

leanwind

Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments

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Executive Summary

Project Background: The Levelised Cost Of Energy (LCOE) produced by offshore wind power at the end of 2013 has been estimated to be between 0.119 to 0.194 Euro/kWh. This is significantly higher than that produced onshore, which in large part is due to the more expensive installation procedure, and the higher associated operation and maintenance costs. However, the offshore wind industry has great potential for cost reduction, and LEANWIND will contribute to the industry target to achieve an LCOE of 0.096 to 0.151 Euro/kWh by 2030 [1]. This cannot be achieved without the implementation of novel innovations in the areas of **Construction, Deployment and Installation**, which is the subject of Work Package 2. This deliverable, Deliverable 2.1, is aimed at setting the background for the scope of work of this work package, highlighting the state of the art, identifying the relevant challenges and constraints and most importantly establishing a design basis for the future technical studies.

Scope of Work: The scope of work for Work Package 2 is to identify the relevant substructure concepts, and associated fabrication methods and installation strategies that will offer the most potential for cost reductions over the next 10 years. The substructure concepts considered for future technical studies include both fixed and floating solutions. For fixed foundations, the technical work has been broken down into gravity based concepts and steel structures, which will be investigated independently using a variety of numerical tools, combined with some physical model testing. Gravity Based Concepts will be considered from a generic standpoint to determine the relative merits of buoyant structures that can initially be floated into position before ballasting versus the more conventional structures installed using heavy lift vessels. This study will include conceptual engineering, detailed analysis, supply-chain studies and economic modelling. The initial study on steel structures will investigate innovations for both jacket structures and also for XL monopiles to determine how the design, construction and deployment can be achieved in a more efficient and leaner manner. The outcome of this work will be to identify key technical modifications that will enable cost reductions. For example, standardising jacket geometries for entire sites by using different pile stick-up lengths will be considered as one possible innovation. For floating concepts, it is recognised that the associated installation strategies (including the turbine erection) are not as technologically mature; therefore the initial aspect of this work will be a conceptual study to identify the concepts that are closest to market. This preliminary investigation will then allow innovations to be applied to one specific form of floating solution, either a TLP, Semi-submersible of Spar concept.

Design Basis: In order to complete the scope of works described above a series of uniform relevant design cases were identified. The relevant design cases are outlined in the table below and cover most of the parameter space for consented and planned wind farms in European waters.



Support by:



	Site co	onditions	Ground conditions				
Design	Water	Distance to	Shallow bedrock	Medium dense sand			
case	Depth (m)	Port (km)					
0	20	30	×	×			
1	40	30	Gravity bases	XL Monopiles Gravity Bases			
2	60	100	Lattice Structures Gravity Bases	Lattice structures Gravity Bases			
3	100	30	×	Floating foundations			







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1. Introduction and background

1.1 Project description

The Levelised Cost Of Energy (LCOE) produced by the offshore wind power at the end of 2013 has been estimated to be between 0.119 to 0.194 Euro/kWh. This is significantly higher than that produced onshore, mainly due to the more expensive installation procedure, and the higher associated operation and maintenance costs. However, offshore wind power has great potential for cost reduction, and an industry target is for the LCOE to be as between 0.096 to 0.151 Euro/kWh by 2030 [1].

It is expected that in the short-term, improved logistics infrastructure for installing wind power plants reduce the costs. However, in the long term, the application of larger turbines and the improvement of efficient manufacturing and installation processes determine the trends [2].

Despite expectations, in recent years, offshore wind costs have slightly increased. This can be attributed to the increase in material prices, wind farms moving to deeper waters and more exposed sites and in part to the rapidly increasing demand for supply chain capacity [3].

The share of cost of support structure is much more significant for offshore wind turbines. In an onshore turbine, the support structure accounts for approximately 6% of the total cost, whereas the cost of construction and installation of an offshore support structure usually ranges between 19% and 21% of the capital expenditure (CAPEX) of the offshore wind farm [4], [5]. The reason to such a gap lies in the different design approach that offshore wind support structures require [4]. Therefore, optimization of substructure costs during production, transportation and installation can considerably reduce the costs of offshore wind farms [5]. These were also identified as the highest potential sources of cost reduction in the German market, following the financing costs for wind farm development [2].

The main objective of the LEANWIND project is to contribute to reducing the overall cost of offshore wind energy, through modification of the current state of foundation design, logistics, transportation, installation, and operation and maintenance of the wind farms as part of an integrated framework.

1.2 Scope of work

This report is the first deliverable produced by Work Package 2. The main purpose of Deliverable 2.1 is to define the scope of work for the rest of deliverables in this work package. It is intended to provide a historical overview of the foundation types currently in practice, as well as introduce the emerging and developing concepts. The current status of industry and the prospective future trends will be outlined to provide insight for defining a general design basis, and identifying realistic design scenarios.

The main constraints and challenges in the state of practice of deployment and installation strategies are identified and described. Clarification will also be provided on the challenges and strategies that will be further explored during the lifetime of the LEANWIND project. An overview of various design considerations will be provided along



with factors that will influence the final design choices that will be made in this project. Relevant design standards and legislation will be identified along with the software and modelling tools that are anticipated to be used throughout the LEANWIND project. Various design scenarios will be developed, which will cover a range of possible scenarios that account for important design factors and parameters.

In summary this report is primarily a scoping document that aims at providing a general overview, setting directions and outlining the framework for the subsequent technical studies.



2. Definitions and concepts

2.1 Definition of general terms

- □ Support structure: This term represents the entire structure that supports the wind turbine generator, including the sea-bed constructions.
- □ Foundation: This is referred to the lower part of the support structure, that maintains direct contact with the soil, and transfers the load into the sea bed.
- □ Mooring: It is referred to the system that is used to connect the floating structure to the sea bed.
- Secondary steel construction: The part of structure that is attached to the substructure and facilitates the access to the wind turbine and support structure [4]. Boat landing platform, access ladder, main platform, J-tubes, and sacrificial anodes are parts of the secondary steel constructions.
- □ LCOE: The levelised cost of energy is the average cost of generating one unit of electrical energy over the lifetime of the generation plant [2].

2.2 Foundation concepts

Various design solutions have been proposed for the construction of offshore wind foundations. In waters with relatively shallow to medium water depth, bottom-fixed steel or concrete foundations are usually employed. However, with the recent shift in the industry towards deeper water sites, with subsequently higher wind resources, floating platforms become a viable option. The various possible foundation concepts are briefly introduced in the following sections.

2.2.1 Monopiles

Monopiles are single large-diameter piles that are installed in the sea-bed by either driving or drilling. The load-bearing mechanism of monopiles is similar to a laterally-loaded pile, where the shaft friction and end-bearing capacity provide resistance towards the horizontal forces and overturning moments exerted by wind, wave and the turbine loads. Monopiles are currently the most preferred type of support structure in offshore wind industry. The design methodology is straight forward, and the associated cost of manufacture and installation is relatively low compared to other available options.

2.2.2 Jacket structures

Jacket structures become viable options in deeper water sites, i.e. more than 20 m water depth according to the DNV Offshore standard [6]. The overturning moments and horizontal forces are transferred to the piles at the seabed through the truss action of jacket members. The foundation reacts in a push-pull manner at the seabed, with piles being only axially-loaded. Production of jacket structure involves elaborate manufacture of specifically-designed joints, and hence is much more costly and time-consuming when compared to monopiles. Future improvements in the design and manufacturing procedure can reduce the costs if they can facilitate serial production. It should be noted that for the purpose of this report and future work, Tripile and Tripod support structures will be treated as a subset of jacket foundations. It is worth noting that jackets and tripods can be installed using conventional driven pile technology or by employing any one of a number of alternatives, including suction caissons, screwpiles, partially drilled or fully drilled solutions.



2.2.3 Gravity Base Foundations (GBF)

Gravity Base foundations are massive reinforced concrete structures that utilise the dead weight of the structure for resisting the overturning moments and sliding shears. The self-weight of the structure is a trade-off between the manufacture, transportation and installation costs, and the structure's reliability in resisting the service loads. It is a common practice to minimise the dead weight of foundation to facilitate transportation, and increase the dead weight of the installed foundation by in-place ballasting. Due to the massive weights, gravity bases are applicable at competent and laterally consistent sites, with homogeneous soil profiles.

2.2.4 Suction buckets

Suction buckets are large diameter cylinders, with an open end. Although they resemble GBFs in shape, the installation and load bearing mechanisms are different. They are driven into the sea-bed by creating negative pressure in the soil underneath. Decommissioning is possible by reversing the installation process. Suction buckets can be used either as an independent foundation concept, or in combination with jacket structures. In the former case, they can be installed with an integrated transition piece, eliminating the need for grouted connection, and in the latter case, where suction bucket replaces traditional jacket piles, their prominent advantages include noise reduction and facilitated decommissioning.

2.2.5 Floating foundations

Floating foundations become an economically efficient option in water depths beyond 60 m, when bottom-fixed designs are no longer viable and the offshore site is deep enough to allow for efficient mooring [7]. The main challenges encountered in implementation of floating foundations is to maintain stability, an acceptable range of displacements, efficient mooring and at the same time avoiding costly designs, manufactures, installation and maintenance [8]. The most commonly investigated concepts in floating offshore foundations are ballast-stabilised floaters (i.e. Spar Buoy), buoyancy-stabilised floaters (i.e. Semisubmersible), and mooring-stabilised floaters (i.e. Tension Leg Platforms) [9].

2.2.6 Innovative concepts

It should be noted that the above-mentioned list is not exhaustive. Innovative foundation concepts have been employed or are currently under development. These include, but are not limited to, Tripiles, Tripods, Key Stone jacket, and novel variations of gravity base foundations. These concepts are discussed in more detail in the relevant sections of document.



3. State-of-the-art

3.1 Recent developments

In 2013 there were 21 offshore wind farms either completed or under development. The newly grid-connected wind farms add an additional 1.6 GW of wind power capacity. 47% of these new developments were installed in UK, followed by Denmark (22%), Germany (15%), and Belgium (12%) [10]. Figure 3-1 shows the distribution of these wind farms in various regions. It can be observed that most of the construction takes place in the North Sea. This is followed by Baltic Sea, and a small share of construction in the Atlantic Ocean. It should be noted that the 6% figure pertaining to the share of construction in the Atlantic Ocean is inclusive of the deployments in the Irish Sea.



Figure 3-1 sea basin share of 2013 annual installations [10]

The majority of turbines grid-connected in 2013 were the 3.6 MW generators manufactured by Siemens (69% of the total capacity). Siemens was followed by BARD (48 units of 5 MW turbines, accounting for 15% of the total grid-connected capacity), Vestas (41 units of 3 MW turbines, comprising 8% of the total grid-connected capacity), and Senvion, which installed 18 units of their 6.15 MW capacity turbines, accounting for 7% of the total capacity. Alstom and Gamesa have both installed demonstration turbines with respectively 6 and 5 MW capacities in 2013 (Figure 3-2) [10].





Figure 3-2 wind turbine manufacturers' share of 2013 annual installations in MW [10]

Regarding the foundation type, monopiles continued to dominate the market in 2013 with 490 units installed, comprising 79% of the total number of foundations commissioned. Tripods were the second most common type of foundations in 2013 (87 units installed, equivalent to 14% of the total installation), followed by jackets and tripiles [10]. The average size of wind farms constructed in 2013 was 485 MW, showing 70% increase in the average wind farm capacity compared to 2012. This confirms the interest in industry towards implementing turbines with higher capacities in larger arrays and bigger wind farms [10].

3.2 State of the art in offshore wind industry

A total offshore wind capacity of 6.6 GW has been installed and grid-connected at the end of 2013. The existing 69 wind farms across Europe can generate 24 TWh of wind energy in a normal wind year. This is equivalent to 0.7% of the total electricity consumption in Europe. The UK is leading the market with a total installed capacity of 3.7 GW (56% of the total installed capacity of Europe). Denmark has the second highest installed capacity of 1.3 GW, accounting for 19% of the total installed capacity of EU (Figure 3-3) [10].





Figure 3-3 installed capacity (MW) - cumulative share by country [10]

The world's first offshore wind farm was built in Denmark in 1991, with a total output of 4.95 MW. The Vindeby WindPark consists of 11 turbines of 0.45 MW capacity each. The support structure concept adopted for this wind farm was concrete gravity base foundations [4].

The first commercial wind park in the UK was North Hoyle, off the north coast of Wales. It was installed on monopile support structures in 2003. The Alpha Ventus demonstration site was installed in 2009 in Germany, using 5 MW REpower and AREVA turbines on jacket and tripod support structures [11].

In recent years, the general trends have been towards construction of larger wind farms, with an increased overall capacity, utilising larger turbine sizes, moving the sites further offshore, with increasing water depths. Wind farms are planned with overall rated capacities between 0.5 and 1 GW. Also the maximum capacity of turbines installed in offshore wind farms has increased from 2 MW in 2000 to 6.15 MW (Thornton Bank 2) in 2012. The next generation of turbines are under development with even higher capacities. The average size of the turbines grid connected in 2012 and 2013 was 4 MW, up from 3.6 MW in 2011. Only 24% of the turbine models announced in 2012 had rated capacities of less than 5 MW [5]. Figure 3-4 illustrates the move towards deeper and further offshore sites.





Figure 3-4 Average water depths and distances from shore (bubble sizes represent the capacity) [10]

European wind farms are mostly located in the North Sea (66% of the total capacity). However, 17% of the total capacity is located in the Baltic Sea and 16% in the Atlantic (it should be noted that the figure given fo the Atlantic Ocean also includes the wind farms located in the Irish Sea) [10]. The potential of exploiting wind power in the Mediterranean is restricted due to the current technological limitations in deep offshore wind farm construction. It should be noted that almost 66% of North Sea also has a water depth of between 50 m and 220 m [5]. The bathymetry of available sites off the North Sea coast of Germany mainly includes deeper water sites. Many of the projects planned in the Scottish Territorial Waters (STW) are also located in particularly deep water. Over half of the anticipated installed capacity will be located in water depths of greater than 40 m [11].

The demand for increased size of turbines, deeper water installations, and increased distance to port impacts the suitability of traditional foundation options, such as monopiles and jackets for the wind farms under construction. Hywind (2.3 MW Siemens turbine), and Windfloat (2 MW Vestas turbine) are the first offshore wind turbines installed on floating substructures, in 2009, in Norway and in 2011, in Portugal, respectively. Several wind turbines on floating support structures are also in a test phase: SeaTwirl, SWAY, and Poseidon in Europe, Kabashima Island concept, Fukushima project 1, and WindLens in Japan, and DeepCwind floating turbine in the US [5].

Europe's offshore wind turbines mostly rely on fixed foundations, with the vast majority of existing structures being monopiles. Gravity based foundations and space frame structures are the second and third most utilised support structures. Recent developments in wind energy generation technology resulting in greater turbine capacities, coupled with licences being issued for developing deeper water sites has resulted in stiffer fixed-bottom foundations being increasingly adopted in favour of monopile foundations.



These changes are also leading to the adoption of unconventional emerging technologies, such as floating foundations, that are specifically designed for deep water sites [5]. The following diagram presents the percentage share of each foundation type in the currently operating wind farms.



Figure 3-5 Percentage share of different foundation types in the currently operating offshore wind farms [10]

The design, fabrication, and installation of turbine foundations in an offshore wind farm makes up around 30% of its total capital costs. As a result, innovative and cost-effective foundation designs could lead to significant reductions in capital costs for future wind farms [12].

A broad overview of the most common foundation concepts for offshore wind turbine support structures, along with a brief introduction of a number of emerging concepts has been provided in this section.

3.3 Monopiles

Monopiles are single, large diameter (4 to 6 m) steel tubes which are driven into the sea bed and provide lateral restraint to resist the applied environmental loading by mobilising horizontal earth pressures in the near surface soils. The method of transfer of loads is through a combination of shaft friction and end-bearing capacity for vertical, and through bending for horizontal loads. The dominant design criterion for the monopiles is the overall deflection and vibration during loading. Large diameters are required to provide enough stiffness for the lateral load, although this increases the hydrodynamic loads [13].



The Monopile foundation system consists of two pieces; the pile that extends out of the sea bed, and a transition piece that is placed over the pile (Figure 3-6). Transition piece has a larger diameter to allow it to slide over the pile and provide a vertical overlap of approximately 10-12m. The purpose of the transition piece is to facilitate the turbine connection and to correct the vertical tolerance of the monopile so that the turbine tower can be installed within an agreed offset. Monopiles used in the offshore wind sector are typically driven 20 to 30 m into the sea bed resulting in relatively low pile slenderness ratios of 5 to 6.



Figure 3-6 Details of a Monopile Foundation [14]

As of today monopiles are the dominant type of foundation for offshore wind farms. The first offshore wind farm utilising monopiles was the Lely Wind farm in Netherlands, constructed in 1994 in water depths in the range of 2.5 to 5 m. Typical weight of monopiles falls within a range of 500 to around 800 tonnes (in deeper sites like Walney 2), making them one of the lightest choices for the offshore foundations [13].

As the turbine sizes and water depths increase, larger monopile diameters are required. This will lead into a number of implications, such as increased demand for steel, increased hydrodynamic loads, limitations in the manufacturing process, e.g. welding of plates with thicknesses higher than 100 mm, and limitations in the pile driving hammers and equipment [13]. Therefore, a tipping point can be found, at which the total installed cost of using monopiles outweighs the cost of other designs.

Currently, this tipping point is approximately 30 m to 35 m of water depth, although work is underway to extend the operational range of monopiles to include larger turbines in deeper water [15]. The largest monopile installed so far is at London Array wind Park, with a length of approximately 60 m, a diameter of 5.7 m and a penetration depth of around 25 m [4].

The transition piece represents the weakest part of the monopile concept. An integrated transition piece is not feasible unless if the monopile is drilled to the sea bed; therefore, a transition piece is usually connected to the monopile using grout or cement as an



offshore installation process. It is worth noting that over the past decade, one of the main problems emerging in the offshore wind sector is associated with the use of grouted connections between the monopile, transition piece and turbine tower. The high lateral cyclic loads during turbine in-service conditions appear to have caused significant grout fatigue damage that ultimately compromised the performance of connection. This problem was readily overcome through the use of shear keys as already implemented in the oil and gas sector. Weld beads are implemented in the inside surface of transition piece and outside of the monopile, to increase the sliding resistance of grout and steel.

In 2010, DNV (Det Norske Veritas) launched a Joint Industry Project (JIP) to further investigate the grouting connection issue in offshore wind industry. This JIP also suggested using a conical shaped connection instead of the existing tubular configuration, in order to minimise the risk of grout crumbling (Figure 3-7) [13].



Figure 3-7 Transition Piece. Left: old design with tubular connection; Right: new design with conical connection [16]

Another emerging concept that has the potential of eliminating the need for a separate transition piece to be installed is to use the concrete Monopile. The concrete monopile with its core pre-stressed, would be cheaper in terms of material and manufacture. However, concrete monopile needs to be drilled to the sea bed, a procedure that is more expensive than the steel monopile installation. A driven concrete monopile could also be feasible however a specific driving flange detail would be required to allow the impact hammer install the monopile without damaging the transition joint with the turbine tower.

3.4 XL monopiles

The popularity of monopiles in offshore construction is diminishing as more wind farms are planned further offshore and in sites with deeper water. However, a new generation of monopiles are emerging with increased diameters (up to 10m are being proposed) that make them suitable for deployment in larger water depths (Figure 3-8). The Danish company MT Hojgaard conducted a feasibility study to compare the viability of XL monopile and jacket foundations in 35 m water depth with a 6-MW turbine. In this investigation that took into account the incurred cost and associated risk during design, manufacture, installation, operation and maintenance, XL monopiles were identified as the optimum solution [17].

One of the key challenges with impact driven piling is the noise generated, which creates a significant environmental risk for marine mammals and as a result strict noise thresholds are already enforced for some wind farms in Germany and other areas of



Europe. Extending to larger diameter monopiles will require larger diameter hammers, which in turn are most likely to have an additional noise element. Alternative solutions to this problem include vibratory hammers or screwpile technology.



Figure 3-8 Monopiles [17]

There are currently XL monopiles installed in water depths of 32 metres, and designers believe that this foundation type has the potential of being deployed in up to 60 m water depth, however, this is subject to alleviating transportation, storage and installation challenges that the large components would impose on the construction logistics. New installation vessels and driving equipment have to be developed if monopiles greater than 7 m diameter are to be deployed. Other challenges include bending and welding plates with large thicknesses, the possibility of plates buckling during driving as the ratio of pile diameter and plate thickness increases, and the increased noise emission from driving large piles into the sea-bed that can harm the marine life [18].



Figure 3-9 XL monopile transportation [18]

In order to be able to release the full potential of XL monopiles, current design methodologies that are targeted towards conventional monopiles should be improved



and modified. The calculation methods and existing theories for modelling soil-pile interaction should be updated to reduce the conservatism and uncertainty in the design [18].

3.5 Gravity base Foundations (GBF)

Gravity based foundations have been used extensively in the Baltic Sea, a typically calm sea with shallow waters. The use of concrete for these foundations has several benefits, including reducing exposure to relatively volatile steel prices and removing the need for sea bed piling [17].

Due to the heavy weight of Gravity base foundations their installation and transportation usually requires heavy lift vessels and cranes. However, alternative concept designs of concrete or concrete-steel hybrid gravity base foundations have been introduced with the aim of achieving cost-effective installations in deeper water and harsher conditions. These new designs do not need the costly heavy lift crane vessels required for existing concrete foundations and for piled steel foundations [19]. The self-buoyant gravity base foundations can be floated and towed to the offshore site, where it can be filled with ballast and lowered to the seabed, using standard tugs (Figure 3-10).



Figure 3-10 Self-buoyant Gravity base foundation [20]

The Auxiliary-buoyant gravity base foundations require special transport vessels for buoyancy support. This design concept requires further ballasting of the foundation at site, but results into a reduced volume of concrete being consumed (Figure 3-11).

In this section, an overview is provided on the existing and emerging concepts for concrete gravity base foundations.





Figure 3-11 Auxiliary Buoyant Gravity base foundation [21]

Offshore Wind Farm	Country	Installed Capacity (MW)	Number of turbines	Water depth (m)	Distance from shore (km)
Avedore Holme	Denmark	10.8	3	0.5 to 2	0.05 to 0.1
Breitling Demonstration	Germany	2.5	1	2	0.5
Choshi Offshore Demonstration Project	Japan	2.4	1	12	3.1
Donghai Bridge 1	China	102	34	10	8 to 13
Ems Emden	Germany	4.5	1	3	0.5
Kemi Ajos	Finland	30	10	3 to 8	2.6
Kitakyushu Demonstration	Japan	2.0	1	14	1.4
Kårehamn	Sweden	48	16	8 to 21	7
Lillgrund	Sweden	110.4	48	4 to 10	7
Middelgrunden	Denmark	40	20	3 to 5	2
Nysted 1	Denmark	165.6	72	6 to 10	10.8
Pori Offshore 1	Finland	2.3	1	9	1.2
Rodsand 2	Denmark	207	90	6 to 12	8.8
Rønland	Denmark	17.2	8	0 to 2	0.1
Sprogo	Denmark	21	7	6 to 16	10.6
Thornton Bank 1	Belgium	30	6	12 to 27.5	26 to 27
Tuno Knob	Denmark	5	10	3 to 6	6
Vindeby	Denmark	4.95	11	2 to 6	1.5 to 3
Vindpark Vanern	Sweden	30	10	3 to 13	7

Tahla	2_1	State	oftha	art	racorde	of	Gravity	/ Raca	Foundations	(GRFc)	١
abic	<u>о</u> т	olulo		anc	1000103	01	aravity	Dusc	1 oundations	(UDI 3)	/



Half of the offshore wind farms with GBF currently ongoing are located in Denmark. In fact, the first ever commercial offshore wind farm was Vindeby, which was installed in 1991. It consists of 11 turbines that total 4.95 MW of installed capacity supported by GBFs. The second GBF offshore wind farm was Tunø Knob, and was installed four years later in Denmark as well. It has very similar characteristics to Vindeby regarding the installed capacity, the number of turbines and site conditions. Therefore, the shape and dimensions of their foundations are practically the same. The foundations used at these two sites are concrete conical caissons and were built in dry dock near the sites and floated to their final destination [22].



Figure 3-12 Vindeby offshore wind farm [23]

After a period of ten years since the installation of Vindeby, the third GBF wind farm was erected in Middelgrunden. It has a greater installed capacity than the two previous ones, but the concrete caissons design and transport were similar. In the case of Middelgrunden wind farm, the lower part of the steel tower together with the transformer, switchgear and control systems, were installed on the foundations in the dry dock before floating the foundations to the site [24].



Figure 3-13 Foundations for Middlegrunden in dry dock [24]



Nysted 1 included 72 GBFs that were built in Swinoujscie, Poland, and transported on barges to the site, where the crane barge EIDE V lifted them from the transport barge and positioned them in their final location. It was constructed in 2002.



Figure 3-14 Nysted foundations loaded out on barge EIDE V [25]

The transport and installation procedures required that the weight of the concrete foundation units be minimized. This was achieved by designing a hexagonal base structure with six open cells and a shaft and ice cone at the top. The base dimension is 15 m and the maximum height 16.25 m (Figure 3-15) [36].



Figure 3-15 Installation of ballasted concrete Gravity based foundation [26]

Rødsand II project was approved in 2008. Construction of the wind farm began in the second quarter of the following year as extension of Rødsand I. The transport of the GBF was executed by Rambiz heavy lifting pontoon, transport pontoon and auxiliary equipment. Also in 2009, Sprogø Wind Farm began the construction of 7 turbines to be installed at water depths ranging from 6 to 16 m.

More recently, three test turbines were installed as part of the process of optimization of 500 wind turbines DONG Energy had purchased from Siemens Wind Power for the



Avedore Holme project. Two turbines were erected in 2009 and placed only a few meters off the coast at a water depth of approximately two meters and the third turbine was installed and put into operation in 2011, placed on an installation island approximately 100m off the coast [23].

Other GBF offshore wind farms to mention include the Vindpark Vanernand, Lillgrund, and Kårehamn in Sweden. The Kårehamn wind farm was commissioned in 2013, and is formed by 16 Vestas turbines (V112 3.0 MW); it covers a range of 8 to 21 m of water depth, at a distance of 7 km offshore.



Figure 3-16 Lillgrund offshore wind farm view [23]



Figure 3-17. View of Vindpark Vänern. [23]

Germany has two single turbine demonstrations on GBF. These are Breitling Demonstration and Ems Emden, both located practically onshore. The Kemi Ajos wind farm in Finland combines 2 onshore and 8 offshore wind turbines placed on an artificial island. Another wind farm in Finland is Pori Offshore 1, a steel-shell or steel caisson gravity foundation.





Figure 3-18 Kemi Ajos combined onshore and offshore wind farm. Offshore positioned in artificial islands [23]



Figure 3-19. Steel-shell caisson gravity foundation [23]

A new design approach and offshore marine operation procedure was developed in 2006 for construction of the foundations for the first phase of the Thornton Bank Offshore wind farm, located approximately 30 km off the coast of Belgium. The offshore construction works started with dredging the foundation pits. Installation of a two-layer gravel bed within very narrow vertical tolerances created a sub-foundation for installation of the GBF. The latter installation and positioning works were performed by the twin shear leg crane heavy lift vessel Rambiz, which transferred the GBF from the onshore construction site to its final position [27].





Figure 3-20 Lowering of the GBF, in front of quay wall and on its way out to sea [27]



Figure 3-21 Construction of gravity based foundations for the Thornton Bank [25]





Figure 3-22 Kitakyushu Demonstration Project [23]



Figure 3-23 Choshi Offshore Demonstration [23]

The majority of GBFs installed so far are located in shallow waters, and relatively close to the shore. Installation of GBFs in greater water depths, require heavy lift vessels such as Rambiz, which ultimately increases the total cost of installation. Modifications in the design and installation of GBFs are required to render them as competent and cost effective options in deep water sites. A few of the emerging concepts recently introduced will be discussed in Section 3.6.

3.6 Emerging concepts in Gravity Base foundations

3.6.1 GBF integrated solution

An innovative foundation concept and installation procedure (Figure 3-24) was proposed by a joint venture of three companies to address the deficiencies that exist in the supply chain network. The joint venture was initiated through the Carbon Trust foundations competition [28].





Figure 3-24 GBF ® [25]

GBF ® proposed a pre-stressed concrete foundation, weighing over 3000 tonnes, suitable for a wide range of sea-bed soil conditions. It is comprised of a hollow conical stem, with a circular raft footing of continuous reinforcement. GBF® presented an innovative procedure for the installation, by introducing the design of a Transport installation Barge (TIB). It is a purpose built barge that reduces the need for costly jack-up vessels and cranes, which can be towed by relatively low cost tugs. This innovative concept has been used by the joint venture VINCI in collaboration with GBF that offers a different gravity base design with the TIB (Figure 3-25)



Figure 3-25 The foundations and turbines are mounted onshore then transported to sea and released onto the seabed [28]

A steel frame lifting system will be used to assemble the tower elements and the nacelle onto the concrete base foundations. Once positioned, the turbine hub and the rotor



blades will be connected to the nacelle. Once complete, the lifting system will be used to lower the assembly and its foundation into the water, where it can be picked up by a vessel. In order to ensure connectivity between the barge vessel and the turbine assembly, the barge will be ballasted down to the level of the base to connect with it, and thence re-floated to the transportation depth. The transportation barge and the turbine can thus be towed to the wind farm location, where the turbine and its foundation can be ballasted down to the prepared sea floor. Once the gravity base is in place on the sea floor, the caisson can be filled with ballast sand to ensure that it remains stable. The transportation barge can then disconnect from the installed structure, re-float to the required transit depth and be towed back to the shore [23].

Decommissioning and complete removal from the sea-bed is possible by reversing the installation procedure. This foundation is still at the de-risking stage, subject to tank testing on model scales and verification of satisfactory performance during the various stages of construction, transportation, installation, ballasting, and release mechanism [23].

3.6.2 Crane-free

Crane-free is an innovative foundation concept developed in a collaboration between Sea Tower and MT Højgaard. Efficiency in terms of production, cost-minimal mass installation and ease of decommissioning are the key aspects of this concept (Figure 3-26). One of the primary benefits associated with Crane-free is that it is designed as self-floating, thus requires only low-cost towing vessels in order to transfer to and install at the offshore site. Expensive, weather sensitive vessels can therefore be eliminated, imparting significant cost-savings compared to options employing these vessels [30].



Figure 3-26 Sea Tower [30]



This concept foundation is best suited to water depths in the range of 20-25 m, with the final weight of the foundation residing between 6000-7000 tonnes. The installation process is directly reversible thereby easing the processes of removal and decommissioning.

Installation of the structure works on the principle that when the structure is orientated correctly above the zone of installation (Figure 3-27), a series of hydraulic valves can be opened. This allows the intrusion of water into the foundation thus sinking it. Skirts located along the base then penetrate the sea floor soil due to the weight imposed by the foundation mass. The presence of these skirts can provide extra lateral resistance and thereby reduce the need for massive structural deadweight to resist horizontal motion and overturning moments.

Dredging and levelling of the sea floor is not required as part of the installation although it is recommended that for granular sub-grades, some element of scour protection should be utilised. Full contact is maintained between the bottom slab of the substructure and the sea-bed material by injecting concrete into the voids (Figure 3-28).



Figure 3-27 Sea Tower installation using three tugs [30]



Figure 3-28 Sea Tower concrete injection for filling the voids [30]

3.6.3 Gravitas

Gravitas is a foundation concept which incorporates a circular reinforced concrete caisson with a conical upper portion attached to a cylindrical steel tower (Figure 3-29). It can be towed to an offshore installation site and is defined as self-buoyant. It is



ballasted using sand and can be installed using only two standard tug boats. The flat base of the structure can have skirts attached if required for the site specific conditions. This concept foundation is best suited to water depths up to 60 m.



Figure 3-29 Gravitas [20]

3.6.4 Strabag

This foundation concept comprises a pre-stressed concrete structure, most recently configured with three stabilising arms offset at 120 degrees. The preceding version of the Strabag foundation was a quadruped structure. Mass production of this foundation concept is possible. It can be installed in zones where water depths are up to 45 m and is suitable for auxiliary-buoyancy transportation (i.e. assisted with a purpose built vessel). The foundation is configured in such a manner as to reduce the effects of scour and optimize foundation stability (Figure 3-31 and Figure 3-30) [21]. In tandem with this, the amount of work required for subsoil preparation and removal of shallow loose sediments is reduced.



Figure 3-30 Trial of the Strabag Gravity Foundation [21]





The foundation requires scour protection to be provided locally for each of the four/three foundation plates. Once on site, each of the concrete compartments is sand ballasted and the foundation is lowered to the sea-bed. The tower and turbine hub can be installed onto the foundation at the onshore fabrication site and then transported to the installation site using a specifically designed transport unit. This transport unit is capable of transporting the assembled turbine, which weighs over 8000 tonnes, to the site (Auxiliary buoyancy) (Figure 3-11) [21]. The STRABAG Gravity Foundation was tested and certified by DNV-GL during its design phase.

3.6.5 Vici-Ventus

The Vici-Ventus is an innovative foundation concept. It is best suited to water depths on the region of 30 m to 100 m and can be installed in a range of soil deposits from stiff clay and dense sand to softer deposits. A significant advantage of this concept is that little or no seabed preparation is required prior to installation. The substructure can be gravity based, skirt piled or suction bucket depending on the soil condition. The tower can be designed as a space frame to optimize the load transfer. The gravity base foundation is ideally designed to be buoyant, so that it can be towed to the offshore site and ballasted [31]. Onshore assembly is possible, since the support structure has sufficient floating stability to carry the tower and turbine from the onshore construction site to the offshore installation point.





Figure 3-32 Vici-Ventus [31]

The Vici-Ventus space-frame tower is designed with vertical legs with a constant outer diameter and variable thicknesses. Nodes have superior fatigue capacity, and are cost effective to fabricate due to their relatively uniform design (Figure 3-33). The space frame can be installed on a concrete foundation that is ballasted with sand and gravel, on suction buckets, or piles driven to the sea-bed, depending on the soil condition [29]. On a level sea-bed, Vici-Ventus does not require extra site preparation or piling. It is suited for water depths of up to 100 meters, and is not sensitive to fatigue loads. However the application requires a site with firm to hard soil stratum.





Figure 3-33 Vici-Ventus Space frame tower [31]

3.6.6 Sea Breeze - Xanthus Energy

The foundation concept known as Sea Breeze is a Gravity Base foundation that is selffloating. It is best suited to water depths up to 60 m. In tandem with supporting current two or three bladed wind turbines, it is also suitable for supporting future vertical axis wind turbines. The tower element of the Sea Breeze structure is post-stressed and steelreinforced. It is placed in the centre of a symmetrical group of three cylindrical hollow concrete caisson structures. Each of these is equipped with a separate ballast system (Figure 3-34). In terms of foundation stability, steel skirts are used to mitigate the possible effects of liquefaction and also to mobilise stronger soils in competent strata at depths below upper soil layers. In certain design circumstances, the use of suction pile hybrids may be applicable.





Figure 3-34 Pre-stressed concrete Tower and foundation [32]

Once fabricated the foundation is moved to the sea close to the shore, where the turbine and tower can be assembled using cranes operating onshore. The fully assembled wind turbine is then floated to the offshore site (Figure 3-35), ballasted with sand and deployed in place. The various stages are illustrated in (Figure 3-36). Xanthus Energy is now looking for trial test opportunities and partners to develop this concept further.



Figure 3-35 Sea Breeze being towed out to the offshore site [32]





Figure 3-36 the envisaged stages of fabrication, assembly, transportation and installation of Sea Breeze [32]

3.6.7 BAM-Van Oord Consortium solution

The concept for the GBF developed by BAM and Van Oord's consists of a hybrid solution, which has undergone model testing and is adaptable for a range of water depths, wave heights and seabed conditions. This solution consists of a concrete caisson and steel shaft, and is described by DNV as an "optimised and cost-effective design". The GBF's are designed to be mass produced onshore in a quayside construction yard. It is proposed that Mammoet undertake transport and load out of the GBF's using a semi-submersible barge which moves the foundation into deeper water sites. The barge is then submerged and the GBF is floated off and towed to the construction site using standard, ocean going tugs. Kept in position between four anchored tugs, the foundation is ballasted with water to the prepared seabed. Ballasting can be performed using a support vessel [33].

3.6.8 Rockmat

Rockmat is a patented innovative concept of offshore wind foundations suited for rocky or uneven sea-bed. It is a prefabricated self-floating foundation that can be used as an interface between soil and various types of Offshore Wind Turbine (OWT) substructures (jacket, monopile, concrete base). Once the substructure is assembled, the combination of foundation and substructure can be floated to the offshore site, where it is lowered to the sea-bed by water ballasting to the flexible rubber modular form [34].

Only three tugs are required for positioning the foundation during ballasting and installation. Rockmat is also equipped with an underwater levelling system that can adjust the orientation of foundation and eliminates the need for sea-bed preparation.


This makes Rockmat suitable for un-even sites with gentle slopes and irregularities in the order of 1 meter (Figure 3-37). Installation does not require piling, and hence can be conducted in both hard soil layers and bedrock. The space between the foundation and soil is filled with injected concrete to ensure full contact with the sea-bed [34]. It is suitable for use with gravity bases, monopiles and jackets, and the application does not have a limiting water depth. Decommissioning is possible by injecting air into the water-filled compartments, and re-floating the foundation [34].



Figure 3-37 Rockmat concept [34]

3.7 Jacket structures

Jacket structures are suitable for supporting relatively large offshore wind turbines installed in deep water, e.g. 40 m and more (Figure 3-38). Loads are transferred to the piles through axial behaviour of the slender members of the lattice. The relatively small diameter of members categorises the structure as a transparent support structure, with less significant hydrodynamic loads. Piles can be pre-driven or driven through the pile sleeves once the structure is positioned correctly on the sea-bed. These are also axially loaded piles, reducing the need for scour protection, when compared to monopile foundations.

The wide cross-section at the sea-bed provides satisfactory resistance against overturning moments. Jacket foundations also provide a stiffer support structure for their weight, which is approximately in the range of 600 tonnes. This makes them ideal for deep water sites with extreme environmental conditions. Jackets can be fully assembled before float-out installation, and hence reduce the amount of offshore installation required [13].





Figure 3-38 Jacket structure details [14]

There are different types of lattice-framed support structures in terms of geometry and configuration. They can have three, four or six legs, with legs being vertical, angled, or twisted. The three-leg jackets have fewer joints, and also require three piles being driven to the sea-bed. This can reduce both the fabrication and installation time and hence reduce the costs. Holding the three-legged jacket level during the grouting operation and the grout setting time, can be easier in some circumstances, when compared to the more common four-legged jacket. However, it does not provide the same level of redundancy in the support structure [18].

Jackets foundations are relatively expensive to fabricate and install. Manufacturing jacket structures is a costly and elaborate task. Each of the joints needs to be specially fabricated, requiring many man-hours of welding. It is argued that automated production processes have the potential to reduce the manufacture and assembly costs. The tubular section of the lattice tower can be made from standard pipe sections and the symmetry of the design, facilitates the use of prefabricated nodal joint. Jacket structures require extensive corrosion protection, and are susceptible to fatigue. Efficient fatigue design and management requires deep insight of the loads and structural behaviour, along with advance numerical tools. Monitoring and maintenance of the under-water joints is challenging and costly. Also, the slender members are vulnerable to ice loads.

However, jackets are known to have significantly lower mass for the same stiffness characteristics when compared to tripods and tripiles. This is the main driver that justifies their application despite the large manufacturing costs.

3.7.1 OWEC Quattropod[®]

To date, only a few wind farms have been fully completed relying on jacket structures as their support structure. These are Beatrice Demonstrator (2006 – UK; 2 units), Alpha



Ventus (2009 – Germany; 6 units), and Ormonde (2011-12 – UK; 30 units) (Figure 3-39). All these jackets are based on the OWEC Quattropod© design, proposed by the Norwegian company OWEC Tower. The OWEC design claims to have minimised the weight and weld volume. It also provides specific features for boat landing and cable integration.



Figure 3-39 Jackets for Vattenfall's Ormonde farm [35]

The design of OWEC Tower incorporates pre-piling of piles, which aims to reduce the cost associated with installation and overall project timing risks. The way the system connects to the piles is patent-protected. Other developments and product features associated with the OWEC Tower are patent pending. The OWEC Tower system allows for piling to be much cheaper and simpler to complete. This is achieved without the requirement for special installation vessels. The OWEC Tower system is capable of using traditional jack-up platforms, which are ideally available and can prove much more cost effective. Floating crane structures can be used to aid the installation of the fully assembled tower structures. These crane structures are capable of carrying up to four structures at a time, each weighing up to 500 tonnes [36].

3.7.2 Hexabase jacket

The Hexabase jacket is a new type of offshore foundation with a hexagonal configuration that was proposed by German companies. It has a more stable construction, and costefficient production, and is more flexible with regards to transport and installation due to its compact design. It replaces the expensive costume rolled offshore pipes with standard pipe sections; this can reduce the cost of steel manufacture significantly. The hexagonal configuration is targeted towards more level distribution of loads through many small pipes rather than big links. It has grid like construction with small cross-links (Figure 3-40). The reduced diameter of truss members decreases the contact area, and hence the overall hydrodynamic loads. Joint configurations comply to a standard design and can be clustered into three identical categories of X-nodes, K-nodes, and bottom nodes, facilitating the mass production practice [37].





Figure 3-40 Hexagonal geometry, compact pipe sections and identical joints of Hexabase [37]

However, transport and installation of a six-leg structure can be more cumbersome compared to a four-leg design. Installation requires extra piling operations (6 instead of 4), although it should be noted that piles are smaller and can be driven using smaller and less expensive hammers and equipment [18].

3.7.3 Keystone Twisted jacket

Keystone twisted jacket is a patented inward battered guide structure, with three supporting legs angled around a central pile. This innovative offshore foundation reduces both cost and risk compared to traditional offshore foundations. The structure has been designed for quick and efficient installation and has also been optimised with respect to the amount of steel. Twisted Jacket reduces the steel consumption by 20% compared to an optimised conventional jacket structure, and its manufacture requires a fewer number of welds. In addition, the keystone structure does not require a driving template during installation, and is suitable for 30 m to 60m water depth [38].



The twisted jacket has fewer joints to fabricate, but the sections are heavier. Also, the twisted legs require twisted piling, which needs more elaborate installation process. The concept has been trialled with a met mast, but is yet subject to passing all the required industry insurances [18].

The structure requires the installation of a central pile, over which the guide structure is lowered and fixed in place. Three preloaded raking piles are then driven through the guide structure to penetrate the seabed to the required depth. This concept has been used to support offshore oil and gas facilitates in the Gulf of Mexico and the robust nature of the concept has been truly tested when subjected to extreme loading from Hurricane Katrina. A prototype of this concept was installed in 2011 to support a metmast in UK Hornsea Round 3 offshore wind farm.



Figure 3-41 Keystone Twisted Jacket details [12]

3.8 Tripods

Tripod adapts the monopile foundation design to deeper water sites, by providing a larger base, and transferring the loads through axial behaviour of slender members at the lower part of the support structure (Figure 3-42). The structure consists of a central cylindrical section, similar to monopile, which is connected to the wind turbine base. The lower part consists of relatively slender diagonal braces connecting the main tubular section to the pile sleeves. From the main joint downwards the transfer of loads relies



mainly on axial loading of the members. Since the piles are axially loaded, the tripod foundation becomes lighter than the monopile foundation. The relatively slender diagonal braces allow water mass to pass through the structure relatively unobstructed, and reduce the hydrodynamic loading, although this is not the case for the structure from the main joint upwards [13].



Figure 3-42 Details of Tripod Structure [14]

The relatively light weight makes it feasible for the structure to be manufactured far from the installation site. This support structure is not suitable for water depths below 6 to 7 meters due to the requirement for sufficient water depth for service vessels [4]. Besides this, the main joint is a complex element that is susceptible to fatigue and requires much effort in designing and engineering.

The Tripod installation methodology is very similar to the post-piled installation of a Jacket. The Tripod is loaded onto a barge and sailed to site. A heavy-lifting vessel lowers the tripod to the seabed guided by ROVs (Remotely Operated Vehicles) or divers. After lowering the Tripod, the piles are driven in the seabed with a hydraulic or vibrating hammer through the sleeves. When the three piles have been driven, the connection between piles and sleeves is filled with grout or concrete (underwater cement grouting). The first Tripods were installed at German Alpha Ventus site (42m water depth) for 6 Areva Multibrid 5MW wind turbines in spring 2009. To date Tripod is the preferred substructure design for Areva Wind. The next offshore wind farm using Tripods is the German 400MW Borkum West II farm (2011-2014; 2 phases).





Figure 3-43 Tripod manufactured by WeserWind and loaded onto a special pontoon at Bremerhaven for Borkum West II offshore wind farm [39]

3.9 Tripile

The Tripile foundation is an adaptation of the traditional monopile foundation (Figure 3-44), with three piles being connected to a transition piece above the water surface. The transition piece is welded from flat steel elements, and is jointed to the piles with permanent grouting. Therefore, no bolted or welded connection is required between the piles and the transition piece. The tower, turbine, and rotor are then mounted on top of the Transition Piece. The transition piece is fitted with a work platform and stairs, while the boat landing is mounted on one of the piles.



Figure 3-44 Bard Tripile design [40]



The increased strength and wider base provides better resistance against overturning moments, making the structure suitable for deeper water sites. The Tripile design is also easily adaptable to various soil conditions, since each pile can be designed and manufactured appropriately to match site specific conditions. The German wind turbine manufacturer Bard Engineering GmbH developed the Tripile design. It was first tested in 2008 in the Hooksiel Offshore Wind Farm with a 5 MW turbine. Positioning the three piles accurately during installation is a challenging task, and requires the assistance of a sea-bed template and Global Positioning Systems. One of the advantages compared to monopile is that the transition piece is completely located above water. This eliminates the under-water installation and grouting procedure that is necessary for monopiles.

The tripod and tripile design is more difficult to mass produce, when compared to jacket structure. These foundation types do not use standard steel sections; members usually have greater thicknesses, which make the welding procedure more difficult and less suitable for automation. More importantly, their joints have a relatively complex geometry that makes mass production challenging.

3.10 Suction Caissons

Suction caisson technology has been used in the oil and gas sector for several decades. Thousands of suction caissons have been installed as foundations and anchors for various facilities around the world. The loading conditions for the wind sector are dramatically different, but this technology still has huge scope to facilitate rapid installations. Suction caissons can be used to assist levelling of a traditional GBF or alternatively can be used to support a jacket or tripod structure. Care must be taken to ensure that the resulting structure is capable of resisting the geotechnical tension loads.

3.10.1 Universal foundation suction bucket

One foundation concept, that has emerged as a potentially low cost alternative is the Universal Foundation concept, where the primary beneficial aspects of different foundation solutions such as GBF, monopiles and suction buckets are incorporated into a hybrid design known as Universal foundation (Figure 3-45). It is applicable to various site conditions, homogeneous deposits of sand, silt, and clay, as well as layered soils. Suction caisson installation in rock is not possible, and can also prove challenging in hard clay and till. Universal foundation is applicable in water depths of 25-35 m. The most important design parameters that can be adjusted are: skirt length, shaft height, shaft diameter, and bucket diameter [41].

Suction bucket is a large diameter cylinder, resembling a gravity base foundation in shape and size. However, 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, a combination of wall friction of the skirts and vertical bearing capacity of the cap keeps the bucket in place. This installation practice reduces the noise associated with the common pile driving methods. Suction buckets provide the possibility of integrating the transition piece, and hence eliminate the need for grouting



the transition piece as an extra offshore operation. Removal is possible by applying water pressure under the foundation, and lifting the skirts from the sea-bed [41].



Figure 3-45 Universal Foundation [41]



Figure 3-46 Suction Bucket foundation [42]

Since installation is reliant on the pressure difference, a minimum water depth is usually required to ensure the feasibility of this concept [42]. Suction buckets can be decommissioned by reversing the installation process, and pumping water inside the inversed bucket, to force it out of the sea-bed. Other advantages include the ability of floating the structure to the site and the avoidance of heavy lifting equipment and pile driving requirements. A prototype monopod suction caisson (12 m diameter, 6 m skirt length, and 150 ton weight) was installed in 2002 at the Aalborg University offshore test facility in Denmark and more recently two suction bucket metmast installations were completed in the Dogger Bank zone in the UK (Figure 3-46).



3.10.1 Suction piles

Suction piles consist of a tubular steel cylinder with a closed top (Figure 3-47). Pumps are attached to the top of the pile to create a negative pressure under the cap, and facilitate penetration of the pile into sea-bed. Once installed to the target depth, negative pressure is removed, and the load bearing capacity is maintained by a combination of shaft friction and end bearing capacity of the pile top. This is a proven concept that has been in practice for many years in oil and gas industries, and has the capacity of eliminating the need for drilling/driving the piles offshore. This method of installation eliminates the noise of piling operation, and limits the installation costs and challenges significantly. Piles can be fully removed from the sea-bed by reversing the installation process [43].



Figure 3-47 Suction piles [43]

3.11 Floating foundations

It is expected that in the next few years the installed offshore capacity and the mean water depths and distance from shore will increase with the construction of new offshore wind farms in countries like UK, Germany, France or China.

However, many of the areas with high wind resources and relatively low water depths are currently being developed (or are expected to be in the next few years). Therefore, it has become necessary to investigate foundation technology suitable for water depths of greater than 50m. For depths over 50m (with much better wind resources and thus are more suitable for higher capacity turbines) many of the existing fixed foundation solutions may not be economically viable. For such depths, especially for those countries in which the water depths increase rapidly at short distances from the coast (USA, Spain, Japan, Norway, etc.) the use of floating platforms may prove a viable solution.

There are currently more than 30 floating offshore turbine projects ongoing. These include some experimental projects in test phase and 3 full scale operating projects:



Hywind, Windfloat and the Fukushima Project. However, the number of wind turbine manufacturers included in the consortia developing the projects is very limited and clearly a constrain for future development.

Floating platforms are normally classified depending on the way they keep the stability and provide buoyancy. In addition, it is necessary to point out that mooring systems may allow or restrain some of the global motion modes: surge, sway, heave, roll, pitch and yaw. Table 3-2 summarises different types of floaters and the movements allowed in each type (C: compliant, R: restrained). It may be noted that restrained movements may allow displacements in the order of a few centimetres, while compliant movements can go up to the order of a few meters.

Foundation type	Surge	Sway	Heave	Roll	Pitch	Yaw
Deep Draught Floaters (DDF)	С	С	С	С	С	С
Semi Submersibles	С	С	С	С	С	С
Barges	С	С	С	С	С	С
Tension Leg Platforms (TLP)	С	С	R	R	R	С
Heave Restrained TLP (HRTLP)	С	С	R	С	С	С
Heave Restrained DDF (HRDDF)	С	С	R	С	С	С
Ship-shaped	С	С	С	С	С	С
Truss Structures	С	С	С	С	С	С
Articulated Tower*	С	С	R	С	С	С
Compliant Tower*	С	С	R	R	R	R
* These structures are fixed to the seabed. However, they use buoyancy as a vital feature in their load bearing mechanism.						

Table 3-2 Floating platforms movements [44]

3.11.1 Deep draught (Spar) floater

This type of platform is formed by a cylindrical hull submerged almost its entire length, with a tank providing buoyancy in its upper part and a lower ballast tank which counteracts the thrust (Figure 3-48). Stability is achieved by lowering the position of the structure's centre of gravity below the centre of buoyancy, thereby producing a righting pair. This system is called weight induced stability. The structure is expected to be very stable (especially for transport and installation although movements during normal operation are to be considered and included in the Turbine Control System), easy to construct and capable of being deployed at great water depths. The system is moored by catenaries to keep its position, although in some cases vertical taut spread is combined to reduce heave movements (SWAY).





Figure 3-48 Spar platform (Hywind) [45]

Currently the main problem associated with SPAR type platforms is the necessity to install them at very deep waters as the submerged part of the platform (which gives stability) often has a very high draft to counteract the effect of the turbine. Therefore, designs under development are focused on reducing the minimum required water depth. Currently, it is not possible to install the turbine in port due to the high water depths required. Therefore, the turbine needs to be installed in an area close to shore but with a sufficient water depth which may significantly increase the installation costs as a crane barge will be required. Additionally, the movements transmitted to the wind turbine are not negligible during normal operation and then the turbine control system has to be adapted. Major maintenance activities will normally be conducted offshore.





Figure 3-49 Hywind Spar towing to be up-ended [46]

Several platforms have been deployed so far, e.g. Hywind (in operation since 2009, Siemens 2.3MW turbine, Norway), Kabashima Island (2MW spar prototype, Japan) and SWAY concept (1:6 prototype installed in Norway). Future improvements of this technology could focus on the following aspects:

- Towing of the platform and assembly of the WTG: Offshore activities may be reduced or simplified. Development of specialized vessels for spar towing and up-ending.
- Concrete may be used for cost reduction.
- Minimum required draft shall be reduced.
- Turbine control system improvement to maximize production

3.11.2 Semi-submersible

The semi-submersible platforms proposed for the offshore wind sector are in many ways similar to the submersible platforms commonly used in Oil and Gas industry but can be installed at deeper water as its structure does not require to be directly supported on the seabed (only catenaries are required). Semisubmersible platforms consist on an upper hull providing buoyancy and a lower ballast hull providing stability being then a free-surface stabilized structure. These structures have different draft configurations depending on the ballast included, allowing them to have less required draft for port and transport operations. Once reached final installation site the platform is ballasted so that the lower hull is not affected by waves and provides the necessary stability. Normal configuration includes a number of columns (usually 3 or 4), connected by bracings, and providing required stability and floatability. Some other designs under development are "barge" type floaters. The anchoring system is by catenary/taut lines made of wires, ropes or chains anchored to the seabed.





Figure 3-50 Semisubmersible platforms scheme [47]

The main advantage with this type of platforms is that they generally require a limited water depth associated with its reduced draft which enables the transport of the platform including the turbine from port to the final installation site, thus significantly reducing installation costs and risks. However, among the problems associated with semi-submersible platforms, is the need to ensure the stability of the platform through mobile ballast or by platform geometry (weights), stability (increasing the size of the platform), and the movements transmitted to the turbine (control system may be modified) especially in heave. It is normally a relatively heavy structure requiring high steel or concrete mass or significant dimensions thus increasing the construction requirements.



Figure 3-51 Semi-sub Technical Description [39]

These platforms can be constructed onshore, installing the turbine to the platform at a port and then towing the complete platform by conventional tugs. Once it has reached



final destination, the platform is connected to the mooring lines and evacuation cables installed previously and ballasted. Regarding maintenance activities, in case of major maintenance required, the platform can be towed back to port although most of the activities can be performed offshore as the platform is accessible from the columns.

There are several semi-submersibles concepts ongoing with some of them on a prototype-demonstration status. The most advanced are: Windfloat, Fukushima project and VolturnUS. Windfloat prototype (Vestas V80 2MW turbine) was first grid connected in December 2011 in Portugal. Fukushima Project (Mitsui design, 2MW Hitachi turbine) was connected in November 2013 in Japan, while VolturnUS (1:8 prototype, 20 kW was connected in June 2013 in the United States). Some other platforms are being designed as a multipurpose platform for various WTG and/or wave ocean converters.



Figure 3-52 Semi-sub prototypes: Windfloat [48], Fukushima Project [49], VolturnUS [50]

Future aspects to be developed for this technology may consider:

- Heave motions on the platform affecting the turbine
- Active ballast system requirements to reduce maintenance issues
- Concrete may be used for cost reduction.
- Reduction in material and welds for cost reduction
- Turbine control system improvement to maximize production.

3.11.3 Tension leg platform (TLP)

TLPs are very similar to the semi-submersible, but unlike them, are attached to the seabed by means of tensioned tendons. The hull of the platform has a buoyancy excess that keeps the tension on the cables. In a heel situation, the tension of the tendons and the weight of the structure produce a righting moment that keeps the stability. This system eliminates the roll, pitch and heave movements allowing sway and yaw. By eliminating the vertical oscillation of the cable the evacuation connection is simplified, dynamic turbine loads are reduced and wave resonance phenomena decreased.

The conventional arrangement of a TLP platform is a hull with 3-6 legs interconnected horizontally and submerged. Tendons are connected to the legs. The buoyancy and ballast tanks are calculated based on the thrust required. The anchor system consists of a number of tendons which are wires made of metal or synthetic materials. These tendons are connected to the seabed by gravity anchors, suction anchors or steel driven piles.



Such platforms have been used in the oil & gas industry to depths up to 1500 m. The system provides significant material savings as less steel is required. However it is expected that this method will become more expensive at greater depths due to additional anchor cost. It must also be considered that a minimum depth will be required to ensure the correct tensioning of the cables. These structures have less steel mass compared to fixed foundation structures due to its operational concept allowing them lower material and fabrication costs.

Technical description



Figure 3-53 TLP technical description [39]

As a last point, it is important to note that although this technology is considered to have fewer movements and hence less impacts to the turbine, it presents difficulties mainly for towing and turbine installation as the platform is not inherently stable. The TLPs require additional buoyancy elements (floaters or barges) that significantly make more expensive the transport and installation activities. 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. Similarly, there are concerns regarding the tensioning system life, materials, and measures needed to ensure the safety in case of tendon failures (despite TLP platforms normally include redundant tendons). Currently there is not any TLP platform installed, although TLP prototype project (ETI support, Glosten, and Alstom, UK) is expected by the period of 2015 to 2017.





Figure 3-54 TLP design: Glosten PelaStar [51]

Future aspects to be developed for this technology could consider the following items:

- special barge of additional buoyancy elements design and associated costs and risks,
- fatigue issues and safety associated to tendons and materials. transition issues when installing,
- installation process (connection to terminal pre-installed tendons) to be checked, and
- turbine control system improvement to maximize production.

Operational experience at least at a prototype scale is required to confirm the viability of these platforms.

3.11.4 Alternative concepts

The key innovations in offshore wind support structures are mainly focused on the development of new installation methodologies, and improvement of the foundation design concepts, with the aim to reduce associated costs. The most important fields of innovation, giving consideration to the global competition themes ran by Carbon Trust in 2009, can be listed as follows [13]:

- Manufacturing costs,
- Transport and installation costs,
- Potential for serial production,
- Improved structural design and durability,
- Improved maintenance and accessibility,
- Easier decommissioning.



3.12 Comparison of advantages/disadvantages of each foundation type

NREL investigated the cost-effectiveness of various foundation concepts in different water depths. These are summarised in the diagrams of Figure 3-55. Suitable ranges of water depths for various foundation concepts was also proposed by DNV (Figure 3-56) [52].



Figure 3-55 Cost of substructures in various water depths (after NREL)



Figure 3-56 Range of applicability of the available technologies (after DNV)



4. Industry challenges

4.1 Prediction of future trends

A number of scenarios can be envisaged regarding the future development of wind farms. The potentials of cost reduction in the offshore wind market in Germany are investigated in [2], where two different scenarios are considered, for rapid and slow growth in the installed capacity of wind farms:

- Scenario 1: addition of 9GW of offshore wind capacity in Germany and over 20GW in Europe by 2023
- Scenario 2: addition of 14GW of offshore wind capacity in Germany and over 40GW in Europe by 2023

The economics of wind farm development in each scenario was then investigated at three different sites, with water depths of 30, 40, and 50 m, and distances to port of 40, 80, and 120 km. The time frame considered in Prognos-Fichtner's investigation was up to the year 2023. Within this timeline, the turbine capacities were considered to be 4, 6 and 8 MW, with the 8 MW turbine representing the average capacity of 7.5 to 10 MW turbines [2]. Table 4-1 provides a summary of the wind farm specifications and turbine capacities, anticipated in each scenario.

	Scenario 1				Scenario 2			
Initial Operation	No. of turbines	Turbine capacity (MW)	Hub height (m)	Rotor diameter (m)	No. of turbines	Turbine capacity (MW)	Hub height (m)	Rotor diameter (m)
2013	80	4	90	120	80	4	90	120
2017	75	6	100	145	75	6	100	145
2020	75	6	100	154	56	8	110	164
2023	75	6	105	164	56	8	115	178

 Table 4-1 Plant and wind farm configuration in the two scenarios [2]

Another study was conducted focusing on the UK market.

Table 4-2 and

Table 4-3 summarise the anticipated turbine capacities and topographies of the offshore site [11].

Turbine	Nominal	Rotor	Sample manufacturers				
capacity	power range	diameter					
(N/N/N)	(1/1/1/)	(m)					
		(111)					
4	3-5	<145	AREVA M5000-116, BARD 5.0, GE 4.1-113,				
			Repower 5M and 6M, Siemens SWT 3.6-107 and 120, Vestas V112-3				
6	5-7	145-162	Alstom Haliade 150-6MW, BARD 6.5, Siemens SWT-6.0-154				
8	7-9	162-180	MPSE Sea Angel 7MW, Samsung 7MW, Vestas V164-7.0MW				
10	9-12	>180	AMSC Windtec Sea Titan 10MW				

Table 4-2 Summary of turbine classes considered [11]



Table 4-3 Summary of site specifications [11]							
	water	Distance to	wind speed (m/s)	Sample UK sites			
	depth (m)	port (km)	(100 m above MSL)				
Α	25	40	9	Walney 1 and 2, Westermost Rough			
В	35	40	9.4	East Anglia ONE, Navitus Bay			
С	45	40	9.7	Inch Cape, Neart na Gaoithe			
D	35	125	10	Creyke Beck (Dogger Bank), Heron			
				(Hornsea)			

Table 4-3 Summary of site specifications [11]

Two updated scenarios were proposed by BVG Associates for the anticipated rate of progress in the UK offshore wind capacities [15]:

- Scenario 1: addition of approximately 2GW of newly installed capacity per year from 2018 to 2030 (~24GW)
- Scenario 2: addition of approximately 3GW of newly installed capacity per year up to 2030 (~36GW)

The level of demand each of these scenarios will generate in the supply-chain was then assessed. The implications of this growth in terms of demand for turbines with higher capacities is illustrated in Figure 4-1 and Figure 4-2.







It is observed in the above figures that:

- The rated capacity of offshore wind turbines continue to rise steadily.
- In scenario 1: 5-7 MW turbines kick in 2015 and totally phase out turbines with capacities lower than 5 MW by 2022. Capacities higher than 7 MW start to be introduced in 2022 and represent about a quarter of the installed turbines by 2030.
- In scenario 2: 5-7MW turbines kick in 2015 and totally phase out capacities lower than 5 MW by 2019. Turbines with capacities higher than 7 MW start to be introduced in 2017 and represent about three quarters of the installed turbines by 2030.

The BVG report assumes that the future developments take place in sites with an average water depth of 40 m and average distance from port of 100 km. However, the average water depths are subject to increase when the floating foundation concepts become commercialised. Based on the current progress in the deployment of this concept, BVG predicts that this will happen from 2020 onwards [15]. The fact that higher wind speeds offshore are available at sites with large water depths makes floating wind solutions the only realistic option if these resources are to be harvested [52].

The scale-model floating foundations planned and deployed so far deal with water depths as large as 140 m (Hywind, Spar Buoy concept), and 113 m (Blue H on TLP foundation) [5]. WindFloat was installed in October 2011 off the coast of Portugal, at a site with water depth of 50 m, and 5 km distance from port [48]. Looking at the trends in the site specification of projects under construction, consented or planned, an increase in the average water depths and distances to shore is highly expected, with projects announced up to 200 km from shore and in water depths of up to 215 m [53]. In the UK, Energy Technologies Institute (ETI) has planned demonstrator projects with capacities in the range of 5 to 7 MW in 60 to 100 m water depth [52].

UpWind considered two different water depths of 25 m, and 50 m, for the detailed design of offshore foundations in their project [54]. Also, to conduct a more thorough qualitative assessment of various foundation concepts and comparison of their applicability to varying water depths, they considered the following water depth ranges:



30, 40, 80, and 120 m [55]. A feasibility study was also conducted in UpWind, on a conceptual massive turbine with 20 MW capacity, an ambitious upgrading potential in the future.

A roadmap for the offshore wind development trends expected in the next decade is presented in Figure 4-3 [56]. Based on this figure, maximum water depths of 80 m, and distance from port of 120 km is achievable before 2020.



Figure 4-3 Offshore Wind Roadmap [56]

The range of water depths and distances to port proposed in a number of reports and research studies are summarised in the following diagrams (Figure 4-4 and Figure 4-5). These graphs are then utilised as a bench mark, for determining appropriate and realistic design bases for the LEANWIND project.





Figure 4-4 Summary of the predicted development in terms of water depths



Figure 4-5 Summary of the predicted development in site distance from closest operating port

4.2 Deployment strategies and challenges

One of the most important challenging areas in the wind offshore industry is to identify the potentials of bringing the costs down despite an ever increasing demand for higher turbine capacities to be installed in sites further offshore, with larger water depths. Heavier turbines and deeper water requires more complicated foundations, and imposes more demanding requirements in terms of vessel capacity and range of operational water depths. The longer distance offshore translates into costly and time-consuming grid connection, and maintenance. Also, far offshore wind farms are subject to harsher met-ocean conditions with fewer favourable weather windows that further limits the



operability of vessels. These are the parameters that can considerably increase the cost of offshore wind projects in the newly proposed developments [57].

Optimisation of current practices in the following areas is anticipated to improve the overall cost-effectiveness of the offshore wind industry:

- Mass production and manufacturing techniques
- Logistics and transportation strategies
- Development of established support structure concepts suitable for deep water
- Support structure solutions with reduced number of joints, and reduced amount of offshore installation practice

4.3 Construction

There are several options for construction of Gravity based foundations:

4.3.1 Construction on the barge

Non-buoyant gravity based foundations can be constructed directly on large barges or pontoons, and then transported to site. This can be done using tugs in the case of non-propelled barges. Once in the location, a Heavy Lift Vessel (HLV) is required to load the foundations and lower it into the seawater. This process allows the construction of several foundations on the barge or pontoon at the same time, but the bottleneck appears on site when just one HLV has to position all the foundations.

The method is only applicable in shallow water constructions, since as the water depth increases the weight of gravity base foundation becomes too much to be lifted by the HLVs. Nysted I, Rodsand II, Sprogo, Lillgrund, and Karehamn Wind farms have been constructed using this method.





Figure 4-6 Karehamn. Foundations slabs construction over DN143 barge [58]

4.3.2 Onshore construction on a quay

The foundations are constructed on quay, and then transported to the launching area by means of SPMTs (Self-propelled modular transporter). This is the case of Thornton Bank.



Figure 4-7 Thornton Bank. The lifting of the GBF from the SPMT combination [27]





Figure 4-8 Construction yard for the GBF for Thornton Bank at the port of Ostend [27]

4.3.3 Construction on dry dock

The gravity bases are constructed in a dry dock that is flooded once they are already finished.



Figure 4-9 Middlegrunden: Foundations under construction in dry dock [59]





Figure 4-10 Middlegrunden: Flooded dry dock [60]

4.3.4 Construction on floating dock

A floating dock is a special equipment for the construction of concrete maritime caissons directly on the water. It is comprised of a central pontoon where the slab is constructed and walls are casted with concrete. As construction goes on, the pontoon lowers into the water due to the increasing self-weight of the structure. This procedure has been successfully implemented in the construction of floating maritime structures, but has not been used in the offshore wind industry yet.



Figure 4-11 Floating dock. General view [61]





Figure 4-12 Launch of a concrete floating caisson by using a tug [61]

4.4 Transportation

The method of transportation should be decided by giving consideration to several parameters:

- The foundation type and configuration, in terms of weight, shape, and geometry
- The availability of suitable installation vessels considering the weight and type of structure
- Environmental conditions, sea states, weather windows, etc.
- The distance between construction site and the base-port.

The appropriate transportation method and strategy is also subject to prior approval of a Marine Warranty Surveyor that is assigned by the client, e.g. the wind farm owner or operator. Several Classification Societies have been developing guidelines for the design, transportation and installation of offshore foundations and wind turbines.

4.5 Vessel types

The main tasks of vessels can be listed as; to transfer the support structures and turbines offshore, provide platforms for lifting and installation operations, provide offshore access and accommodation for ship crew and personnel during maintenance operations, loading, transporting and assembling failed turbine components in offshore environment if repair or replacement are required [57]. Attempting to use standard ships for offshore lifting and installation has led into extremely difficult operations, since even small wave-induced motions at the sea level are amplified into large oscillations at the top crane level. This mandates utilising vessels that can have their hull stabilised above the sea level for conducting such operations in deep water and harsh sea conditions. Vessels can be categorised in the following types:

4.5.1 Jack-up Platforms (JUP)

Jack-up platforms (Figure 4-13) are comprised of a buoyant hull, and a number of legs (3 to 6), which can penetrate and stabilise in the sea-floor and raise the hull above the water surface. The JUP can be positioned into location (self-propelled or by towing) with raised legs and floating hull on the water. Once positioned, the legs are jacked down onto the seabed and preloading takes place. During preloading the weight of the barge



and additional ballast water are used to drive the legs into the seabed, avoiding further penetration while the lifting operations are carried out.



Figure 4-13 Self-propelled jack-up platform

After preloading, the jacking system is used to lift the platform above the water to a safe and predetermined height. Jack-up platforms are often used for:

- installation of offshore constructions (wind turbines, oil and gas infrastructures, etc.) (Figure 4-14),
- maintenance of offshore wind farms,
- offshore civil constructions,
- site investigation,
- decommissioning of oil and gas infrastructures,
- providing an accommodation platform (Figure 4-15).





Figure 4-14 Jack-up platform installing a wind turbine



Figure 4-15 Jack-up platform as accommodation platform next to drilling platform

This type of vessels provide a stable base for lifting operations under adverse sea conditions by eliminating the vessel displacements due to surface waves and surges. Jack-up vessels also can provide accommodation for both the vessel and the technical crew, and are cost-effective options in sites with medium to high waves. However, the jacking operation can be time-consuming. Operability of jack-up vessels in deep waters is limited by the length of jacked legs. These vessels require feeder vessels for functioning, and they usually have limited operational speed of around 10 knots [57].



4.5.2 Leg-stabilised vessels

The leg-stabilised vessels use their legs for stability, instead of raising the entire over the water surface. This makes them more suitable for relatively shallow water sites. Elimination of the jack-up operation also results into quicker installation and transportation capabilities when compared to jack-up vessels. However, they have a limited lifting capabilities since the hull remains submerged, and is still subject to some wave-induced motion. Their application is also limited by the sea state in a restrictive way, rendering them as a less desirable option for the future developments [57].

4.5.3 Heavy-lift vessels (HLV)

HLVs are equipped with cranes specialised in lifting heavy loads (Figure 4-16). They are specially designed for offshore installation of pre-assembled modules, and therefore have the highest capacity in crane operations (Figure 4-17). They provide a great flexibility for unusual and heavy cargo, and have favourable stability characteristics. Heavy-lifters are commonly utilised in the offshore oil and gas industry, and hence their availability in the offshore wind market is an issue, subject to significantly high costs. Heavy lifters have slow mobilisation speeds, and might have problems for entering some of the ports, due to their size [57].



Figure 4-16 Heavy lift vessel Rambiz





Figure 4-17 HLV lifting jacket from a barge

4.5.4 Platform Supply Vessel (PSV)

A Platform Supply Vessel is a vessel designed to supply offshore platforms. The primary function of this vessel is the transportation of goods to and from offshore structures. PSV's are often used for transportation of jacket piles and monopiles.



Figure 4-18 Example of a Platform Supply Vessel [62]

4.5.5 Towing tugs

Tugboats are powerful and highly manoeuvrable; they have very good positioning capabilities. A tugboat's power is typically stated by its engine's horsepower and its bollard pull. Tugboats can be used for:

- transport of non-self-propelled vessels (e.g. barges, first generation jack-up, platforms) by pushing or towing them (Figure 4-19),
- water, fuel, food and spare parts supply,
- assistance in case of emergencies,



- crew transfer (Figure 4-20),
- transport of waste (from platforms).



Figure 4-19 Jack-up platform towed by a tugboat



Figure 4-20 Crew transfer from tugboat to jack-up platform

4.5.6 Barge and tugs

Barges are flat-bottomed pontoons used for transporting heavy components, such as jackets, jacket piles, transition pieces and monopiles; they are often not self-propelled and need to be towed or pushed by tugboats (Figure 4-21).





Figure 4-21 Jacket transport by barge and tugboat [36]

4.5.7 Small vessels for minor maintenance

There are a number of vessels with reduced capacity, that are usually employed for maintenance activities when there is no need for transferring bulky and heavy components offshore. The small vessels therefore, cannot be employed in case of blade, generator or tower failure. The following types can be mentioned [57]:

- Mono hull: It is a high speed boat (~25 knots), with maximum wave height for safe access to turbine of H_s =1 m.
- Catamaran: This small vessel has a medium speed of around 20 knots, and a maximum wave height for safe access to turbine of H_s =1.2 m.
- Small Water plane Area Tower Hull (SWATH): It has a medium speed of around 15 knots, and a maximum wave height for safe access to turbine of H_s =1.5 m.

Due to the small number of Leg-stabilised vessels in the market [63], and the high charter rates for the HLVs [6], Jack-up barges are currently the most common vessel types used for foundation and turbine installation in offshore wind market. However, relying on jack-up vessels as the main facilitator of the offshore operation poses a number of challenges that are discussed in more detail in Section 4.5.8.

4.5.8 Jack-up vessels, the most common type in offshore wind market

Most of the existing jack-up vessels have been optimised for offshore oil & gas industry, where their jack-up capacity operates marginally above water in deeper waters. When employed for the installation of offshore wind turbines, the jack-ups should lift turbine components to far greater heights than their standard operating range. This results in considerable delays associated with the time required to raise the jack-up to the target height. Additional time is also required for lowering the vessel once installation is finished. Having been originally developed for the offshore oil & gas industry, jack-up vessels are currently not the most cost-effective options for installing wind turbines. Their costs are usually high during the favourable seasons, when they are also in high demand by the oil and gas industries. Many of the jack-up barges are also still unable to move in wave heights over 1m [64].

4.5.9 Custom vessels

The above-mentioned shortcomings have shifted the developers towards utilising modified and purpose-built vessels suited for offshore wind applications. These costume vessels should be able to move from site to site as fast as possible. The storing capacity should be sufficient to carry a number of turbines at the same time, to reduce the



number of voyages required. They should also be designed for lifting operations in heights that are suited for turbine installation [64].

It has been predicted that reaching the EU target of 40 GW offshore wind energy by 2020 requires construction of new, purpose-built vessels for transportation and installation of turbines [65]. It was also stated that the future generation of vessels should have a minimum of 260 to 290 operational days per year; they should also be able to install wind farms in harsh met-ocean conditions and in water depths of 30 to 40 m [52, 53]. These vessels should have an increased capacity for transporting several turbines or turbine components simultaneously, and should preferably be able to carry pre-assembled turbines, in order to limit the number of offshore lift and installations. Innovative concepts have been already proposed for producing vessels meeting the above-mentioned requirements. A number of these emerging vessel types are introduced briefly in this section.

Jan De Nul multipurpose vessel

The Belgian-based marine contractor is investing in a multi-purpose vessel, with a design that enables it to do trenching, offshore installation support, and cable laying at the same time. The fact that many of the projects Jan De Nul has participated in have demonstrated the potential for utilising multi-purpose vessels have convinced the company to invest in adding a new vessel to its fleet. JDN8628, as the new vessel is preliminarily named, will be innovative in many aspects; it can provide a reliable platform for cable installation and trenching, as well as for rock installation and subsea construction projects. Any combination of the above-mentioned activities can be carried out, provided it remains within the overall capacity of 10,000 tonnes expected from the vessel [66].

Wind turbine shuttle

Wind Turbine Shuttle (Figure 4-22) is an emerging concept with dynamic positioning and relatively fast sailing capabilities (14 knots). It is a SWATH-type vessel, with a compensation system for maintaining the vessel motions at a very low level, which makes it suitable for transporting and installing two fully-assembled wind turbines [67]. Alternatively, the vessel can be used for transporting the support structures, e.g. large jackets or monopiles [68].





Figure 4-22 Wind Turbine Shuttle, suitable for transporting two fully-assembled turbines [67]

A2SEA have modified ships to a hybrid of jack-up and self-sustained container carriers. The vessels are capable of erecting one wind turbine per day, and have been employed for the Horn Rev Wind farm installation. These costume vessels also provide accommodation for the technical crew [64].

Aeolus

Aeolus (Figure 4-23) is an innovative vessel for offshore wind farm transportation and installation, developed by Van Oord. The sailing speed is set at 12 knots, and the crane capacity is approximately 900 tonnes at 30 m radius. Aeolus can accommodate 74 people including ship crew and the installation technicians. Aeolus is planned to be commissioned in spring 2014 [69].



Figure 4-23 'Aeolus': specialised Van Oord vessel for offshore wind farm installation [70]

Van Oord's new cable laying vessel is also planned to be completed by the end of 2014. This is going to be a multipurpose vessel, although the main target is to employ it for


installation of the electricity cables in offshore wind parks. It has a dead weight of 8,500 tonnes, a length of 120 metres, and a beam of 28 metres. The vessel can accommodate 90 people on board, and is equipped with a dynamic positioning system, a cable carousel with a capacity of more than 5,000 tonnes and an offshore crane for laying heavy and long export cables [69].

Windflip

Windflip (Figure 4-24) is another innovative specialised barge for transportation of fully assembled wind turbine and tower to the wind farm site. Windflip can carry one turbine at a time, in a nearly horizontal position, while being towed to the site using conventional tugs, at a maximum speed of 8 knots. Once arrived at the wind farm location, the barge starts filling its ballast tanks, which makes it flip 90 degrees to a vertical position. At this stage the barge is detached from the wind turbine, returns back to its horizontal position by emptying the ballast tanks, and towed back to the port using the tugs, where it is ready to carry another wind turbine [71].



Figure 4-24 Purpose-built transportation barge, 'Windflip' [71]

4.6 Transportation configurations

Foundation components can be transported to the site using either the same vessels that are going to install them (installation vessels), or using transportation vessels, such as barges and feeder vessels. Different transportation configurations can be used for transporting monopiles and gravity based foundations to the site. Monopiles can be capped and wet-towed, while gravity bases can be floated to the site, either using standard tugs or auxiliary purpose-built transport barges. Floating platforms (spar and semi-sub) will normally be transported by towing them by tugs, while TLP require additional buoyancy elements. The choice of appropriate method depends on the size and weight of foundation, the deck load and crane capacity of installation vessel, the distance to port, and transit speed of the vessels, and also the environmental conditions [72].

4.6.1 Using Installation Vessel

The second generation Installation Vessels are capable of loading foundation components directly from the fabricators port and transport them to the installation site. Since it's possible to load on the deck of the installation vessel a number of monopiles (e.g. 6 pieces) and likewise a same number of transition pieces, the vessel will install in series to avoid too much sailing from one position to another position. This method of transportation is suitable for jackets and transitions pieces as well as monopiles. The



non-buoyant gravity based foundations that are not constructed on barges of floating docks, e.g. in the case of Thornton Bank, or the floating gravity bases that are constructed onshore should also be lifted and launched into the water using the HLVs.



Figure 4-25 Heavy lift jack-up vessel Innovation loading and installing several foundations

4.6.2 Using Transportation Vessel

A platform supply vessel (Figure 4-26), or self-geared vessels (Figure 4-27) can be used for transporting the substructure to the offshore site. The Platform Supply Vessel will sail from fabrication yard or storage quay to the offshore installation site, where piles will be unloaded onto the installation vessel (Figure 4-28).





Figure 4-26 Transport of jacket piles by Platform Supply Vessel



Figure 4-27 Transport of MP by Self-Geared Vessel



Figure 4-28 Unloading jacket piles from PSV onto installation vessel

Combination of barges and tugboats can also be used for transportation of foundations. The monopiles, jacket piles, transition pieces or jackets can be loaded on a barge. A tugboat will then sail the barge to the installation site (Figure 4-29).





Figure 4-29 Transport of MP by barge and tugboat

Gravity base foundations that are designed for relatively shallow water depths can be constructed, and then floated to the site on the same barge (Figure 4-30). On arrival at the construction site, they are launched into the water using an installation vessel or HLV.



Figure 4-30 All Karehamn foundations on barges DN143 and DN120 [58]

4.6.3 Float-out transportation (gravity bases)

Floating foundations can be transported using standard tugs. In this case, the hydrodynamic design plays an important role since stability of the structure should be ensured during all the stages of float-out and installation.

4.6.4 Capped and wet-towed (Monopiles)

The transport cycle of the floating monopiles from the onshore base to the offshore installation site consists of the following steps:



Preparing monopile for floating transport

This is done by closing the monopile at both sides with pile plugs; ballasting inlets are foreseen in the pile plugs. Afterwards, towing gear and buoys will be installed on the pile (Figure 4-31).



Figure 4-31 Preparation of monopile for floating transport

Launching monopile at the onshore base

Launching the monopile can be done by either sliding/rolling it down the skid beams installed along the quayside (Figure 4-32) or by lowering the pile into the water with the use of a heavy lift crane (Figure 4-33). Once the pile is afloat, the tugboat will approach and connect to the towing gears (installed during monopile preparation).



Figure 4-32 Sliding/rolling of MP down skid beams on the quay wall





Figure 4-33 Lowering of a monopile into the water by means of heavy lift crane

Towing monopile to the construction site

The monopile is then towed to the construction site with a small tugboat (or workboat). The pile will then be upended by the HLV and transported further to the monopile installation jack up, where the HLV brings the monopile into the piling frame on the installation jack up and lowers it to the seabed until it is in a stable position.



Figure 4-34 Floating monopile transport

4.6.5 Turbine transportation

Turbines are usually transported using the same vessel that installs them. However, in some cases it is also possible that the turbine is transported using a transportation or feeder vessel [72].

4.7 Installation

The main activities for a wind farm installation comprise the following fields:

- foundation installation,
- turbine installation, and
- cable and grid connection.



Any challenging or unforeseen condition that occurs during the installation procedure can impact the speed of installation and other offshore operations negatively, and cause delays in the timeline of the project which translates into financial implications and an increased Levelised Cost Of Energy (LCOE). Time of installation is affected mainly by the soil type, weather windows, availability of vessels and the adopted installation strategy.

In the case of shallow bed-rock, piles need to be drilled rather than driven into the seabed. The drilling operation increases the installation time. Also, if the sea-bed surface is erodible, scour protection is required, which increases the vessel operation timeline. Offshore operations should ideally be conducted in summer since it provides the most favourable weather condition. However, operation requirements, and also high charter rates of vessels during summer do not always facilitate this, and offshore construction can be performed during winter where weather down time is more common. In these cases, delays associated with adverse weather conditions are anticipated, although foundation installation is less affected by high speed wind than the turbine installation [72].

4.7.1 Sea bed preparation

Seabed preparation is a special application for rock placement. The main market exist in pipe-laying companies and oil and gas operators, however the same techniques are applied in the offshore wind farm industry. Sea-bed preparation is an important requirement when gravity based foundations are to be installed. A survey of the seabed condition is carried out prior to commencing the works and also after the installation of each foundation. Surveys will be conducted using a Remotely Operated Vehicle (ROV) launched from the installation vessel.

Dredging (levelling)

Offshore dredging encompasses levelling of the seabed prior to the installation of foundations (e.g. gravity based foundations). This requires the use of dredging equipped with high precision dynamic positioning software to guarantee a high level of accuracy. The seabed levelling can be performed using a trailing suction hopper dredger (Figure 4-35) or a vessel equipped with a ROV "grab and drag" system (Figure 4-36), allowing a precision of up to 10 to 20 cm.





Figure 4-35 Trailing suction hopper dredger (TSHD) "Pearl River"



Figure 4-36 Vessel equipped with a ROV "grab and drag" system



Efficient dredging and levelling can be a challenging task if the shallower layers of soil contain fine particles that seep in and become suspended over the excavated area. The same problem happened in the Middelgrunden wind farm due to the considerable amount of sludge that should be removed from the sea-bed prior to installation of the gravity based foundation [73].

Scour protection (gravel bed)

If the sea-bed surrounding the monopiles and some types of GBFs is prone to erosion due to the underwater currents, scour protection becomes necessary. In this case boulders should be laid on the sea-bed to provide a guard against erosion of the finer soil (Figure 4-37).



Figure 4-37 Scour and scour protection around a monopile foundation [74]

Scour protection is usually laid using the fall pipe vessels (Figure 4-38 and Figure 4-40) or side stone dumping vessels (Figure 4-39). These vessels are equipped with Dynamic Positioning systems class 2 (DP2) and can therefore operate within 500 meter zones of platforms and close to subsea structures. The rock placement will be controlled through a fall pipe to ensure that no damage occurs to the foundation.



Figure 4-38 Rock placement around gravity based foundation by inclined fall pipe system on Fallpipe Vessel "Rollingstone"





Figure 4-39 Side Stone Dumping Vessel "Pompei"



Figure 4-40 Rock placement around monopile foundation by Fallpipe Vessel "Seahorse" with Rock Side Dump Unit

4.7.2 Foundation installation

Jacket structures

Lattice structures should be piled to the sea-bed. This can be done by either driving the pile through sleeves at each corner of the jacket, once it has been placed on the seabed. The other possibility is pre-driving the piles into the sea-bed, and placing the structure on top of the piles.

Installation of jacket piles using a jack-up vessel involves the following steps (Figure 4-41):

- positioning and jacking-up of the jack-up vessel,
- lowering the seabed template,
- lifting the pile into the seabed template,
- placing the pile hammer on top of the pile,
- driving down the pile and monitoring the pile,
- removal of the hammer,
- repeat steps 3-6 for the next piles,
- recover the seabed template,
- · jacking down of the installation vessel, and
- sail to the next location.



Prior to the start of the installation works, the deck of the jack-up vessel needs to be prepared with the required equipment and sea-fastening structures. The Installation jack-up will sail to the site, position and jack-up at the target location. After the transfer of the jacket piles from the transport vessel onto the jack-up vessel, the installation, positioning and levelling of the seabed template may be started. The piling template secures an accurate positioning of the piles which is required for the further installation of the jacket structure.



Figure 4-41 piling template installation sequence

The piles will be upended from their horizontal storage position into their vertical position and will be lowered into the template using the on-board crane. The pile driving procedure starts after the pile has been placed in the sleeve of the seabed template. A hydro-hammer is lifted from the deck and placed onto the pile. At the start of the hammering process and at regular intervals during hammering, the verticality and penetration of the pile is checked. When the pile is driven to its target depth, the hammer is stopped and restored back onto deck (Figure 4-42).



Figure 4-42 Hammering jacket piles positioned into the seabed template



After the piles have been installed at one template location, the template must be recovered to install the next set of piles on the next location. Once the template is recovered at the final location the jack-up vessel is ready to leave the site.



Figure 4-43 Jack-up vessel Goliath performing pre-piling on the Borkum West II project in Germany

Installation of the jacket support structure can be carried out using a HLV. The main steps of installation are as follows:

- positioning of the heavy lift vessel,
- lowering ROV for seabed survey,
- pile cleaning & pile dredging (prior to jacket installation),
- lift-off jacket from transport barge,
- place jacket onto the pre-piles,
- survey location, heading and level of jacket,
- grouting jacket pile connections,
- sailing to next position on site.

Prior to the start of the installation works, the deck of the heavy lift vessel needs to be prepared with the required equipment and sea-fastening structures. The HLV will sail to the installation site and will be positioned with 4 anchors. Prior to installation of the jacket, the piles have to be dredged and cleaned. This is done by lowering a dredging pump with low and high pressure nozzles into the pile to loosen the soil and to clean the pile (Figure 4-44).





Figure 4-44 Dredging and cleaning tool

Once the dredging and cleaning procedures are carried out successfully, the transport barge with the vertically positioned jacket positions itself close to the HLV. Then, the sea fastening are removed and the lifting equipment is connected to the jacket, so that the crane can start lifting the jacket. Once the jacket is lifted high enough, the barge moves away (Figure 4-45).



Figure 4-45 Lifting jacket from the transport barge

When jacket piles are fully penetrated, the jacket will rest onto the top of the pre-piles. The operation is monitored and guided using a ROV, which is deployed prior to the start of operation, and transmits images during the operation (Figure 4-46).





Figure 4-46 ROV is used for monitoring the installation

Once the jacket rests on the piles, and its verticality is ensured, the grouting operations commence. These are aimed to provide a sound and reliable connection between the piles driven into the seabed and the jacket mounted on top of the piles.

Gravity based foundations (GBFs)

Once the seabed is prepared and the foundation has arrived, installation of foundation at site involves the following steps:

- Positioning the structure: It should be done using a combination of GPS systems, other tracking and monitoring equipment such as cameras and dynamic positioning devices, and divers.
- Hoisting and lowering procedures,
- Sand or water ballasting to fill the cells and provide the required weight for the gravity based foundation [60].

Different strategies can be adopted regarding the installation of foundations and assembly of tower, turbine, etc.

- The gravity base foundations can be transported on site on a barge or pontoon, and then installed separately using a heavy lift vessel.
- The pre-assembled foundation and tower can be transported and installed onsite. The nacelle and turbine can be installed on site. This strategy was employed for installation of the Middlegrunden wind farm.
- The emerging concepts in gravity base foundations, e.g. Strabag (Figure 3-11), are considering adopting a pre-assembled foundation and turbine, which will be delivered to the site fully formed and installed in place thus eliminating the timeconsuming and challenging offshore installation procedures.

Monopile foundations

Different strategies can be adopted for monopile installation, depending on the number and type of vessels available. Once arrived onsite, the piles are upended by a crane or another pile gripping device. This is usually the loading that determines the required crane capacity. The pile is then driven to the sea-bed using a hydraulic hammer or drilled, in case of presence of a shallow bed-rock. The required installation time depends on the soil type, size of the pile, and hammer weight. Drilling usually adds to the



installation time. Once the monopile is fixed and secured in place, the transition piece is grouted, occasionally bolted, to the monopile (Figure 1-12) [72].



Figure 4-47 Transition piece being placed over monopile [75]

The various configurations for transportation and installation of monopile and transition piece are as follows [72]:

One installation vessel

One installation vessel is used for both transporting and installing the foundation. The vessel can transport and install all the foundations first. Then transport and install all the transition pieces. The second possible configuration is that the vessel transports both the foundation and transition piece, and installs them simultaneously and in sequence.

• One installation vessel and one feeder vessel:

In this configuration, a feeder vessel is used to transport the components onsite, where the installation vessel installs the foundation and transition piece. This will save the installation vessel several trips to the port.

• Two or more installation vessels:

In this configuration the two vessels can operate separately with each installing foundations and consequently the transition pieces, or they can work together, with the first vessel installing the foundations, and the second installing the transition pieces. While using two installation vessels reduces the overall installation time considerable, it usually does not cut it in half. Therefore, the number of boat days per foundation in this configuration increases.

The objective of Floating platform foundations is to install the combined platform and turbine on pre-installed cable and mooring lines reducing offshore activities. The



anchoring and mooring system will be site and type specific. Once reached final site installation, the platforms will be ballasted up to the final installation draft and connected to the mooring and cable.

4.7.3 Turbine installation

Turbine installation is the next stage after installation of foundations. First, tower sections should be mounted on top of the foundation/transition piece. Then the nacelle is installed, following by installation of rotor and blades. The common practice in installing the turbines is to use jack-up barges for both transportation and installation. If two jack-up vessels are available, both of them can jack out, allowing all the lifts to be stationery. In the case of Blyth offshore wind farm, using a standard barge as the transportation mean of turbines was identified to be the major source of delay [76].

Turbines typically consist of seven components: two tower sections, three blades, nacelle and hub. Some, or all of these components can be pre-assembled onshore, to reduce the number of risky offshore lift operations. The degree of pre-assembly has an impact on the appropriate lifting vessels as well as the expected installation time [72].

Different turbine installation strategies can be categorised based on the number of lifts required by each method. These are summarised in Figure 4-48. Pre-assembly of turbine blades hinders their transportation by limiting the number of blades that can be stored on the deck and transported at the same time. However, it reduces the number of heavy lifts required. Considering the fact that installation of the turbine blades is the most wind sensitive offshore operation, decreasing the number of required lifts can lead into reducing the overall installation time considerably.

It should also be noted that the combination of rotor and blades is still unlikely to weigh more than the nacelle. Therefore, the pre-assembled turbine blades are not the weight limiting lift and do not have any negative implications on the minimum requirements for crane capacity [72].



Figure 4-48 Diagrammatic representation of turbine installation methods [72]



The first configuration involves the minimum pre-assembly (only nacelle and hub are joined onshore), 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.

In the second method, 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 [72].

The third configuration 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 [72].



Figure 4-49 Installation of a pre-assembled rotor at Alpha Ventus [77]

The forth 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 (Figure 4-50), 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 [72].





Figure 4-50 Nacelle and blades in the Bunny Ear configuration; Installation of Alstom's 6MW Haliade 150 [78]

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 [72]. In the case of floating platforms, the turbine will be normally installed over the platform at port (or near port in the case of Spar platforms) and then towed to site.

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 (Figure 4-51).



Figure 4-51 The Rambiz installing a fully assembled turbine at Beatrice [79]



Installation of the entire turbine in one lift requires heavy lift vessels with a crane capacity of at least 500 tonnes. Transportation of the pre-assembled turbine also might be challenging; proposals for purpose-built transportation vessels have been suggested, that are suitable for carrying the entirely pre-assembled turbine (Figure 4-22). The most appropriate strategy for turbine installation should be selected by giving consideration to several parameters, such as the availability and cost of vessels, their maximum crane capacity, the turbine model and weight of each component [72].

4.7.4 Grid connections

Transmission of electricity using high voltage connections, minimises the current and hence the power losses, particularly when the electricity is transmitted over long distances. This has led to the application of High Voltage Direct Current (HVDC) cables for grid connecting large wind farm developments located further offshore. In this case an offshore substation is usually required to step up the voltage upon collection from the wind, and before transmitting it ashore [64]. For instance, at Horns Rev wind farm, 34 kV cables were used to transmit electricity from individual turbines to the substation transformer, after which the voltage is increased to 150 kV [80].

There are different techniques for laying the cables in an offshore wind farm:

Simultaneously lay and bury using plough

This is the most economic and most common method of installing the electricity cables. In this method, the cables are fed into a plough, which is pulled at the sea-bed by a cable laying vessel or barge. A high pressure water jet washes the sea-bed, making the cables sink in a trench of approximately 2 metres depth. It should be noticed that only certain ground conditions permit the application of this method [64]. The method has been used for laying the cables at Scroby Sands, North Hoyle, Barrow, Rhyl Flats, OWEZ, and Gunfleet Sands [80].

Anchoring

Electricity cables are laid on the sea-bed and then anchored using an auxiliary method, such as concreting the cables or using steel hooks. This approach can be very troublesome since the unforeseen and strong underwater currents can interfere with the anchoring procedure. This installation method was used at the Backstigen Wind farm [81]. Apart from being difficult to carry out, anchoring has the problem that the cables are not embedded in the sea-bed, and are hence prone to damage due to collision with objects and equipment [64].

Trench excavation

In this method a trench is pre-excavated. Cables can be laid in the trench using a cable laying vessel or they can be laid on air bags, and lined up along the excavated trench, so that divers can guide them into the trench by deflating the airbags. The trenches are then covered with the excavated deposit. This approach was employed at Middlegrunden and Lillgrund [72], [73].



4.7.5 Other installation challenges

Safety of divers

Many of the stages during installation of foundations, also cable installation and later maintenance involve the use of divers. Diving operations are high risk activities that require careful planning, monitoring and safety considerations. Diving can be complicated due to unpredictable weather conditions and rough sea states. In some cases access to skilled divers can become a bottleneck of the installation procedure [64].

Traffic control

In the case of very large developments, and peak operation times, there is a large amount of sea traffic due to transportation of vessels and tugs. This sea traffic require many man-hours of work to be co-ordinated and supervised [64].

4.8 Decommissioning

An offshore wind farm has to be removed from the sea at the end of the lifetime. Decommissioning might also become necessary if the Offshore Wind Turbine (OWT) is no longer functional due to a damage, technical problems or withdrawal/expiry of the approval.

This is to ensure the safety of navigation and to protect the marine environment. Depth, position and dimension of any component that is not entirely removed, should be publicised to avoid any risks to the shipping or fishing activities [82]. Wind farm components can be re-used, recycled, or disposed on land, upon removal from the site. These are the followings [83]:

- rotor (blades and hub), nacelle (rotor shaft, gear, generator, and cooling units), tower and foundation,
- scour protection materials,
- interconnecting power cables within the wind-farm,
- power cable to shore,
- converter stations with technical equipment and foundation.

4.8.1 Regulations and guidelines

In this, the IMO (International Maritime Organization) published "Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone" in 1989. Furthermore, the OSPAR Commission (Convention for the Protection of the Marine Environment of the North-East Atlantic) adopted a legally binding regulation for the disposal of disused offshore oil and gas installations in 1998 [83].

In Germany approvals specify that all the embedded components shall be cut and removed from the seabed at such depth to ensure they do not pose any danger to shipping or fishing activities, even if this requires relocation of the sediment at the seabed [83].

When the installation becomes 'disused', extending the life of the installation, or reusing the infrastructure in a beneficial way, will often be preferred. However, when extending its life or finding a beneficial reuse is no longer possible a decommissioning programme



should be carried out [84]. The decommissioning programme should cover: the general requirement to remove installations; exceptions from the general presumption in favour of removing the whole of an installation; sea-bed clearance; how installations are to be removed; how waste is to be dealt with; notification and marking of any remains; and monitoring, maintenance and management of the site after decommissioning [84].

Drawing on the IMO standards, set out five situations in which other solutions (namely, leaving in place or partially removing an installation or structure) may be considered. However, even in these situations, items will not necessarily be allowed to remain on or in the sea-bed. Decisions will be made on a case-by-case basis. The five situations are where:

- The installation or structure will serve a new use, whether for renewable energy generation or for another purpose, such as enhancement of a living resource (provided it would not be detrimental to other aims, such as conservation). In these situations, it would be expected that the decommissioning programme sets out the eventual decommissioning measures envisaged should the installation or structure finally become 'disused' and a point reached when extending its life or finding a beneficial reuse is no longer possible.
- Entire removal would involve extreme cost. It is considered that design decisions should, as far as possible, result in installations which are affordable to remove, but it is recognised that some elements, such as deep foundations, may nonetheless be costly to remove.
- Entire removal would involve an unacceptable risk to personnel.
- Entire removal would involve an unacceptable risk to the marine environment.
- The installation or structure weighs more than 4000 tonnes in air (excluding any deck and superstructure) or is standing in more than 100 m of water and could be left wholly or partially in place without causing unjustifiable interference with other uses of the sea [84].

4.8.2 Decommissioning of Gravity Base Foundations

Regarding concrete gravity base foundations, a specific report was prepared by a task force of the International Association of Oil & Gas Producers (OGP) Decommissioning Committee. Although every concrete GBF has unique features which need to be considered on an individual basis, there is a range of generic concrete GBF decommissioning options that can be considered. These can be summarised as follows [82]:

- reuse at existing location,
 - o in energy related applications, such as carbon capture/storage
 - o for other commercial or research activities
- full removal
 - o reuse at another location
 - $_{\odot}$ $\,$ inshore deconstruction with onshore recycling and disposal
 - o offshore disposal
 - offshore demolition, transport to shore with onshore recycling and disposal
- partial removal
- leave wholly in place
 - with topside (turbine and tower in the case of offshore wind farms) removed and with suitable navigational aids installed



Operators should investigate the viability of each of the above decommissioning options on a case-by-case basis. This investigation must be sufficiently comprehensive to enable a reasoned judgment on the practicability of each disposal option, and to allow for an authoritative comparative evaluation [82]. In order to avoid impacts on the environment, best available techniques should be used for the removal of the components.

4.8.3 Under-water cutting techniques

During decommissioning, monopiles and jacket piles have to be cut, up to 2 meters below the seabed. Cutting the piles can be done using either underwater gas/oxygen torches (Figure 4-52), or by means of an abrasive water jet (Figure 4-53).

In the first method, 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. It contains a top frame which can be laid down on top of the pile. On top of this frame a winch is mounted to lower the cutting tool into the pile. The cutting tool is equipped with cutting arms which rotates inside the pile. At the end of each cutting arm there is a special underwater gas/oxygen cutting torch which can easily cut through the steel.



Figure 4-52 Cutting and lifting tool with torches

If the abrasive water jet is to be used, the internal jet should be connected to a containerized ultra-high pressure pump (3000 bar), and lowered into the jacket pile or monopile. Cutting is initiated by creating a hole in the pile wall and rotating the nozzle around it to continue piercing. The frame of the cutting tool has the capacity to lift the pile on the deck.





Figure 4-53 Abrasive water cutting tool

4.8.4 Avoiding diving operations

Diving operations should be avoided whenever possible and should only be used as the last resort having considered and risk assessed all other viable options first, e.g. utilising remotely operated vehicles – ROVs (Figure 4-54).

The possible diving operations are limited by the allowable depth and time. During diving, decompression tables should be used (e.g. Netherlands Diving Centre tables and the Bühlmann Decompression Table) to determine the maximum time a diver can spend at a certain depth and return safely to the surface. Regardless of the decompression procedure in use, time keeping is critical. For this reason, all dives will be conducted on an elapsed time basis using a stopwatch. Upon successful completion of a dive, the diver has to stay in the immediate vicinity of the decompression chamber for at least 1 hour.

If ROVs are used, there is no waiting period between the two consequent dives; they can spend an unlimited time at depth with no need of the decompression facilities. Unlike a diver, a ROV can operate at the same time as a vessel is using its dynamic positioning (DP) tools. This provides further flexibility in timing of the operations, and allows the vessel to maintain its position more accurately. ROV can also be employed for conducting inspection during installation and decommissioning operations under conditions that would be too hazardous for the divers to operate.





Figure 4-54 Performing underwater inspection by ROV



5. Design basis

5.1 Geotechnical design

The geotechnical design considerations and the soil-structure interaction depend on the type of foundation employed.

Laterally loaded monopiles transfer the load by mobilising displacement-induced pressure in the surrounding soil. Their effective clamping depth can be calculated in terms of soil and pile parameters, making a small number of assumptions. Axially loaded piles transfer the load through a combination of shaft resistance and end bearing capacity. Assuming a linearly increasing effective soil pressure, the shaft friction can be determined according to Coulomb's theory for frictional material, and bearing capacity can be calculated using the theory of Prandtl, Terzaghi and Brinch-Hansen [85].

Suction buckets also transfer the load through the end bearing capacity and side friction. However, the bearing capacity of suction bucket, caused by pressing the cap against the soil plug that forms inside the bucket, is much more significant compared to that of an axially loaded pile. Long-term tensile loads drain water out of the soil that is trapped underneath the suction cap. In this case, skin friction will be the only mechanism of load transfer. The time-scales required for these phenomena are dependent on parameters such as bucket dimensions and the sea bed soil material [86].

Geotechnical design of gravity base foundation involves providing sufficient bearing capacity for the dead weight of the structure, accompanied by the inclined loads and overturning moments. The sliding resistance should also be checked, and accommodated either by increasing the dead weight of the foundation or by installing skirts that provide additional resistance to sliding [85].

Regardless of the foundation concept employed, it is essential to consider the soilstructure interaction and the behaviour of the entire system under a range of limit states including ultimate, serviceability, and dynamic conditions. This should also include a consideration of soil damping.

5.1.1 Scour protection

Scouring can result into erosion of the sediments surrounding the foundation. This can reduce the bearing capacity and resistance of foundation, and drop the first natural frequency of the structure [85]. Axially loaded piles are reported not to be sensitive to the scour issue. Scour is more serious in foundations with larger diameter, such as XL Monopiles, or gravity bases. The larger dimension of these structures causes higher disturbance of the current around the foundation, accelerates the wave speed, and increases the scouring action potential. Wherever required, scour protection can be applied on the sea-bed sediments, in the form of a filter layer of relatively small stones, covered by an armour layer of dumped rocks to keep the stones in place [55]. The effect of scour has to be assessed on rigid body movements and natural frequencies. If no scour protection is provided, a depth allowance equal to 1.5 times the pile diameter should be considered when calculating shaft friction of the piles [85].



5.2 Structural design

The support structure itself should be designed to withstand the structural stresses incurred due to transfer of the load from wind turbine to the foundation. Some of the possible failure modes are listed in this section:

5.2.1 Yielding

The yield stresses of the structural material can be exceeded due to non-cyclic loading which occurs in ductile materials and leads to localized damage (e.g. micro-cracks and dislocations) at the stress concentration points. This localized damage can be the starting point of macro-cracks or fatigue cracks. It will mostly happen during transport and installation. Micro-cracks are hardly visible and require an infrared device to be detected.

5.2.2 Ductile fracture

It is referred to the condition where an extensive plastic deformation takes place in the structure before rupture. It occurs after yielding, when the micro-cracks coalesce and form a visible crack. If yielding is controlled, this mode of failure is unlikely to occur.

5.2.3 Brittle fracture

Exceedance of stresses from the ultimate strength under non-cyclic loading mostly occurs in brittle materials. Although brittle materials are not usually employed in the wind turbine support structures, ductile materials may become fragile under given environmental conditions and extreme loadings. A ductile material can rupture in a brittle mode when subject to excessive low temperatures, e.g. in contact with ice, or to impact, e.g. collision with a boat.

Challenges exist related to fatigue of steel and concrete substructures including the risk of unstable crack growth and brittle failure. Related to this it could be cost optimal to plan for inspections during the design lifetime and then use smaller safety factors in design (and thus less material).

5.2.4 Structural instabilities

The most important sources of structural instability that may lead to permanent damage and potential failure are local and global buckling. Local buckling may occur before global yielding and is specific to the steel structure considered. Correct sizing of the structural dimensions can prevent buckling to a great degree. Excessive deformations may also be observed as a result of elastic distortion leading the limitations of equipment being exceeded (excessive RNA accelerations and displacements).

Another important aspect that should be considered in structural stability considerations is design for withstanding overturning moments. This mode of failure is usually overcome by increasing the dead weight of the structure in Gravity based fondations.

5.3 Hydrodynamic loading

Small waves can be modelled using the linear wave theory, whereas the higher waves should be modelled with nonlinear theories, such as Stokes' model or Dean's stream function. The extreme stresses usually occur with highly nonlinear, non-breaking waves. If linear wave theory is employed for modelling the hydrodynamic loads, regardless of the wave height, the extreme forces are usually underestimated. The importance of hydrodynamic loading as a design driver also depends on the type of structure. More



compact structures such as gravity bases impact the movement of water more significantly, compared to structures with slender members, such as jackets and tripods. Gravity base foundations also suffer significant heave forces that can be calculated using Bernoulli's equation or diffraction models [85].

If the combination of wind turbine and support structure has a higher natural frequency (softer structure) the risk of dynamic amplification due to resonance with hydrodynamic loads rises. Single column configurations, such as the monopile, are highly susceptible to this effect. One way to increase the stiffness of monopile is to use larger diameter steel tubes; however, this increase the amount of hydrodynamic loads absorbed by the structure [27].

5.4 Dynamic behaviour

The dynamic behaviour of the support structure is an important consideration in the design of wind turbines. The first natural frequency is the most important indicator of the overall dynamic behaviour of the structure. This can be assessed using Rayleigh's method or through more precise finite element modelling [85]. The natural frequency should be determined so that the high energy excitations, as well as those with higher possibility of occurrence are avoided [55]. The main consideration in determining the allowable natural frequency band, is to avoid resonance with wave frequencies, and the turbine dominant frequencies (1P and nP) [85]. The risk of resonance is assessed by determining the natural frequencies of the structure and comparing it with the spectrum of the excitation forces (wind, waves and wind turbine operating).

5.5 Design for fatigue

One of the important considerations for fatigue design is the natural frequency of the structure. The wave excitations with high frequency of occurrence should be avoided, along with the wind frequencies close to the rotor frequency (1P), which is usually in the range of 0.117 to 0.202 Hz [55]. Detailed explanation of the various design approaches (stiff-stiff, soft-stiff) are beyond the scope of this document.

High-cycle fatigue failure is the most common failure for OWT foundations. The inherent cyclic loads resulting from rotor rotation, blade passing, and waves result in stress concentration and lead into failure. Steel joints are particularly prone to this type of failure, which is exacerbated in the corrosive marine environment. Low-cycle fatigue failure is the result of stress concentration due to excessive vibrations in case of resonance. This type of fatigue failure may only occur if the natural frequency has not been designed and achieved appropriately.

In the common procedure for fatigue design, wind response time series and the wave response time series, extracted from the Met-Ocean condition for the wind turbine, are superimposed. These are then post-processed to determine the total annual fatigue damage based on the annual and directional probabilities of occurrence of these load conditions [54]. Application of S-N curves can determine the allowable number of cycles for each stress amplitude. At welds, joints and other discontinuities in the structure, a stress concentration factor should be applied. Other sources of fatigue damage to the structure are the start-up and shutdown procedures, also the stresses applied during installation phase, such as the pile driving stresses [55].



5.6 Corrosion protection

Offshore support structures are exposed to the harsh marine environment which makes them highly susceptible to corrosion. Therefore, it is mandatory that at least one methods of corrosion protection on the structural steel components is adopted. DNV Guidelines mandate various corrosion protection measures for the components of steel structures depending on their level of exposure. The structural parts in the atmospheric zone should be protected by coating. If the component is located in the splash zone, a corrosion allowance should also be taken into account by reducing the nominal thickness of the member in all the limit-state analyses. All the steel components in the submerged zone should have cathodic protection; however, coating is introduced as an only optional measure for this zone [6].

5.7 Decommissioning

Decommissioning is a relatively new practice, with no established method or procedure for decommissioning of the wind turbine foundations being reported in the literature. However, a number of scenarios can be envisaged for the removal of wind turbine foundations from the sea-bed. The structure can be transported, and re-used at some other location (e.g. in the case of Gravity base Systems). They can be fully or partially removed from the sea-bed. They can be disposed at sea, or be left wholly in place. Operators should investigate the viability of each of the above options on a case-by-case basis, depending on the type of foundation, site condition, and other considerations such as safety, environmental impacts, technical practicality, societal and economic implications [82].

5.8 Software and modelling tools

A number of LEANWIND partners have developed their own in-house design and analysis packages. For instance, the R&D department of French utility Electricité de France (EDF) has for more than 20 years been developing an all-purpose numerical simulation software for implicit structural mechanics released under the GNU GPL license (Code Aster, 2013). Widely used in-house for verification and maintenance of assets and power plants, this Finite Element Analysis (FEA) solution covers a large range of applications such as 3D thermal and mechanical analysis in linear and non-linear statics and dynamics. It can be applied to machines, pressure vessels, pipes, civil engineering structures and so on. Beyond the standard functionalities of all-purpose FEA software for structural mechanics, Code_Aster is also the placeholder for knowledge sharing of numerical models related to the strong research involvement of EDF in various fields: fatigue, damage, fracture, contact, earth materials and porous media, multi-physics coupling, vibration analysis and rotating machinery.

Code_Aster is used for the design of offshore wind turbines. Ongoing developments are held for the integration of aero-elastic forces with an aero-elastic coupling. Hydrodynamic forces are applied to the structure assuming no hydro-elastic coupling occurs. Those forces can be calculated by Morison formula, linear potential theory (Aquaplus developped by Ecole Centrale Nantes) or a fully non-linear potential approach (Numerical Wave Tank).

The following table summarises the codes and numerical tools we envisage we would use in the LEANWIND Project, along with their status, and whether or not they are commercially available.



		sapport off dotard
Package	Company	Availability
FOCUS6	ECN, WMC, EWIS	Commercial
TURBU/PHATAS/ECN AERO Module	ECN, WMC, EWIS	Commercial
ADCoS	ADC GmbH	Unavailable
FAST	NREL	Open-source
LR FAST	LR NREL	Open-source
LR FAST + SACS	LR NREL Bentley	Commercial
FAST ADAMS	NREL, MSC	Commercial
ADWIMO	MSC	Commercial
S4WT	LMS SAMTECH (Siemens company)	Commercial
QBLADE	TU Berlin	Open-source
Sesam Wind	DNV	Commercial
LACflex	LAC Engineering (Ramboll company)	Commercial
HAWC2	Technical University of Denmark	Commercial
SIMPACK	SIMPACK AG	Commercial
Windurance FAST	Windurance	Unavailable
DHAT	GL	Unavailable
Alcyone	CRES, Technical University of Athens	Unavailable
CENER FAST	CENER	Unavailable
FLEX5	Stig Oye, Technical University of Denmark	Unavailable
DUWECS	Delft University of Technology	Unavailable
GAST	National Technical University of Athens	Unavailable
Twister	Stentec	Unavailable
VIDYN	Teknikgruppen, AB	Unavailable
ARLIS	Kirchgassner	Unavailable
Flexlast	Stork Product Engineering (NL)	Unavailable
Bladed	GLGH	Commercial
Ashes Educational (AE)	Simis, NTNU	Available (AE)
FEDEM/SESAM	FEDEM Technology, DNV Partnership	Commercial
ANSYS		Commercial
ABAQUS		Commercial
SACS		Commercial
PLAXIS		Commercial
AQWA		
WAMIT		
Code-Aster	EDF R&D	

Table 5-1 Available Numerical tools and software for modelling the wind turbine and support structure

5.9 Site conditions

5.9.1 Water depth

The water depth is one of the governing factors influencing the choice, and also the cost of the support structures. According to the Prognos-Fichtner study, a 10 meter increase



in water depth (from 30 to 40 m), increases the cost of substructure by 30% in a reference year [2].

For water depths of over 40 m, jacket foundations have been the only solutions deployed to date. However, in the medium-term (from 2020 onwards), the industry expects other substructure concepts for 6 MW generators to be available. In water depths of over 40 m, and longer distances from the port, more than 50% of total installation costs pertains to the support structure, rendering it as a factor of utmost importance [2]. The current knowledgebase and future trends have been used to determine the water depth scenarios outlined in the subsequent section (refer to Figure 4-4 in the previous chapter).

5.9.2 Distance from port

The distance from port impacts several aspects of the transportation, and maintenance planning, e.g. the choice of vessels, the maintenance strategy, the cost of transportation of support structure and wind turbine. Distance from port is an important parameter to be considered if a precise evaluation of the cost effectiveness of the wind farm is to be made, since it has a significant influence on LCOE. The current knowledgebase and future trends have been used to determine the scenarios for distance from port as outlined in this document (refer to Figure 4-5 in the previous chapter).

5.9.3 Soil profile

The soil properties are perhaps the most significant factor for the geotechnical design of the turbine foundation. In many cases it will determine the applicability of foundation types, and is one of the most critical parameters in making the final choice regarding the most appropriate foundation concept. Important design consideration such as scour protection, feasibility of piling, and the amount of required dredging/sea-bed preparation are also determined based on the soil profile and the bearing capacities encountered at the wind farm construction site. Designing for accurate soil-structure interaction is also a challenging process, particularly when considering the range of design conditions from ultimate, service, and fatigue loads.

5.9.4 Met-Ocean condition

The environmental loads resulting from the wind and wave actions on the structure play an important role in the design of support structures for offshore wind turbines. The dominant environmental load on bottom-fixed offshore structures is normally the hydrodynamic forces resulting from the wave action on the support structure. However, specifying representative design values and distributions for the met-ocean variables at the planned wind farm sites is not a straight forward task. Met-ocean design conditions corresponding to a return period of 50 or 100 years should be estimated based on the data that has been usually monitored over a relatively short period of time, in the range of several years. Most of the existing empirical methods for predicting the extreme environmental loads are overly conservative [87].

5.10 Wind farm characteristics

5.10.1 Wind farm capacity

The wind farm size and the turbine capacity are the parameters that determine the overall wind farm capacity. Increasing the turbine capacity can increase the amount of energy produced for a unit of foundation and support structure, and hence can improve



the energy production with minimal increase in the transportation, installation, and maintenance costs. However, it should be considered that higher turbine capacities lead into higher weights and increased loads at the interface level. This will create a demand for more competent foundation and support structure designs, as well as higher capacity cranes and vessels for transport and installation of the bigger turbines.

5.10.2 Interface loads

The turbine interface loads depend on turbine capacity, weight, geometry, aerodynamic properties, among other parameters. Representative interface loads for each wind turbine are usually provided by turbine manufacturers for various met-ocean conditions and wind speeds. Having access to realistic interface loads for the adopted wind turbine capacity can lead into more accurate design, and consequently a reliable cost effective evaluation.

5.10.3 Wind farm layout

The wind farm layout can influence the overall energy output of the entire wind farm. Optimal positioning of turbines can minimise the wake effects and hence maximise the efficiency. Another important aspect of wind farm is the number of wind turbines deployed in the site. The wind farm size can impact the transportation and maintenance costs and strategies, and hence the LCOE.

5.11 Suggested scenarios

In the following sections the proposed design scenarios that are going to be dealt with in the framework of LEANWIND project are introduced. These are determined by giving consideration to the state of the art of offshore wind industry and the expertise of LEANWIND partners in the field that enables them to foresee the future needs. While the proposed scenarios have a basis on existing knowledge, the parameter ranges are largely driven by the direction of future industry development.

5.11.1 Site conditions

The final design scenarios in terms of water depth and distance to port are presented and summarised in Table 5-2. It should be noted that not all the foundation concepts suit the specific ground conditions and water depths envisaged. Therefore, it is essential to identify the appropriate design scenarios for each foundation concept. These are also summarised and suggested in Table 5-2.

	Site conditions		Ground conditions			
Design	Water	Distance to	Shallow bedrock	Medium dense sand		
case	Depth (m)	Port (km)				
0	20	30	×	×		
1	40	30	Gravity bases	XL Monopiles Gravity Bases		
2	60	100	Lattice Structures Gravity Bases	Lattice structures Gravity Bases		
3	100	30	×	Floating foundations		

Table 5-2 Design scenarios for various foundation concepts

The proposed scenarios aim to cover the various range of parameters as should be investigated by different LEANWIND work packages. However, considering the fact that governing parameters in various work packages do not always match, some level of modifications in the application of these design cases are anticipated. For instance,



design case 0 will not be investigated by WP2, since the foundation design is aimed to focus on the new developments which are usually planned for deeper sites. However, this design case is an important scenario from the point of view of O&M optimisation, since it represents the site condition for the majority of currently existing wind farms.

Two different ground conditions will be considered in the design of substructures. A shallow bedrock overlain by clay will represent the sites suitable for installation of gravity base foundations. The specifications of soil profile A is provided in Figure 5-1. A dense sand soil profile, with the specifications listed in Table 5-3 will also be considered as the soil profile B. These are pertaining to a dense marine sand encountered in the west of the Irish Sea.



Dense Marine Sand profile properties				
Material type	Drained, Mohr-Coulomb			
Unit weight (γ_{sat})	20 kN/m ³			
Young's modulus (E')	100,000 kN/m ²			
Poisson's ratio (v)	0.25			
Cohesion (c')	0 kN/m ²			
Constant volume friction angle (ϕ cv)	36 °			
Dilatancy angle (Ψ ')	15° at the seabed level, decreasing linearly to 0 at 50 m below the seabed			
Peak friction angle (ϕ ')	46.2° at 5 m below the seabed 45.2° at 10 m below the seabed 43.0° at 20 m below the seabed 40.7° at 30 m below the seabed 38.4° at 40 m below the seabed 36.0° at 50 m below the seabed			
Lateral earth pressure coefficient (k ₀)	1.0			

Table 5-3 Soil profile B: Dense sand properties

5.11.2 Met-ocean conditions

The discussion regarding finalised met-ocean conditions to be considered for each design case is still ongoing at the time of writing of this report. It will be attempted to use available met-ocean data from sites with the most similarity to the design cases 0 to 3.



6. WP Framework development

This section includes a summary of the individual task descriptions as outlined in the approved Description of Work (DOW) [88], and the approaches adopted for achieving these targets. It has been attempted to reflect the most recent developments in the project and also the discussions between partners regarding how to achieve the desired outputs.

6.1 Task 2.1 approach

According to the Description of work of the project, "This task will precisely define the design constraints and functional requirements surrounding substructure engineering and deployment with the use of lean tools such as value chain mapping" [88].

Task 2.1 has been conducted in close contact and consultation with the following work packages:

- WP3: Novel Vessels and Equipment
- WP4: Operation and Maintenance strategies
- WP5: Integrated Logistics

This was advised in the description of work of the project and has also culminated in the development of this deliverable (Deliverable 2.1). So far, in this study a range of issues across the technology development and state of industry have been examined and identified and a technical approach has been agreed upon for the continuation of the work in this work package, particularly in the tasks focusing on the design of various types of foundations (Tasks 2.2, 2.3, and 2.4).

6.2 Task 2.2 approach – "Gravity Based Substructures"

According to the description of work, in this task, the "Novel means of constructing, installing and decommissioning gravity base foundations will be considered in light of potential efficiencies in cost and time." In this light, a state of the art study will be performed (in conjunction with Task 2.1). The industry knowledge of the consortium will be utilised to develop and investigate various production line scenarios; and this will feed into the Supply Chain report (Deliverable 2.2). Once the gravity base concept with the most potential for cost saving has been identified, conceptual design will start, necessary optimisations and innovative solutions will be considered in the design and deployment, through sensitivity analyses, tank testing to study intermediate stability during load-out and ballasting, and other design validation and cost comparison activities. Findings of this task will feed into the report with the subject of 'Fixed Platform Design' (Deliverable 2.4). For more detailed information about the various steps that should be taken in this task, the Description of Work can be consulted [88]. A schematic diagram of the planned activities within Task 2.2 has been provided in Figure 6-1.





Figure 6-1 Plan of progress of T2.2: Gravity based substructures (Task Leader: ACCIONA)

6.3 Task 2.3 approach – Bottom fixed steel substructures

According to the description of work, "An approach similar to Task 2.2 will be adopted whereby the installation, transport and long-term conditions will be considered" [88]. Once the concepts to be further developed are selected in the concept selection workshop, these will be critically compared to identify their features which could be enhanced or improved. The state-of-the-art jacket detail design issues will be incorporated in a framework that also considers some modelling and analytical engineering tools. The jacket float-out and the hydrodynamic effects will be modelled using CFD software, and the innovative methods for design, construction, transportation and installation of fixed steel platforms will be compared from both a practical and economical point of view. Priority will be given to jacket and large monopiles. Other novel structures will be considered depending on the availability of design data and man hour. A schematic diagram of the planned activities within Task 2.3 has been provided in Figure 6-2.



Figure 6-2 Plan of progress of T2.3: Bottom-fixed steel substructures (Task Leader: EDF)



6.4 Task 2.4 approach – Floating substructures

A risk ranking exercise has been planned as part of this task, where the main barriers to deployment of floating platforms and the primary measures for de-risking this concept are identified. Considering the performance and stability of these floating platforms, the concept with the most potential will be selected. The selected concept will be further developed and tested in Task 3.5. In this task, a specific attention will be given to improving the efficiency of ballasting, mooring line design and anchorage system, in order to identify the optimised combination. Various numerical tools, analytical methods, cost models and physical tests will be employed to validate the proposed innovations and so accelerate the route to market of floating technology. More detailed information about the various steps in this task and the expected outcomes can be found in the Description of Work (DOW) [88]. A schematic diagram of the plan of work is provided in Figure 6-3.



Figure 6-3 Plan of progress of T2.4: Floating substructures (Task Leader: IBR)

6.5 Task 2.5 approach – Turbines

In general, this task will deal with novel deployment, assembly and installation strategies for the wind turbines. Through comparison of the conventional and the innovative methods, the most appropriate strategy for transportation, pre-assembly and installation of the components at a given site will be identified, with focusing on the pre-assembly and pre-commissioning of the turbine components. The task will also consider and evaluate the innovative concepts proposed for the interface between the turbine and substructure, with the aim of minimising the number of required offshore operations for installation and 0&M, and increasing the durability of the joint [88].

6.6 Task 2.6 approach – Common Installation Challenges

The scope of this task is more general and will cover a range of substructure concepts and innovations to smooth and optimise the design process. For example, this task will investigate more efficient means of cable laying by integrating this with foundation deployment and J-tube installation. The operating condition of jack-up vessels will also be investigated and compared with the Dynamic Positioned (DP) vessels. In order to address one of the requirements of industry, a software will be produced to determine



the combinations of deep water sites and soft ground conditions where the application of jack-up vessels is too risky. The output will provide guidelines regarding the range of suitable operational conditions for the functioning jack-up vessels, and will also provide input for the studies dealing with novel vessel development [88].


7. Concluding Remarks

The main objective of the LEANWIND project is to contribute to the required reduction in the LCOE for the offshore wind energy industry through the development of innovations in the transportation and logistics sectors. Construction, Deployment and Installation of the offshore substructures and turbine infrastructure represent a substantial fraction of the total LCOE. According to BVG [11], the support structure contributes to between 14% to 21% of LCOE, and installation comprises between 10% to 18% of LCOE (the figures are given based on the cost analysis of windfarms consented in 2011). Therefore, to reduce the cost of wind energy, new innovations and improved efficiencies are needed in this area. Developing these innovations and designing new solutions to the industry challenges is the core focus of the studies dealing with construction, deployment and decommissioning (Work package 2). This deliverable defines the challenges for different substructure concepts and points towards some areas where there are opportunities for new efficiencies. The scope of technical work was described in detail, which included both fixed and floating concepts. The design basis for completing the technical investigations was also defined, alongside a suite of design scenarios that will be used as input to the technical tasks. The output of these technical investigations will be examined using the economic models that will be developed for analysing the cost benefit of these innovations (the subject of work of WP8).



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