick access to spare parts will give a higher production of energy from the wind farm due to quick response time, but at the cost of keeping spare parts in stock. Larger wind farms, and the potential of several wind farms sharing resources and spares, can reduce the cost of inventory.

An overview of spare part management, strength and weaknesses is given in Table 14.

Spare part strategy	Strengths	Weaknesses
Onshore, not in stock – spare parts will need to be ordered from suppliers when needed	Low inventory cost	Potentially very long response time, this can be reduced through agreements with suppliers
Onshore, in stock	Higher inventory cost Response time is low	Can get a high inventory cost
Offshore, in stock	Very low response time Can be a good strategy when resources are shared between several wind farms	Can potentially be very costly and challenging to keep offshore inventory, especially for larger spare parts

Table 14: Strengths and weaknesses of different spare part strategies

Similar to for assembly strategies, new infrastructure concepts may make other spare part strategies viable options.

3.2.3 Transportation offshore/ onshore

There are several key factors that will drive the future needs of transportation with the logistics support systems for future offshore wind-farms. These include:

- Greater distance from shore to wind farm site (consider the UK Round 3 sites which range from 30km to 70km from shore as compared to the Round 2 sites which range from 12km to 25km from shore) [54]. This has the added implication of deeper water depth for the majority of sites
- Larger offshore wind farms, both in terms of number of turbines and size of turbines.
- A more diversified supply chain which will require greater transportation standardisation and coordination

Considering a break-down of the offshore wind life cycle into three phases (Installation, Operations and Maintenance, and Dismantling) and the supply chain into three geographical categories (on-shore, port, offshore) gives nine potential transportation situations to be considered. The issues relating to ports are covered in Section 3.2.1 so this Section concentrates on the remaining six situations.

Construction Phase – Onshore: The larger turbines and different structure types outlined in 3.1.2 will place further strain on any onshore transportation of any assembled or near-to assembled structures. This may require either a reduced onshore transportation section (by location of assembly facilities at or close to the ports) or innovative multi-modal transport solutions to be developed. Industry standardisation and models for transport cost optimisation could help mitigate some of the rising transport costs.

Construction Phase – Offshore: The logistics transportation challenges offshore in the construction phase relate to the distance from shore and the size of transported components. The inclement and changeable weather conditions on new sites may lead to the need for more advanced transport scheduling algorithms that take account of ocean and weather data to be used. The fleet wide capacity issues for larger vessels may also need to be taken account in the

case where multiple large wind-farms are under construction simultaneously, with European level planning. The most efficient techniques for packing barges with parts should be used.

Operations and Maintenance Phase – Onshore: Many of the parts required in this phase will be smaller or less voluminous than during the construction phase which will have transportation implications. The run out of warranty periods on some existing wind farms and national/local manufacturing initiatives may also have the effect of diversifying the supplier base. This has transportation implications as most sophisticated supply chain models should be built in order to optimise transportation of parts by judicious supplier selection, location, and transport mode choice.

Operations and Maintenance Phase – Offshore: The future larger size and distance from shore of the offshore wind farms may alter the dynamics of optimal transportation for maintenance solutions. Increasing transit distances mean that strategies which include helicopter support and, eventually, offshore-based working will be needed Floating accommodation for maintenance staff may become a viable option. The need to ensure safe, efficient access to the facilities in the wind farm for staff will be an important factor driving maintenance transportation options. Computer-based solutions for efficient combined maintenance scheduling and vessel routing will help control transportation costs, particularly in sites with inclement and variable weather conditions [55].

Dismantling Phase – Onshore: This is perhaps the category with the highest level of uncertainty, as future uses for recycling and re-use of wind farm components are still unclear. It can however, be anticipated that there will be considerable transportation issues arising from the onward inland travel of wind farm components due to the large weight and volume of material involved. Optimal, multi-model transport solutions will be required to ensure that costs of the operation do not escalate.

Dismantling Phase – Offshore: Section 2.2.3 gives the technical details of the at-sea dismantling of an offshore wind farm. In the cases where a large amount of material needs to be transported back to shore, many of the logistics issues discussed for onshore installation exists. There is a need to ensure on a European level that sufficient large-scale transportation vessels are available to ensure that costs do not spiral. There is also a need to efficient pack the transportation vessels to ensure their efficient use.

3.3 Needs and gaps (feedback from IAG, OWIG, industry)

The overreaching need from the offshore wind industry is achieving cost reductions across the board in its supply chain. The sector is optimistic about the prospects of cost reductions in both, the medium and long term. In the near term, it is believed that pressures in the market will drive standardisation and some immediate need of logistics optimisation. These two factors are believed to drive future cost reductions especially in installation and construction phases. Operating costs derived from O&M activities are foreseen to decrease as well but more in the longer term.

The offshore industry sees that the greatest challenges to achieve cost efficient construction methods and logistics can be tackled by increased share of knowledge among stakeholders and

with other industries (e.g. oil & gas) as well as maximising standardisation but without compromising innovation. All possible solutions that can bring cost reductions should be explored, for example, floating structures, specialised vessels able to operate over wider weather windows, specialised equipment and ports able to handle upscaled components of wind turbines as well as modularity of such components and improved models and tools for optimisation of logistics concepts.

A list of topics identified as possible cost reduction measures has been provided by EWEA as a starting point to the LEANWIND project. They have been classified into 6 different groups linked directly with the WPs as seen in the table below.

	Cost reduction Measure	WP Linked
Turbine development	Improvements in range of lifting conditions for blades	WP2 T2.5
	Introduction of whole turbine installation	
	Greater levels of onshore turbine commissioning.	
	Introduction of turbine condition-based maintenance	
	Improvements in inventory management	
	Increase in turbine power rating (>6MW)	
	Introduction of direct-drive drive trains	
	Introduction of mid-speed drive trains	
	Improvements in AC power take-off system design	
	Improvements in workshop verification testing	
	Improvements in mechanical geared high-speed drive trains	
	Improvements in blade pitch control	
	Improvements in blade aerodynamics	
	Optimisation of rotor diameter (150m and above)	
	Improvements in process of blade manufacture	
	Improvements in blade design standards and process	
	Improvements in hub assembly components	
	Improvements in blade tip speed	
	Improvements in blade materials, coatings and lightning prot.	
	Introduction of inflow wind measurement	
	Onshore WTG prototype test site for offshore WTGs	
	Instigate step-change in WTG manufacturing quality	
	Instigate step-change in WTG design for reliability / O&M	
	Increase project design life	
	Optimisation of rotor diameter (4MW)	
	Optimisation of rotor diameter (8MW)	
	Introduction of DC power take-off (including impact of DC array cables)	
	Introduction of direct-drive super-conducting drive trains	
	Introduction of active aero control on blades	
	Introduction of passive aero control on blades	
	Improvements in continuously variable transmission drive trains	
Foundation	Introduction of float out and sink turbine and support structure	WP2

development	Introduction of buoyant concrete gravity base foundations	T2.2-T2.3-T2.4
	Improvements in jacket condition monitoring	
	Improvements in jacket manufacturing	
	Improvements in jacket design and design standards	
	Introduction of holistic design of the tower with the foundation	
	Introduction of suction bucket technology	
	Introduction of floating meteorological stations	
	Standardisation of support structure selection and design	
	Demonstration of new floating offshore wind concepts	
	Improvements in monopile design standards	
	Introduction of single-section towers	
	Improvements in monopile design	
Electrical infrastructure development	Introduction of array cables with higher operating voltages	WP2 T2.6
	Improvements in array cable standards and client spec	
	Introduction of alternative array cable core materials	
	Improvements in array cable insulation materials / design	
	Array cable system design for redundancy	
	Optimisation of array cable installation vessels, tools and methods.	
	Introduction of optimised cable pull-in and hang-off processes	
	Improvements in range of cable installation working conditions	
	Introduction of reduced cable burial depth requirements	
	Standardisation of offshore transmission assets	
	Develop DC or variable frequency collection systems	
Improved Vessel Operations	Widen range of working conditions for support structure installation	WP3
	Improvements in the installation process for space-frames	
	Introduction of flexible sea fastenings	
	Greater use of feeder arrangements in the installation of structures	
	Introduction of feeder arrangements in the installation of turbines	
	Improvements in personnel access from transfer vessel to turbine	
	Improvements in personnel transfer from land base to turbine location	
	Improvements in the installation process for monopiles	
Risk reduction	Improvements in weather forecasting	WP4
	Greater level of optimisation during FEED	
	Introduction of multi-variable optimisation of array layouts	
	Greater level of geophysical and geotechnical surveying	
	Standardised treatment of Uncontrollable Risk	
	Instigate step-change in Investment Risk	
	Step change in wake modelling science and certainty	

	Incentivise early site investigation and FEED work	
	Standardised site investigation technical requirements	
	Standard Industry Risk Register template	
	Shout about success - push good news case studies	
	Improvements in OMS strategy for far-from-shore wind farms	
Supply chain development	Encourage Vertical Collaboration	WP5
	Encourage Asset Growth & Economies of Scale	
	Encourage Horizontal Collaboration	
	Standardised Contract Forms	

Table 15 Needs identified for the offshore industry

3.3.1 Infrastructure improvements

Wind-ready ports

Ports looking to serve the offshore wind sector will need to include the different functions required for projects: manufacturing, foundation production, project construction, operation and maintenance.

Manufacturing

Due to market growth and the large size of turbines, wind turbine manufacturers are increasingly looking towards European portside turbine assembly facilities. Road transportation is becoming less viable for completed nacelles and offshore turbines by definition need to be shipped by sea for installation. There is also significant sense in manufacturing large components (such as castings) close to turbine manufacturing site.

Foundation Production

Whether steel monopiles, concrete gravity bases, jacket or tripod structures, all offshore wind foundations are very large and once produced can only be transported by water. Significant expansion of production capacity is required to meet future demand; hence it is likely that new coastal locations for foundation manufacture/assembly will be established. Compared with set-up times relating to other elements of the value chain, foundation manufacturing facilities can be set up relatively quickly.

Project Construction

Generally, foundations and cables are installed before final installation of turbine topsides. This final activity is most sensitive to sea and wind conditions and hence is typically carried out between April and October. If a distant port is being used for pre-assembly of turbines (i.e. a port local to turbine production), the crane jack-up barge used for installation lifts needs to be self-powered and able to travel relatively fast. If the port is local, then the crane jack-up barge need not be self-powered. The most commonly used installation process to date involves delivery of towers, blades and nacelles to a construction port close to the wind farm. Here, they are pre-assembled ready for transportation by jack-up barge, to the wind farm site. Due to the large number and size of turbine parts, large areas of open storage and pre-assembly space are required for construction. Because of the weight, a high load bearing capacity quay is also necessary.

Operation & Maintenance
Once operational, the maintenance of the wind farm is usually carried out from a nearby port. These ports house the maintenance crew and vessels needed to respond to wind farm faults, plus storage and repair facilities. As wind farms become larger and further out to sea, the use of helicopters and offshore accommodation facilities for this function is likely to become more common.

3.4 Uncertainties and constraints

3.4.1 Turbines

New models which will be commercialised soon do not have track records (only prototype tests) in terms of efficiency, reliability, installation process (methodology to be tested and validated even optimized).

There have been a significant increase in the size of the machines, and the industry is not sure enough about the accuracy of the tools and codes used for the design. The behaviour of a bigger machine cannot be extrapolated from a smaller one and sometimes current design codes or methodologies cannot apply. The long term understanding and forecasting behavior of such big turbines in a very harsh environment is key for developers.

As turbine manufacturers keep on upscaling their turbines, the learning curve cannot really apply which provides uncertainties for developers not only on cost but also on O&M.

3.4.2 Cables

Cable connections, both within the array and export cables are well understood technologies, the main areas of concern are the difficulty and cost of terminating heavy cables during the installation phase and the ability of the industry to supply the quantity of cable required to meet the demand. To date, the current capacity for HVAC cables is about 700km/year and 1000km/year for HVDC cables. This subsea cables manufacturing capacity is able to meet a 3 to 3.5GW/year of offshore wind farms development. Supply chain constraints are expected after 2015.

The installation phase of cables is key and is considered to be one of the most critical operation: cable route issues (e.g.UXO, wrecks, steep slope…), lack of sea bed characteristics, burial issues, connection to the turbine (e.g. J tube), protection including scour protection etc.

The cable repair process and detection is also an area of concerns and requires better condition monitoring systems, cost effective and efficient repair methodology.

3.4.3 Foundations

General constraints

- **Uncertainty about the most suitable foundation design expected for the long terms will be used in the long term.** The industry trend towards larger turbines and sites in deeper waters means that there is uncertainty about which foundation concepts will dominate in

the long term. As a result, companies may delay and eventually cancel investment plans in new mono pile manufacturing facilities. [2]

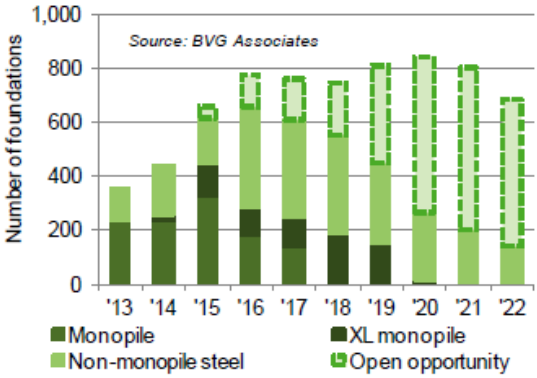

Figure 39 - Projected demand for foundations for European offshore wind to 2022 (by year of manufacture, offset from turbine installation by two years). (Source: BVG2013)

- **Constraints in the communication between developer, designer and constructor due to long distance of industry suppliers.** Hence opportunities for cost reduction could be missed. Any delays in delivery will have significant cost implications in installation vessels contracted. [2]
- **Lack of experience in decommissioning offshore renewable installations**. It increases the risk that developers are unable to provide a fair valuation of decommissioning costs.
- Technical achievements, the availability of finance, a regulatory climate that incentivizes investments and social acceptance are parameters that all will have an impact on the market size for offshore wind and affect also the development of floating solutions[8].
- **Future projects may need more land for installation.** For projects further from shore in harsh conditions, larger lay-down areas may be required to mitigate weather risk, by being able to better utilize good weather conditions by having sufficient stock. [33]

Monopiles

- **The size of monopiles is constrained by the physical capacity of specialist plate manufacturers and challenges associated with the welding of very thick steel plate.** Established manufacturers are also involved in the production of transition pieces on which the turbine tower is fixed. [4]
- **Deeper water constrains the cost effective application of monopiles.** As previously mentioned, industry is extending the window for monopile foundations which will benefit from new manufacturing and installation technology. [33]
- **Piling noise mitigation measures may be required.** The effect of piling on the health and behaviour of sea mammals is an environmental concern still to be solved. [33]
- **The main supplier of steel for monopiles is located in western Germany with close proximity to the existing monopile suppliers.** The leading supplier of heavy steel plate to the monopile market is located near the north east French border, making it well placed deliver to the main fabricators in Belgium, the Netherlands, Denmark and Germany. (BVG 2014)

[8] http://www.thecrownestate.co.uk/media/5537/uk-floating-offshore-wind-power-report.pdf

- **Existing standards for modelling soil-pile interactions are conservative.** The method of p-y[9] approach used for the design is highly empirical and relies on 'old' test data from piles of less than 20 per cent of the diameter of those being installed today. Work is underway to develop a more relevant data set. [33]
- **The capacity to install XL monopiles is limited.** [33]

Jacket and other steel foundations

- **Jacket capacity currently exceeds demand but will need to ramp up prior to 2015 to meet projected demand.** [4]
- **Interaction with other sectors can affect the supply chain for offshore wind steel structures.** There is a risk that increased demand in oil and gas and nuclear sectors will limit the availability of yard capacity and workforce. [2]
- **The production process for jackets is more labour intensive than that for monopiles.** The production of tubes is highly automated but the final assembly of jackets involves a range of manual or semi-mechanised processes. [2]
- **Production capacity constraints are likely to mean that split sourcing will be required for larger projects.** Developers with projects requiring more than 50 non-monopile foundations will use two or more suppliers, with related additional contracting resource and quality management resource required. For larger projects, the option may be split-sourcing a proportion of the project and retaining a fraction that will be awarded to the best performing supplier. [33]
- **Cost reduction is currently focused on achieving marginal gains through more streamlined manufacturing.** Although there has been a strong focus in the industry on developing new and innovative foundation designs to achieve cost reductions, the gains that have been made so far have been through investment in facilities that have allowed easier handling of foundation designs and more streamlined production flow between production stages. [33]
- **Routinely used standards for steel structures might result conservative.** To revise partial safety factors for loads and materials based on inspection regimes and consequences of failure would provide an optimised design. [33]

GBF

- **High cost of transport and installation of the concrete solutions using a heavy-lift vessel.** For currently installed foundations and also for deeper gravity bases that are non-buoyant (such as Thornton Bank), a HLV is required for transport and installation, which results costly due to the high charter rate of this type of installation vessel. [33]
- **Non-buoyant designs have a high investment hurdle for demonstration.** Some novel concepts involve a bespoke vessel for installation. For a commercial wind farm the costs can be borne by the project but the investment for a one-off demonstration project would be high. Without opportunities for demonstration, however, these will be unavailable to the market. [33]
- **Lack of economically viable demonstration opportunities for self-buoyant foundations.** Although the long term behaviour of gravity base structures is well understood, there is

[9] The p-y method is a method of analysis the ability of deep foundations to resist loads applied in the lateral direction.

still uncertainty about the proposed installation strategies that involve floating the structure to site and lowering it to the sea bed. [2]

- **Space required in dock.** Gravity bases that are constructed on dock may need large space for assembly and storage.
- **Limited number of suitable construction sites.**

Floating foundations

- **Lack of experience in commercial offshore wind farms.** Despite several full-scale and test pilots are currently installed in European waters and new concepts and technologies are under development there is no experience based on commercial offshore wind farms.
- **Restrictions in the design due to movements that affect the rotor**. Controlled motions and the way they affect system performance and strategies for controlling the rotor, are linked to the dynamic response of the floating structure. [54]
- **Deeper waters and higher distance to shore, where floating foundations are suitable, might imply higher O&M costs.** Supply chain and port infrastructure requirements for floating turbines may be similar to those of fixed bottom offshore wind, but the economics of deep offshore projects are different in terms of installation and operations and maintenance (O&M) costs. [54]

3.4.4 Vessels and equipment

- **Lack of port and ship handling and lashing logistics' standardization**: These issues are nowadays dependent on particular solutions provided in manufacturers handling manuals and/or based on maritime surveyor's decisions.
- **Difficulty in defining standardized lifting points for components and subassemblies, due to specific manufacturers design**. Lack of common guidelines to define lifting points reduces standardization possibilities for ancillary and lifting systems and related equipment.
- **Restrictions to present optimization strategies due to high volumes and dimensions of new turbines**. I.e impossibility of quayside rotor assembly due to reach or loading capacity problems will make unfeasible the single lift or bunny ear installation strategies unfeasible, so principles as minimal lifts may be questioned.

3.5 New logistics solutions for further offshore wind farms

Further offshore wind farms require large-scale production. Some of the novel logistic solutions propose the optimization the whole process, and include the design of specially equipped terminals. There is a tendency to reach high levels of preassembly before the foundation is transported, so in many of the solutions, a specially built vessel is required. Some examples are the ones presented below.

- **STRABAG Terminal in Cuxhaven.** It is expected that up to 80 completely assembled wind turbines can be taken from there to wind parks in the North Sea.
    - Foundations are produced and the wind turbines are fully assembled in the construction yard.
    - The complete unit is then taken by the STRABAG Carrier to site once the footprint has been prepared.

- Foundation is ballasted with sand and the surrounding areas are filled in again with sand.

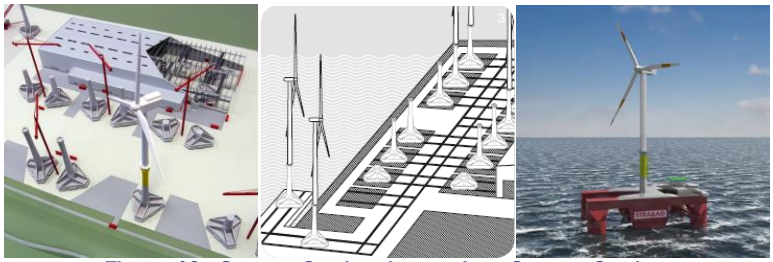

Figure 40 - Source: Strabag innovations Source: Strabag

- BAM and Van Oord solution
  - GBSs are designed to be mass produced onshore in a quayside construction yard.
  - Mammoet undertake transport and load out of the GBSs, moving the foundations into deeper water with a semi-submersible barge.
  - Foundations are towed to site using standard, ocean going tugs.
  - A Trailing Suction Hopper Dredger prepares an excavation into which gravel is placed using a Flexible Fall Pipe Vessel.
  - Finally, foundations are lowered and filled with sand.

Figure 41 - GBF solution proposed by consortium BAM-Van Oord. Source: Bamnuttal-Van Oord

- CRANEFREE Seatower.
  - Foundations are constructed on batches followed by the installation of steel pieces
  - GBSs are transported afloat to site and lowered by 3 towing vessels
  - Water enters inside the foundation and it increasing weight lowers it and pushes it into the seabed.
  - Concrete is injected to fill the void between the soil and the base and the foundation is filled with sand to provide enough self-weight (6000-7000 tonnes), and scour protection is layered.

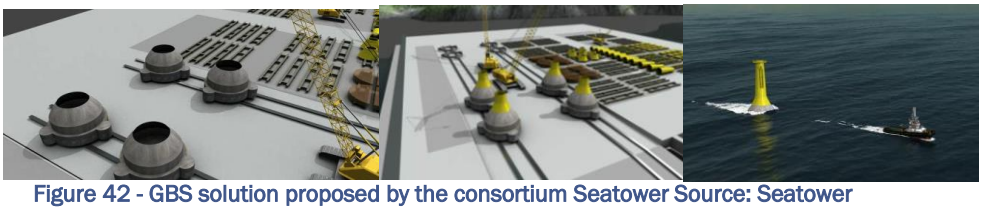

Figure 42 - GBS solution proposed by the consortium Seatower Source: Seatower

- VINCI in collaboration with GBF
  - The turbine and foundation assembled on shore before being lowered into the water

- The Transport Installation Barge (TIB) rises up to the level of the foundation and picks both elements and lowers to transportation depth. Tugs undertake transport.
- Once positioning has been verified, the TIB releases the gravity base.

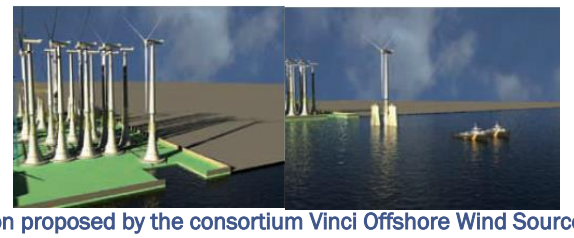

Figure 43 - Source: GBS solution proposed by the consortium Vinci Offshore Wind Source: Vinci offshore Wind

- VICI VENTUS
  - The base structure can be constructed on floating barges, in a dry dock or on a quay
  - The remaining shaft is cast while the structure is moored in sheltered waters
  - The tower and turbine may be lift installed inshore

Figure 44 - Source: GBF solution proposed by the consortium Vici Ventus

- Signal International

  Signal International based in Texas has a manufacturing capacity of nearly 60,000 tons of steel per year. Their facilities are equipped with crane hooks 65' in height, multiple work stations, and a 400 tonnes load out, facilities have the capability to build multiple structures simultaneously.

  An industrial line has been developed to manufacture jacket structures by the assembly of modules.

Figure 45 - Solution proposed by Signal international. Source Signal International

3.6 Integrated logistic potential/ Opportunities for optimisation

3.6.1 Foundations

As a summary of all the processes described in this document, some graphs have been produced outlining the existing/future lines of production and installation of offshore wind farms.

The idea of the following graphs is to provide a general overview of the whole process involved according to each type of foundation (monopile, GBS, jacket and other steel structures), separating the activities that are undertaken **on land**, i.e. before lowering to the water, **transport** activities once the foundation is in the water, and **offshore** activities that have to be undertaken in site.

Then, the different options in each phase (on land activities, transport activities and offshore activities) are reviewed, trying to sketch all the existing possibilities so that combinations of them can be easily identified, and also constraints and bottlenecks can be detected so that unnecessary steps can be avoided.

In addition, a graph of turbine installation is provided at the end of the three possibilities, since it is common to the three foundation types.

3.6.2 Monopiles

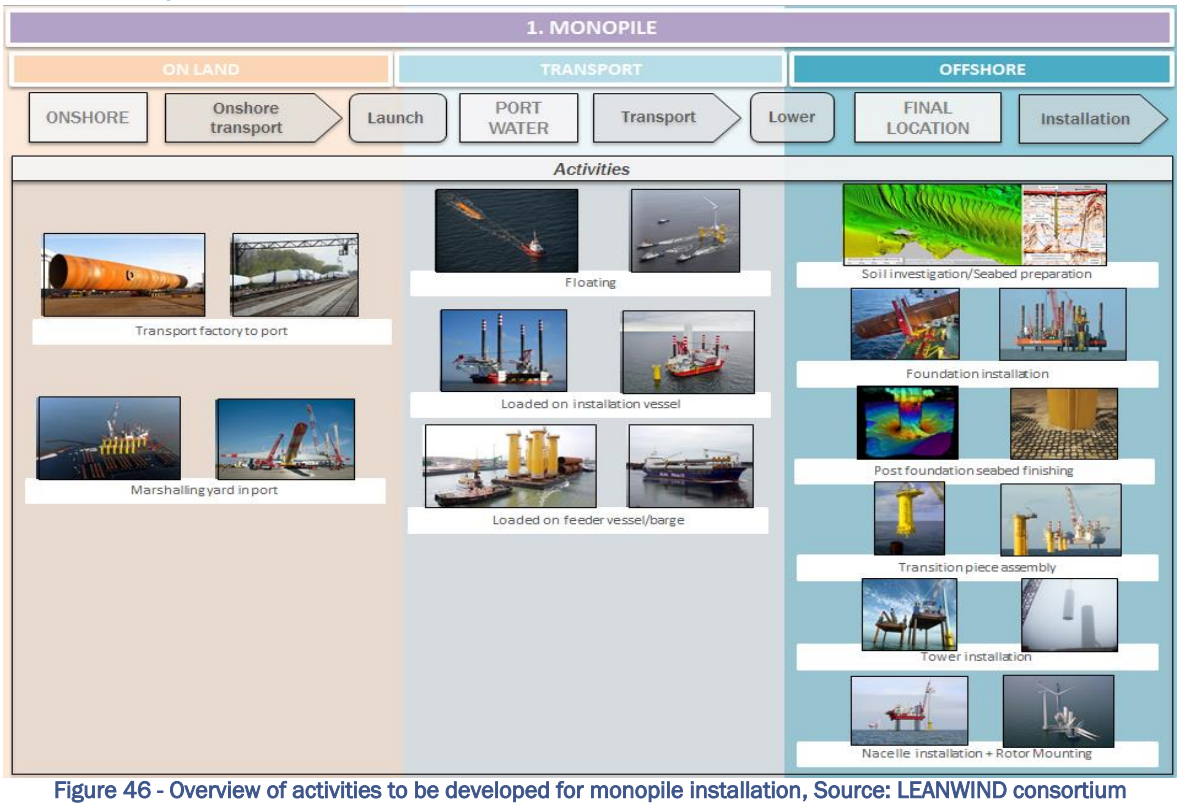

Figure 46 - Overview of activities to be developed for monopile installation, Source: LEANWIND consortium

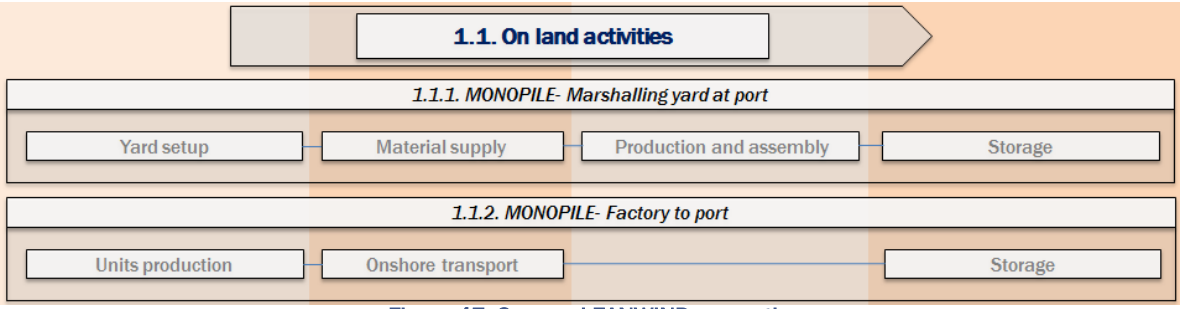

Figure 47, Source: LEANWIND consortium

The two main options identified for monopiles manufacturing (*1.1. On land activities)* are:

- Marshalling yard at port (1.1.1) - This option requires enough space at port to host all the equipment required for monopiles manufacture and assembly. The material is supplied straight in port. If production on port is adapted to transport capacity, no extra storage capacity would be required.
- Factory to port (1.1.2) - The units are produced in an industrial plant, so onshore special transport is required regarding large sizes and weights of monopiles. Storage space might be considered for units waiting to be installed.

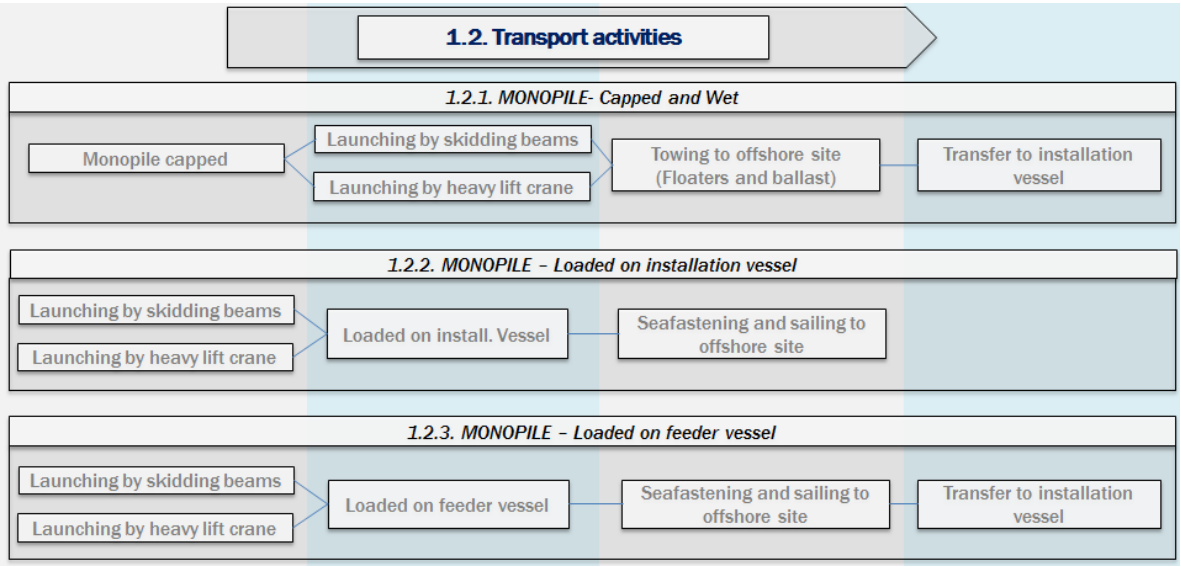

Figure 48 - Source: LEANWIND consortium

Three options for monopile transport (*1.2. Transport activities)* have been identified. In all cases, it can be decided whether launching the monopile by means of skidding beams (either rolling or sliding) or loading it by a heavy lift crane.

- Capped and wet (1.2.1) - Some space is required on port to prepare the monopile. Then, standard tugs are used to transport the foundation afloat to site where needs to be lifted to the installation vessel (possible bottleneck).
- Loaded on installation vessel (1.2.2) - The monopiles are properly fastened and transported directly in the installation vessel. Various units can be transported at a time.
- Loaded on feeder vessel (1.2.3) - The monopoles are transported on a supply vessel and transferred to the installation vessel in site. This is an extra operation compared to

loading foundations directly in the installation vessel, but increases availability of transport vessels.

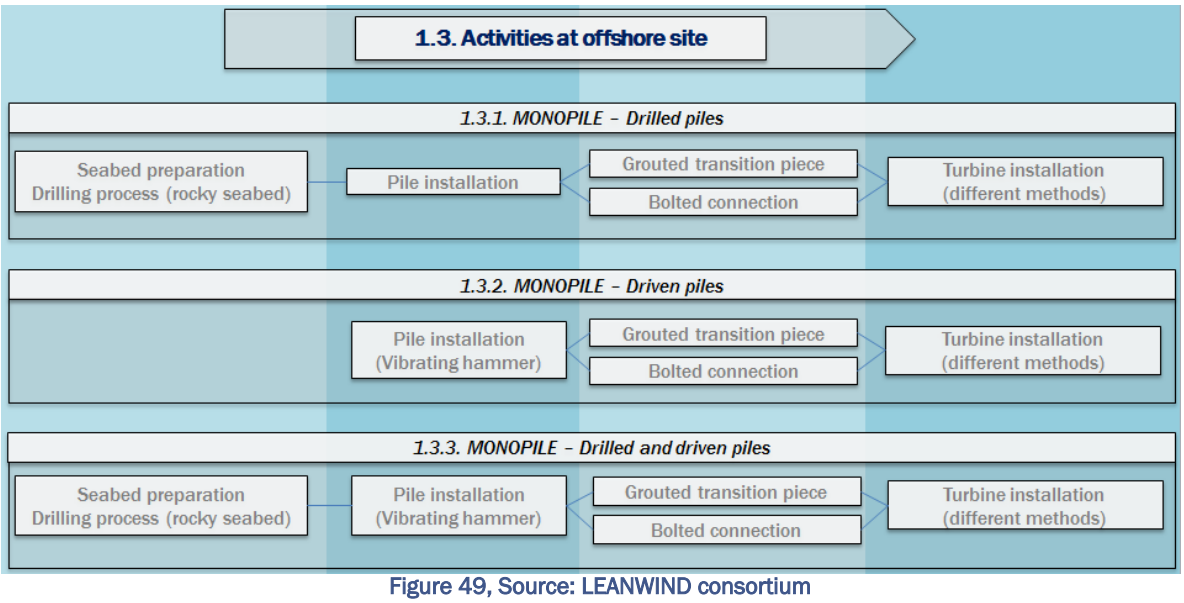

Figure 49, Source: LEANWIND consortium

Once in site, three installation processes have been identified depending on the type of soil apart from the turbine installation that will be explained later.

- Drilled piles (1.3.1) - Previous to the foundation pile installation, a drilling process is required in rocky soil.
- Driven piles (1.3.2) - This process does not require seabed preparation. It is undertaken by vibrating hammer or a hydro hammer, but is not valid for rocks.
- Driven and drilled piles (1.3.3) - When the soil has the potential of resulting in refusal of monopiles during driving prior to attaining their terminal elevation, (due, for example, to the presence of weathered and weak sedimentary rocks), a combination of both driving and drilling activities can be considered to ensure the suitability of monopiles as a solution[10].

The other decision to be considered is whether install a grouted transition piece or a bolted joint.

[10] New BAUER Flydrill system drilling monopoles at Barrow Offshore Wind Farm, UK. Manfred Beyer and Wolfgang G. Brunner

3.6.3 Gravity Base

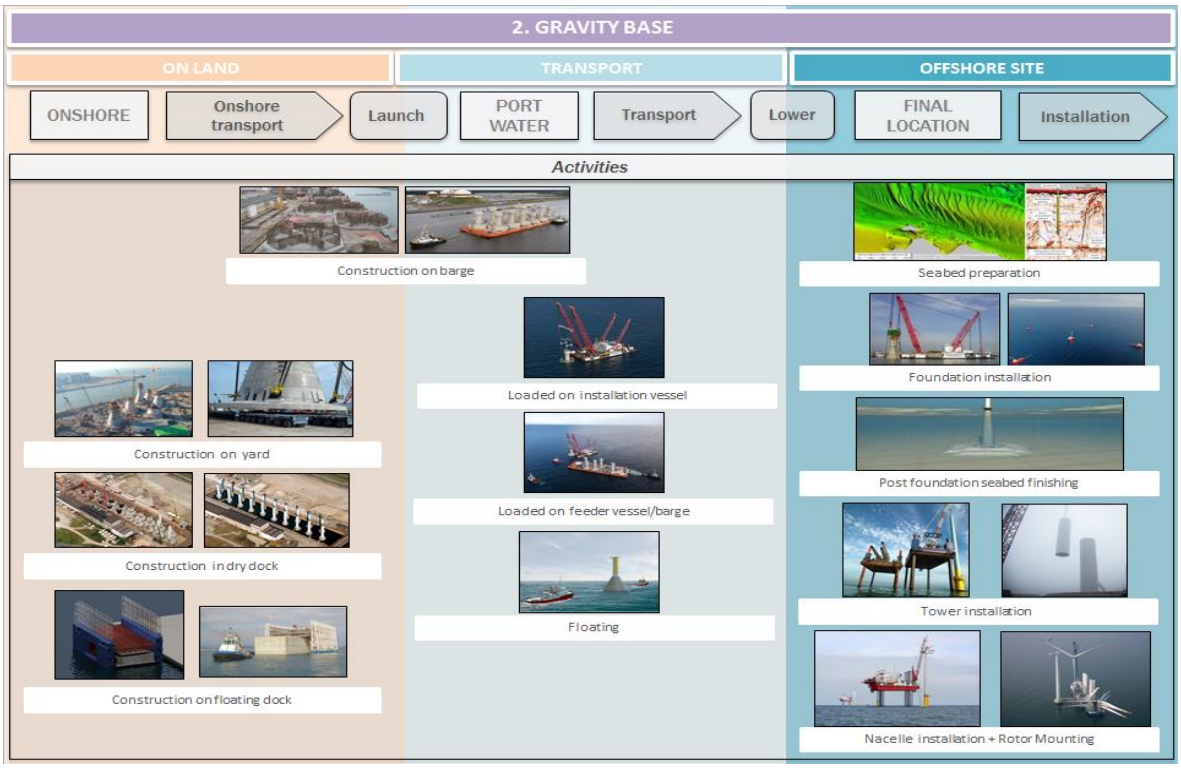

Figure 50 -Overview of activities to be developed for GBS installation. Source: LEANWIND consortium

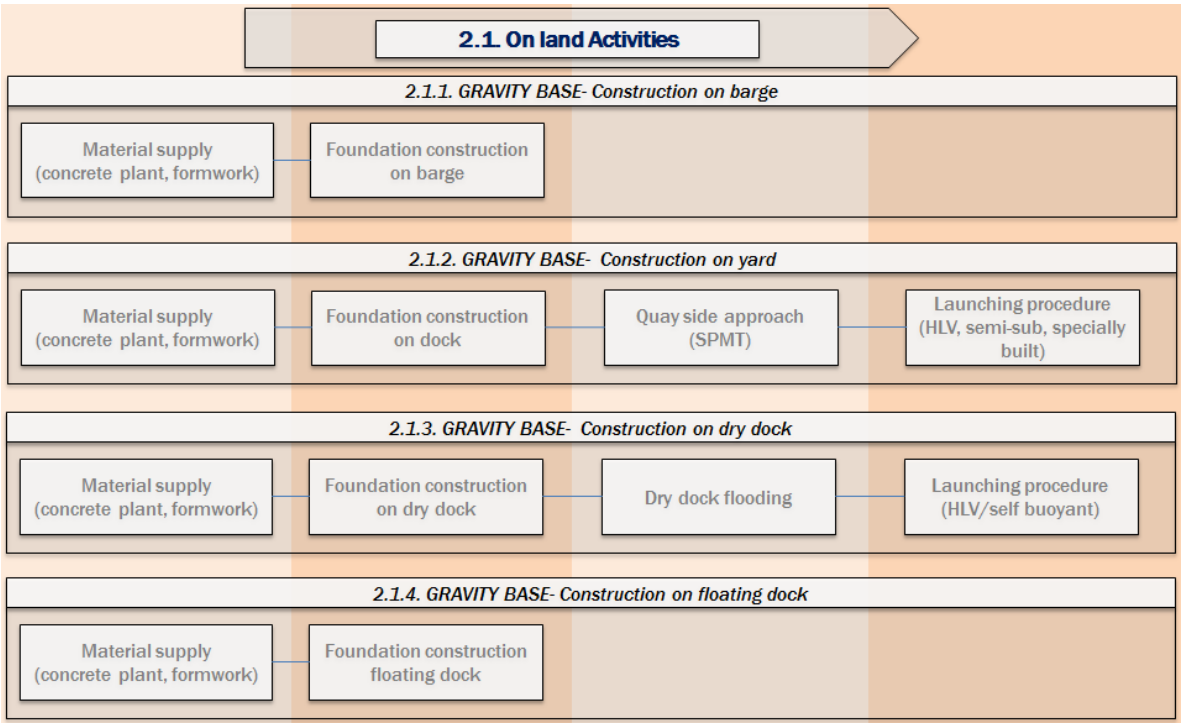

Figure 51, Source: LEANWIND consortium

Regarding GBFs, the following four production processes have been identified. Two of them are not built on land, but they can be considered in section *2.1 On land activities* since they are built in port water.

- Construction on barge (2.1.1) - This option is only suitable for small dimensions and weight foundations. Yard space is reduced since the construction is carried out on the barge which in the water side. Only some equipment must be placed in the land side (lifting equipment, material supply).
- Construction on yard (2.1.2) - Construction on a yard requires a large space in port. This procedure is suitable for bigger and heavier foundations, to be installed at greater water depths. Therefore, a number of SPMTs are required for quay approaching which can be a cumbersome manoeuvre. To accomplish the launching operation, a Heavy Lift Vessel could be required (solution adopted in Thornton Bank), but also other options for launching can be used, such a semi-submersible vessel (solution proposed by BAM and Van Oord), or special built barges.
- Construction on dry dock (2.1.3) - The dry dock offers the advantage of facilitating the launching procedure since it is achieved by flooding. Dry dock might offer the problem of availability, and draft should be considered to enable the vessel enter the dry dock to carry the foundations (this was the case of Middlegrunden), but also self-buoyant foundations could be constructed in a dry dock, so tugs would be required.
- Construction on floating dock (2.1.4) - This option offers the possibility of reducing space at port since foundations are constructed in water side. This process is suitable for large floating foundations with the limitation of draft. The launching procedure is avoided, since foundations remain afloat, so standard tugs can undertake this manoeuvre.

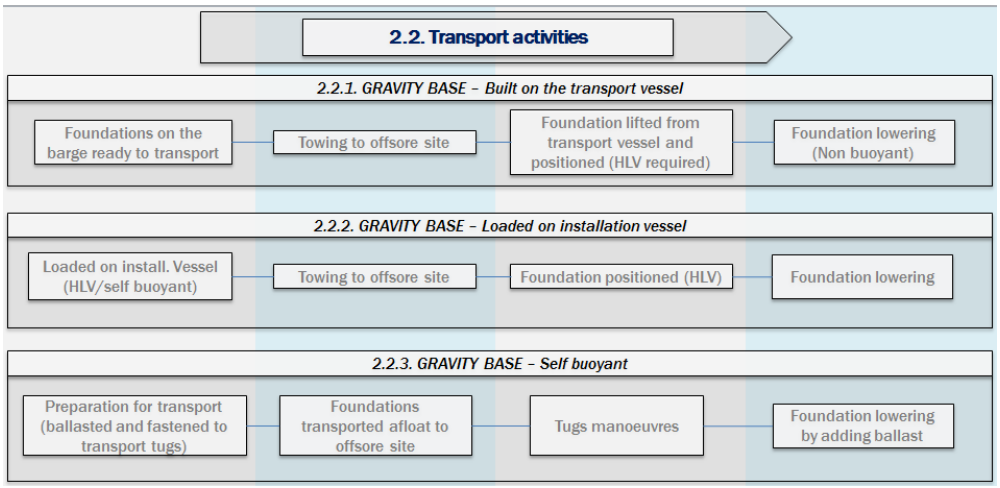

Figure 52 – LEANWIND consortium

The options for GBS transportation (*2.2 Transport activities)* are conditioned by the construction method.

- Built on transport vessel (2.2.1)- While this process allows for multiple foundations transported at a time on the same barge a bottleneck appears when a HLV is required to lift the foundations and lower them into the ground.
- Loaded on installation vessel (2.2.2)- The installation vessel in this case would be a HLV, with the correspondent constraints of this vessels, that might have undertaken the launching procedure in *2.1 On land activities.* This activity is linked to *2.1.2 Construction on yard* and *Construction on dry dock.*
- Self buoyant (2.2.3) -In case that foundation design allows for self buoyancy of the structure, standard tugs would be required to accomplish the transportation. This activity

is linked to *Construction on yard* (BAM and Van Oord solution), *2.1.3 Construction on dry dock* considering buoyant structures and 2.1.4 *Construction on floating dock* which will be self-buoyant, otherwise this option would not make sense. For lowering these foundations, the tugs must be positioned in the precise way to allow for this manoeuvre.

In general, self-buoyant foundations require the addition of ballast to be lowered to the ground, and non-buoyant foundations are lowered due to its self-weight.
As self-buoyancy requires high volumes of material, the use of additional floaters could be an opportunity for optimisation.

An opportunity for optimisation is considering preassembly before transport of part of the superstructure (e.g. lower part of the turbine tower) or even the whole trubine. In the latter case, a specially built device for accomplishing the transport would be required.

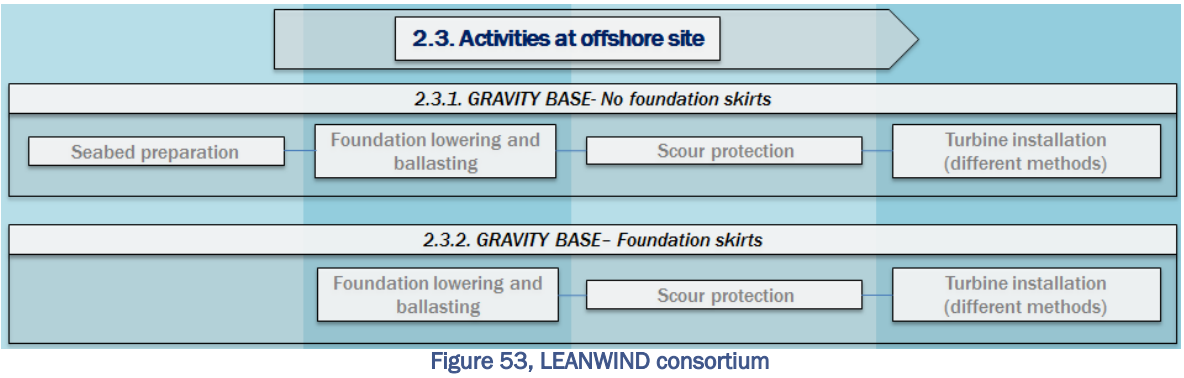

Figure 53, LEANWIND consortium

Before GBFs are on site, two possibilities exist for seabed preparation:

- No foundation skirts (2.3.1) - Gravity base foundations usually need seabed preparation before positioning it in place. This involves an extra activity that requires special equipment.
- Foundation skirts (2.3.2) - In this case, foundations include skirts that provide extra lateral stability. This could avoid the need for previous seabed preparation, but would require the injection of grout in the void existing between the foundation slab and the seabed to ensure horizontality (see CRANEFREE solution in Section 3.5)

In both cases, scour protection in required.

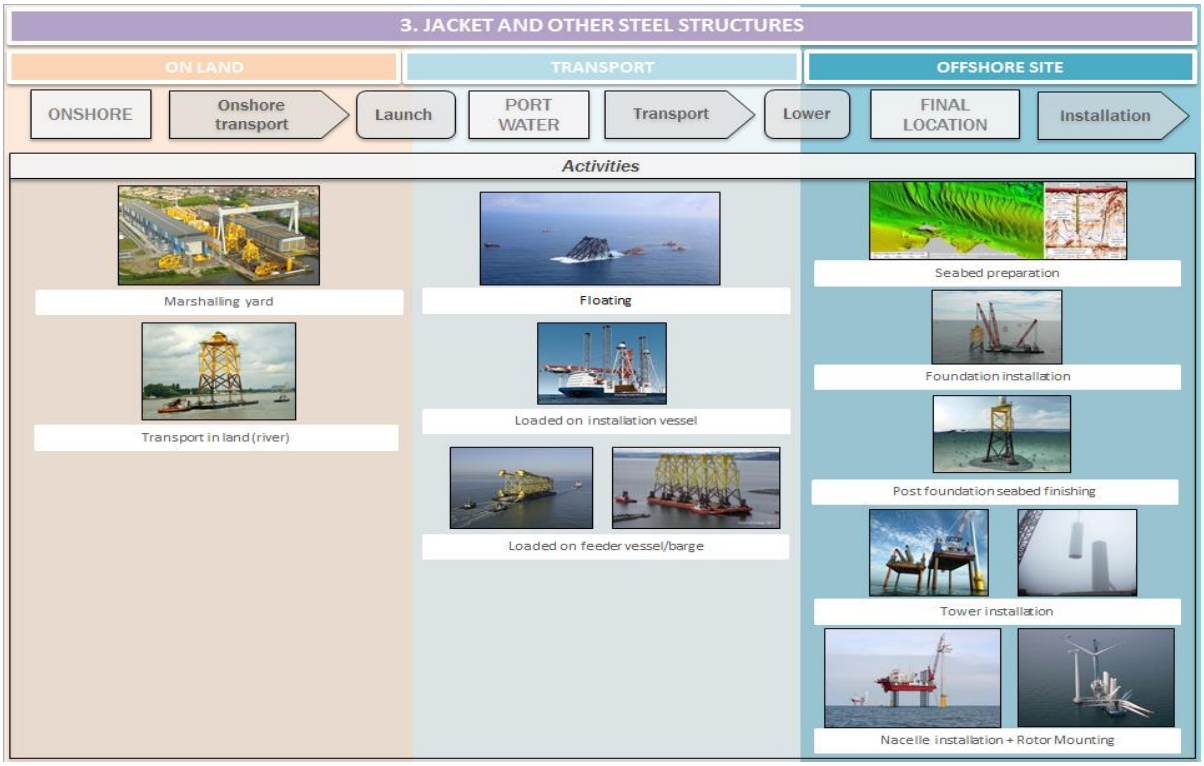

Figure 54 - Overview of activities to be developed for jacket and other steel structures installation, Source: LEANWIND consortium

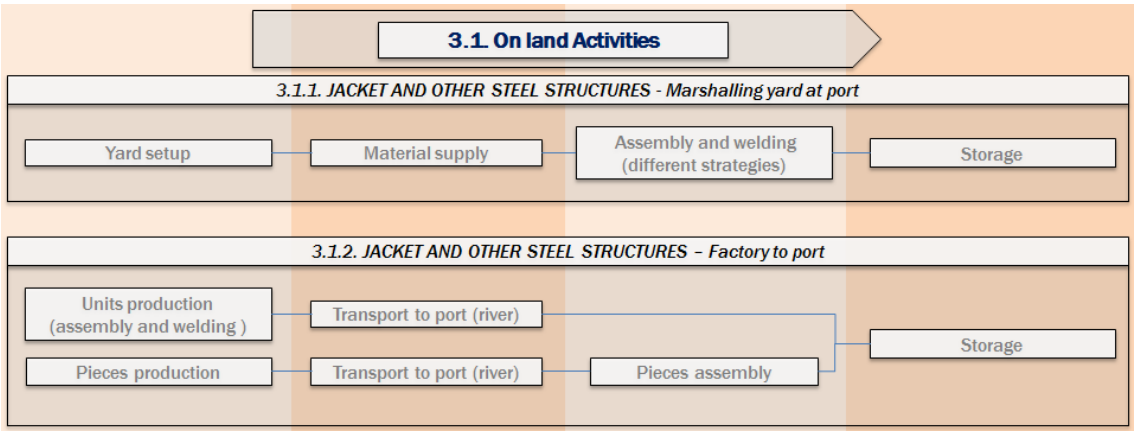

Figure 55 – LEANWIND consortium

The two main options identified for jackets and other steel structures for *3.1. On land activities* are the following:

- Marshalling yard at port (3.1.1) - This strategy requires a wide construction yard including buildings workshops and store areas where the different activities involved take place (material supply, welding). Wherever possible, large sub-assemblies are constructed undercover to ensure no delays from weather downtime and contamination of the works specially ensuring the welding process. Where sub-assemblies are too big for available workshop space then temporary buildings are erected to accommodate construction. The sub-assemblies are moved to final erection site and final assembled.
- Factory to port (3.1.2) - When considering the supply of factory elements not based in the port, two options appear. On the one hand, the units are produced in the industrial plant,

in that case, regarding large size and weight no onshore (rail or road) transport would be feasible, but where possible, river transport could be considered. On the other hand, complete sections of the structure can be supplied by factory, so that the pieces can be transported by onshore means and can be assembly in the port yard. This option would reduce space at port compared to *3.1.1*. Pieces storage space might be considered for units waiting to be installed.

In global terms, other opportunities for optimisation are [33]:

- The standardisation of tube sizes, welding procedures and node designs enables lower cost manufacture. A number of jacket designs under development use standard tubes. This potentially lowers the cost of steel although the steel mass may be greater.
- There is increasing interest in supply from low cost countries. Jackets and tripod fabrication have a higher labour content than monopiles, which makes supply from low cost countries more attractive. This is particularly likely where there are strong heavy engineering sectors such as shipbuilding. Despite this, the amount of deck space needed to transport space frames may result in little cost benefit and there is a higher risk to project schedules if any problems arise. Solutions may include the transport of partially assembled sections or designs that enable more efficient use of deck space.

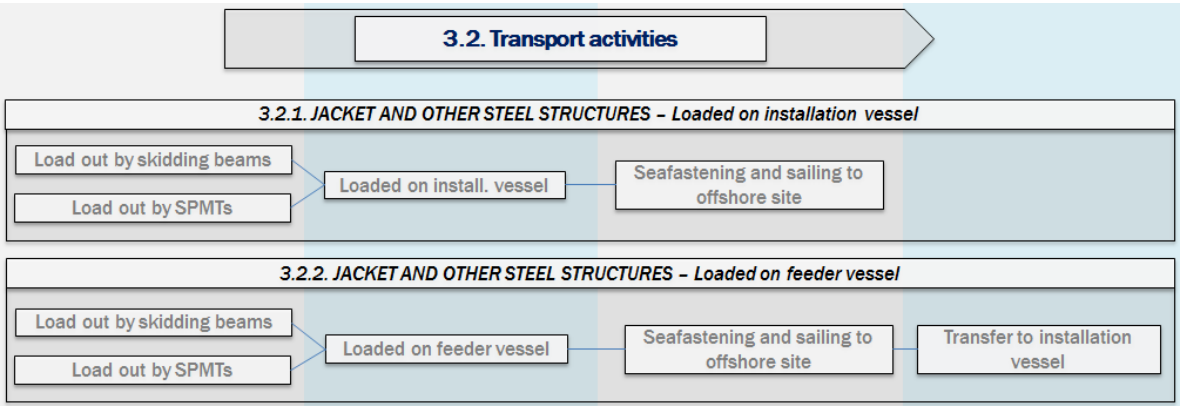

Figure 56, LEANWIND consortium

For steel structures transportation, three different possibilities have been identified. In all cases, the decision of launching system must be made considering both options: skidding beams or SPMTs.

- Loaded on installation vessel (3.2.1) - The structures are properly fastened and transported directly in the installation vessel. Depending on the dimensions and weight, various units can be transported at a time.
- Loaded on feeder vessel (3.2.2) - The structures are transported on a supply vessel and transferred to the installation vessel once arrived on site.

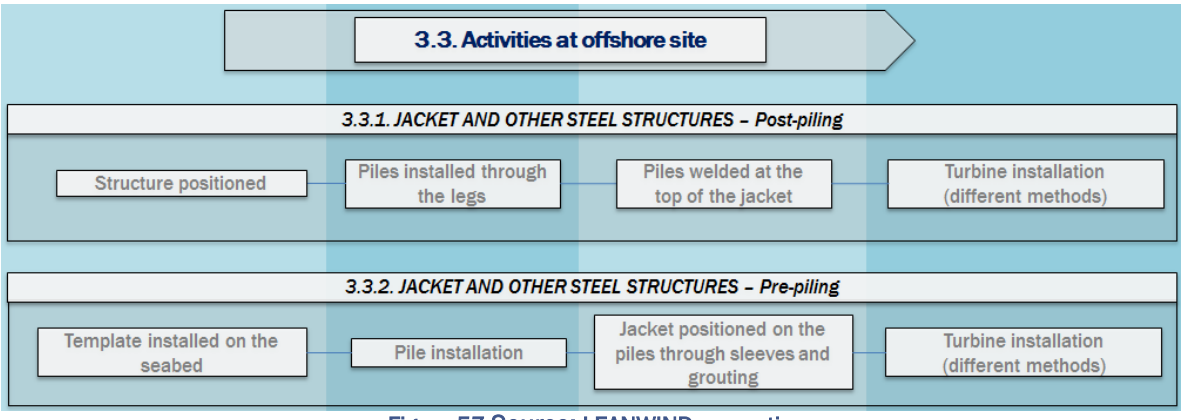

Figure 57 Source: LEANWIND consortium

The two possibilities detected for fixing the foundation to the soil are described below:

- Post-pilling (3.3.1) - The structure is usually positioned on the seabed and afterwards, piles are driven through pile sleeves at the bottom of the structure, or the piles can also be driven through the legs of the structure. When talking about jackets, piles and the top of the structure are usually welded. In this case, the structure is fixed to the ground at the moment of the installation on site, so offshore activities extend longer.
- Pre-piling (3.3.2) - A template is used to drive the piles at the right place. Once the piles are positioned, the gap between the sleeves and the piles filled with grouting material. The pre-pilling option allows spending less time during the installation of the jacket and allows for undertaking seabed preparation activities separately from structure installation.

3.6.4 Turbine installation

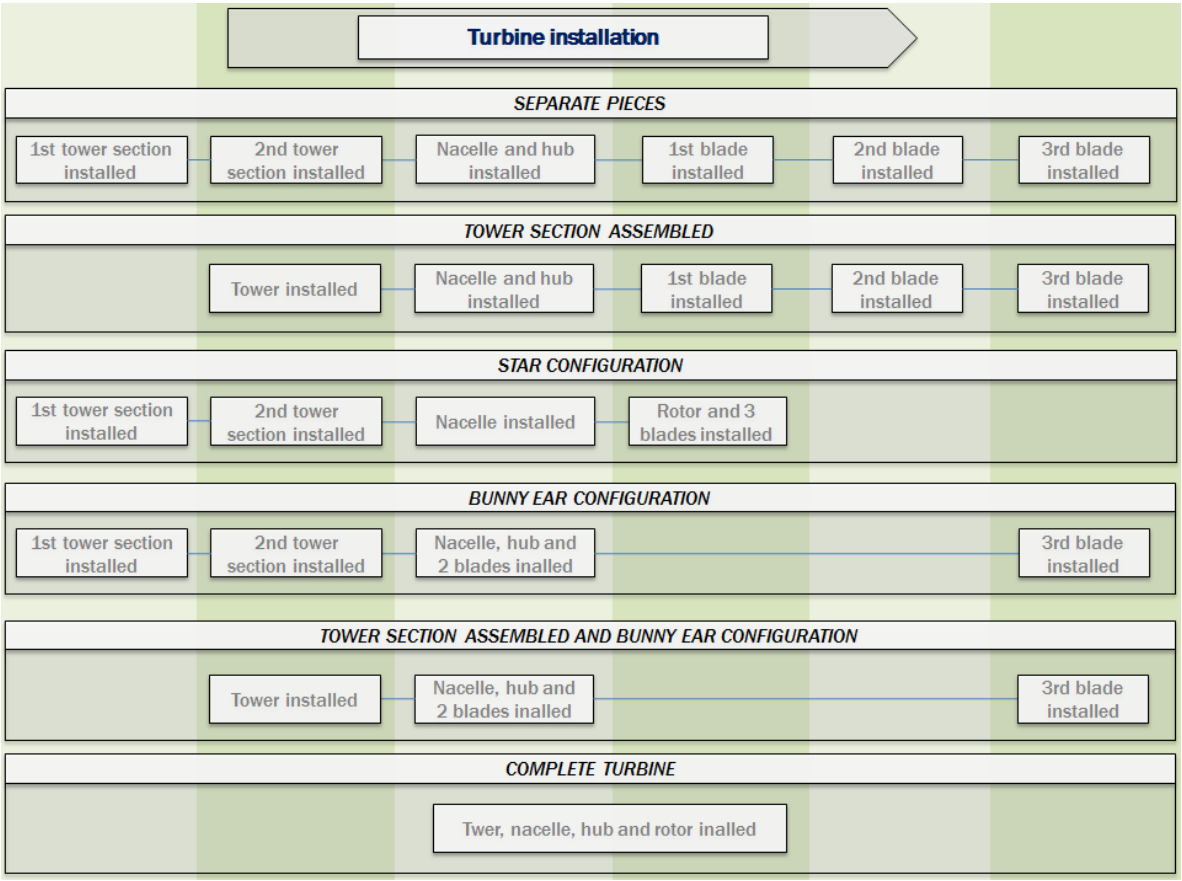

Figure 58, Source: LEANWIND consortium

- **Separate pieces**. This configuration involves the minimum pre-assembly and hence requires the maximum number of offshore lifts. This method suits wind farms that are located far offshore, since a large number of turbine elements can be stored offshore and transported to the construction site in one trip. The strategy was adopted for turbine installation at Sprogo and Lynn and inner dowsing wind farms.
- **Tower section assembled.** The tower sections are also assembled onshore and are installed in a single lift. The three blades are each lifted separately. This method was used in Rhyl flats and Burbo bank.
- **Star configuration**. It involves the pre-assembly of rotor (hub and the three blades). The tower is installed in two separate lifts, followed by installation of the nacelle and the pre-assembled turbine. This strategy distributes the weight among the lifts. The assembled rotor is unlikely to weigh more than the nacelle on its own. Therefore, this lift is usually not the critical lift. This approach was used in a number of developments, such as Nysted, Alpha Ventus, Lillgrund, Arklow, and Thornton bank.
- **Bunny ear configuration**. This configuration involves installation of tower in two separate lifts. Then the nacelle, hub, and two blades, pre-assembled onshore, are transported in a bunny ear configuration and installed. The last blade is installed independently. In this installation strategy, the third lift, corresponding to the installation of nacelle, rotor, and the two blades is the critical lift, determining the requirements for crane capacity. This method was adopted in Horns Rev, North Hoyle, Scroby Sands, and Kentish flats.

- **Tower section assembled and bunny ear configuration:** Another possible configuration is to assemble tower onshore, and install it in a single lift; transport the nacelle, rotor and two blades in a bunny ear configuration, and install this pre-assembled combination in the second lift. The third blade is installed separately. This installation strategy distributes the weight evenly between the two heaviest lifts, and was utilised at Prince Amalia, and OWEZ wind farms.
- **Complete turbine:** The recently proposed strategies aim at onshore assembly of the tower and turbine, transporting and installing it in a single lift. This method has not been employed at any large scale wind farm installation so far. Wind turbines at the demonstration project Beatrice were installed using this approach.

	MONOPILES		
1.1.	On land activities		
1.1.1	Marshalling yard at port	Large space required in dock	Space constraint
		Need for planning to reach an industrial production line	Production bottleneck
		Less storage space required	Space constraint improvement
1.1.2	Factory to port	Special onshore transport requirements due to large dimensions and weights	Transport bottleneck
		Industrial line production (high quality of product)	Opportunity for material optimisation
		Storage space increased	Storage constraint
1.2.	Transport activities		
1.2.1	Capped and wet	Transport afloat allows for less specialised vessel (such as tugs)	Transport availability
		Suitable for XL monopiles (large volume so that self-buoyancy is obtained)	Suitable for large monopiles
		One unit at a time.	Suitable for reduced distance to port
1.2.2	Loaded on installation vessel	Reduced dimensions of monopiles	Suitable for large monopiles
		Big installation vessel with upending frame on board required	Transport availability limited
1.2.3	Loaded on feeder vessel	Transfer to the installation vessel is an extra operation. Transfer requires calm sea state	Transfer operation bottleneck
1.3.	Offshore activities		
	Drilled piles	Requires previous drilling	Suitable for rocky soil
			Extra operation
1.3.2	Driven piles	No need for seabed preparation	Suitable for not rocky soil
1.3.3	Drilled and driven piles	Used when refusal potential exist	Extra operation
Other	Grouted transition piece	Need for transition piece	Extra operation
Other	Bolted connection	Eliminates the need for transition piece.	Opportunity for material optimisation
		Turbine and monopile joint at	Time-consuming offshore

		offshore site	activity
2.	GBS		
2.1.	On land activities		
2.1.1.	Construction on barge	Reduced dimensions and weights of foundation required	Suitable for shallow waters
		Reduced space in yard (cranes and equipment, formwork, material supply) since construction is undertaken in port water.	Space constraint improvement
2.1.2.	Construction on yard	Large dimensions of GBS that need to be constructed on yard require large space at port	Space constraint
		Difficult quayside approach procedure due to high weight of GBSs	Load out bottleneck
		Need for heavy lifting equipment to lower into the water that might have availability constraints (HLV)	
2.1.3.	Construction on dry dock	Special facility at port	Availability constraint
		Enough draft required for allowing both HLV enter/self-buoyant foundation float	Draft constraints in port water
		For non-buoyant foundations a HLV is required	Availability constraint
2.1.4.	Construction on barge	Foundations constructed in port water side	Space constraint improvement
			Draft constraints in port water
2.2.	Transport activities		
2.2.1.	Built on the transport vessel	Multiple foundations at one time but a HLV for lowering all of them	Installation bottleneck
2.2.2.	Loaded on installation vessel	For non-buoyant foundations a HLV is required	Availability constraint
2.2.3.	Self-buoyant	Standard tugs required	Availability improvement
		Additional buoyancy provided allows for reducing dimensions of foundations	Opportunity for material optimisation
Other	Preassembly	Part of the turbine assembled before transport	Suitable to several options regarding turbine installation
		Complete turbine assembled before transport	Custom built device required
2.3.	Offshore activities		
2.3.1.	No foundation skirts	Seabed preparation required	Extra activity
		Separate offshore activities: seabed preparation and structure installation.	Reduction of time-consuming offshore activity
2.3.2.	Foundation skirts	Injection of grout in the void existing between the foundation slab and the seabed	Time-consuming offshore activity
3.	JACKET AND OTHER STEEL STRUCTURES		
3.1.	On land activities		
3.1.1.	Marshalling	Need for several buildings for	Space constraint

	yard at port	material supply, manufacture, assembly and welding	
		Need for planning to reach an industrial production line	Production bottleneck
3.1.2.	Factory to port	Whole units produced in an industrial plant that need to be transported to port. Need for alternative transport strategy (e.g. transport by river)	Port location constraint
		Modules produced in plant. Special onshore transport requirements due to large dimensions and weights	Transport bottleneck
		Modules produced in plant. Reduced space required.	Space improvement
		Modules produced in plant. Increased storage area	Space constraint
Other	Standardisati on	Standardisation of tube sizes, welding procedures and node designs	Availability improvement
3.2.	Transport activities		
3.2.1.	Loaded on installation vessel	Special vessels required	Availability constraint
		Increased time for jacking up	Time-consuming offshore activity
3.2.2.	Loaded on feeder vessel	Higher number of units to be delivered at one time but only one installation	Transfer operation bottleneck
3.3.	Offshore activities		
3.3.1.	Post-piling	Activities at offshore site need longer time	Time-consuming offshore activity
3.3.2.	Pre-piling	Separate offshore activities: seabed preparation and structure installation.	Reduction of time-consuming offshore activity
			Extra activity

Table 16

3.6.5 Vessels and equipment

The necessities observed in the equipment and vessels required for installing the foundations, were listed in D3.1. According to each scenario proposed and the correspondent foundation suitable, the table shown below highlights the possibilities of actuation due to the constraints found.

Case	Water depth (m)	Dist. To Port (km)	Foundation Type	Installation Vessel Type Foundation	Installation Vessel Type Topside	Main Challenges	Possible Solutions	Cost reduction potential impact
0	20	30	Monopile	Jack-Up	Jack-Up	No industrial standard for sea fastenings	Standardised and flexible sea fastenings	Medium
						Time for positioning	Improved DP / manoeuvring performance	Medium
						Quality of weather forecasts	Improved decision support	Medium
						Weather windows for Jacking	Improved Jack-Up design	High
						Time for Jacking	Increased jacking speed	Low
						Weather windows for crane lifts (tower and blades)	Improved damping of relative motions	High
							Consider whole turbine installation "All-in-one"	High
			Gravity based	Tug	Jack-Up	Time for positioning for foundation installation	Improved tug coordination (3 tugs)	Medium
							Relaxed positioning accuracy	Medium
						Reduce time for tow	Increase transit speed by reducing structure drag	
1	40	30	Jacket or tripod	Jack-Up	Jack-Up	Limited space for foundations on installation vessel	Consider feeder arrangement	High
						Time for positioning	Improved DP / manoeuvring performance	Medium
						Quality of weather forecasts	Improved decision support	Medium
						Weather windows for Jacking	Improved Jack-Up design	High
						Time for Jacking	Increased jacking speed	Low
						Weather windows for crane lifts (foundations,	Improved damping of relative motions	High

						tower and wings)		
							Consider whole turbine installation "All-in-one"	High
						Lifting jacket through splash zone	Jacket design	-
							Crane heave control/ compensation	-
				DP Float/ Sheer-leg	Jack-Up	Weather windows for positioning (incl. DP)	Improved holding capability	-
						Weather windows for sheerleg crane lifts	Crane heave control/ compensation	-
			Gravity base structure	Tug	Jack-Up	Time for positioning for foundation installation	Improved tug coordination (3 tugs)	Medium
							Relaxed positioning accuracy	Medium
						Reduce time per tow	Improve GBS design for reducing drag during tow	-
2	60	100	Jacket or tripod	Jack-Up	Jack-Up	Limited space for foundations on installation vessel	Consider feeder arrangement (offshore lift requires low waves / winds)	High
						Time for positioning	Improved DP / manoeuvring performance	Medium
						Quality of weather forecasts	Improved decision support	Medium
						Weather windows for Jacking	Improved Jack-Up design	High
						Time for Jacking	Increased jacking speed	Medium
						Leg length	Increased leg length	Low
						Weather windows for crane lifts (foundations, tower and wings)	Improved damping of relative motions	High
							Consider whole turbine installation "All-in-one"	High
						Splash zone challenges, (foundation design	Jacket design	-

						dependent)		
							Crane heave control/ compensation	-
				DP Float/ Sheer-leg	Jack-Up	Weather windows for positioning (incl. DP)	Improved holding capability	-
						Weather windows for sheerleg crane lifts	Crane heave control/ compensation	-
			Floating	Tug + DP floater	Jack-Up	Relative motion between crane and topside during installation	Whole turbine tow-out	-
							Reduction of relative motion : SPAR gripper	-
3	100	30	Floating	DP Floater	DP Floater	Relative motion between crane and topside during installation	Whole turbine tow-out or damped foundation / assembly method	-
							Reduction of relative motion : SPAR gripper	-
				Tug	DP Floater	Increase in sea state for towing operations	Improved prediction of hydrodynamic response	-
						Handling of mooring		-
Case	Water depth (m)	Dist. To Port (km)	Foundation Type	Installation Vessel Type Foundation	Installation Vessel Type Topside	Main Challenges	Possible Solutions	Cost reduction potential impact
0	20	30	Monopile	Jack-Up	Jack-Up	No industrial standard for sea fastenings	Standardised and flexible sea fastenings	Medium
						Time for positioning	Improved DP / manoeuvring performance	Medium
						Quality of weather forecasts	Improved decision support	Medium
						Weather windows for Jacking	Improved Jack-Up design	High
						Time for Jacking	Increased jacking speed	Low
						Weather windows for crane lifts (tower and blades)	Improved damping of relative motions	High

							Consider whole turbine installation "All-in-one"	High
			Gravity based	Tug	Jack-Up	Time for positioning for foundation installation	Improved tug coordination (3 tugs)	Medium
							Relaxed positioning accuracy	Medium
						Reduce time for tow	Increase transit speed by reducing structure drag	
1	40	30	Jacket or tripod	Jack-Up	Jack-Up	Limited space for foundations on installation vessel	Consider feeder arrangement	High
						Time for positioning	Improved DP / manoeuvring performance	Medium
						Quality of weather forecasts	Improved decision support	Medium
						Weather windows for Jacking	Improved Jack-Up design	High
						Time for Jacking	Increased jacking speed	Low
						Weather windows for crane lifts (foundations, tower and wings)	Improved damping of relative motions	High
							Consider whole turbine installation "All-in-one"	High
						Lifting jacket through splash zone	Jacket design	-
							Crane heave control/ compensation	-
				DP Float/ Sheer-leg	Jack-Up	Weather windows for positioning (incl. DP)	Improved holding capability	-
						Weather windows for sheerleg crane lifts	Crane heave control/ compensation	-
			Gravity base structure	Tug	Jack-Up	Time for positioning for foundation installation	Improved tug coordination (3 tugs)	Medium

							Relaxed positioning accuracy	Medium
						Reduce time per tow	Improve GBS design for reducing drag during tow	-
2	60	100	Jacket or tripod	Jack-Up	Jack-Up	Limited space for foundations on installation vessel	Consider feeder arrangement (offshore lift requires low waves / winds)	High
						Time for positioning	Improved DP / manoeuvring performance	Medium
						Quality of weather forecasts	Improved decision support	Medium
						Weather windows for Jacking	Improved Jack-Up design	High
						Time for Jacking	Increased jacking speed	Medium
						Leg length	Increased leg length	Low
						Weather windows for crane lifts (foundations, tower and wings)	Improved damping of relative motions	High
							Consider whole turbine installation “All-in-one”	High
						Splash zone challenges, (foundation design dependent)	Jacket design	-
							Crane heave control/ compensation	-
				DP Float/ Sheer-leg	Jack-Up	Weather windows for positioning (incl. DP)	Improved holding capability	-
						Weather windows for sheerleg crane lifts	Crane heave control/ compensation	-
			Floating	Tug + DP floater	Jack-Up	Relative motion between crane and topside during installation	Whole turbine tow-out	-
							Reduction of relative motion : SPAR gripper	-
3	100	30	Floating	DP Floater	DP Floater	Relative motion	Whole turbine tow-out or	-

						between crane and topside during installation	damped foundation / assembly method	
							Reduction of relative motion : SPAR gripper	-
				Tug	DP Floater	Increase in sea state for towing operations	Improved prediction of hydrodynamic response	-
						Handling of mooring		-

Table 17

4. WP Framework development

The overall objective of WP5 is to determine reductions in the cost of energy by increasing the efficiency of logistics operations in all aspects of the offshore wind farm supply chain.

This will be achieved by:

- Determining the key industry challenges and opportunities necessary for optimising offshore wind farm logistics
- Analysing and optimising the separate parts of the offshore wind farm supply chain (on-land transportation, ports/supply bases and offshore transport) based on identified challenges and opportunities;
- Developing a holistic supply chain model based on the analyses and models developed for the different supply chain stages.

Task 5.2 will specifically look at transportation to coastal bases, task 5.3 will analyse capabilities and requirements of a port to be suitable for offshore wind farm development. Moreover, task 5.4 will look at transport from coastal bases to offshore wind farm and finally, task 5.5 will identify supply chain optimization.

This report gives a clear basis of the current constraints in different phases of an offshore wind farm project (installation, O&M, decommissioning) and at different level (infrastructure, equipment, method).
Therefore, it will serve as input especially for task 5.2 and 5.4: on the basis of the identified challenges and constraints that the industry is currently facing, the next tasks will look at potential solutions. In this sense, this report should be considered as a framework context and a starting point for all other tasks.

5. Conclusions

This report has analysed the state-of-the-art of logistics for the offshore wind industry, and has provided an overview of current methods and identified future needs based on future prospects.

It is essential that the offshore wind industry achieves cost reductions to become a viable future energy source that is competitive with conventional power production. Optimization of the logistic system is a key driver for cost reductions in the different phases of a project: from manufacturing and foundation production, to construction and installation, operation and maintenance and decommission.

The sector is optimistic on the prospects of cost reductions in both medium and long term. In the short term, it is believed that market pressures will drive standardization and create a need for optimization of the logistics system. This will then give future cost reductions especially in the construction and installation phase. Cost reductions in the O&M phase are also foreseen, but more in the longer term.

As the offshore wind market is developing, it is expected that the requirements from the logistics system will be greater and more specialised. Not only the number of wind turbines installed will increase, but future trends are oriented towards the construction of larger wind farms in terms of installed capacity. This requires turbines with greater rated capacity, hence also bigger and heavier components. Future wind farms are also expected to be located further from shore and in deeper water.

Future trends point in the direction of higher level of preassembly before foundations and other components are transported from manufacturer. Bigger and heavier turbines and other components make road transportation a less viable option, and foundations can only be transported by sea.

A major bottleneck for the offshore wind sector is the lack of sufficient infrastructure in Europe. To improve the current infrastructure, a close relationship between offshore wind farm developers and ports is necessary. Today, the most common installation process involves the delivery of all components to a construction port close to the wind farm site. Bigger and heavier components will require such a port to have large areas of open storage and preassembly space, and a high load bearing capacity quay. A minimum number of specially adapted ports are critical for the offshore wind market. These ports will need to be committed to work with the offshore wind sector, supplying the necessary facilities, infrastructure and skills.

Cost reductions through analysis and optimization can be obtained in all phases of an offshore wind project life-cycle: installation, operation and maintenance and decommissioning.

The report has analysed the main features, advantages and disadvantages and logistic needs for different types of substructures. In a developing sector as the one represented by offshore wind, there are clear uncertainties. Some examples include the bigger winds turbines soon to be commercialised which currently only exist as prototypes, and the movement of wind farms to deeper water further offshore, where monopiles, most commonly used today, are likely not to be suitable. Hence, it is not possible to determine which foundation concepts will dominate in the future.

Offshore logistics for the O&M phase consist of the transportation of personnel and spare parts from an onshore base to the offshore wind turbines. The focus is thus on ports, infrastructure and vessels. There are some existing models and tools for O&M at offshore wind farms, and these can be divided into two main groups: Decision support models that consider main parts of the logistic system, and operational models, that consider more short-term and day-to-day logistic operations and strategies. Most of the existing tools either treat the logistic system as a smaller part in a larger analysis or considers only a smaller part of the logistic system. Hence, there seems to be a lack of tools that mainly consider the logistic system.

The lack of experience in decommissioning offshore wind installations increases the risk that developers are unable to provide a fair evaluation of decommissioning cost. The decommissioning phase will require similar resources as the installation phase, and the logistics will, to a great extent, depend on the foundation selection. Other elements affecting the decommissioning procedures are the support structure, the water depth and soil conditions.

Vessel and equipment challenges will be driven by present and future developments but also by present gaps. Challenges include, but are not limited to:

- Increasing transit speed and maximum permissible significant wave height in both transit and during operation,
- Improved manoeuvring performance to reduce positioning time,
- Maximization of deck space,
- Increase operating water depth and increase the wind speed limit for crane lifts.

Optimization for present conditions and components, together with adaption and upgrading to meet the requirements of new wind farm sites, components concepts and dimensions should be considered.

For equipment used in inbound logistic, the biggest challenge seems to be the lack of standardisation of handling procedures.

In general, the greatest challenges to achieve cost-efficient logistic methods for the offshore wind industry can be tackled by increasing the share of knowledge among stakeholders, using the experience of other industries (in particular oil and gas), and maximizing standardisation without compromising innovation. All possible actions and solutions that can lead to cost reductions should be explored, e.g. floating structures, specialised vessels that can operate over wider weather windows, equipment and wind-ready ports that can handle up-scaled components and improved models and tools for optimization of logistic concepts.

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