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List of Abbreviations

Acronym	Description
AMS	Arklow Marine Services
DP	Dynamic Positioning
CAPEX	Capital Expense
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CoG	Center of Gravity
CTV	Crew Transfer Vessel
c_w	Drag Coefficient
DCR	Daily Charter Rate
DNV	Det Norske Veritas
EDF	Électricité de France
GBF	Gravity Base Foundation
GDG	Gavin and Doherty Geosolutions Ltd.
HLV	Heavy-Lift Vessel
FCB	Floating Crane Barge
Hs	Significant Wave Height
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
JUP	Jack Up Platform
LAT	Lowest Astronomical Tide
LCB	Longitudinal Centre of Buoyancy
LCF	Longitudinal Centre of Flotation
LCG	Longitudinal Centre of Gravity
LR	Lloyd's Register
MWS	Marine Warranty Surveyor
MHWS	Mean High Water Spring
MPV	Multi-Purpose Vessel
NREL	National Renewable Energy Laboratory
O&M	Operations & Maintenance
OPEX	Operational Expense
OWA	Offshore Wind Accelerator
POLCOMS	Proudman Oceanographic Laboratory Coastal Ocean Modelling System
RAO	Response Amplitude Operator
SOV	Service Offshore Vessels
SPIV	Self-Propelled Installation Vessel
SWAN	Simulating Waves Nearshore
SWATH	Small Waterplane Area Twin Hull
SWL	Safe Working Load
TIV	Turbine Installation Vessel
Tz	Zero-Upcrossing Period
VCG	Vertical Center of Gravity
WFSV	Wind Farm Service Vessel
WP	Work Package
WRF	Weather Research and Forecasting
WTG	Wind Turbine Generator
XL	Extra Large

Executive Summary

This report details the second stage in the design process undertaken as part of the EU LEANWIND FP7 project work package focusing on novel vessel design. This focus is directed towards vessel types used for both wind farm installation and O&M. The objective of this work is to make efficiencies by considering innovations to existing vessels and designing new vessels concepts tailored specifically to industry requirements. This report takes the findings from the previous report identifying the industry challenges: *WP Framework/Industry Challenges Report – novel vessels and equipment*, to further develop novel design concepts for existing/future installation vessels.

For this report, a detailed review was undertaken of existing vessel concepts and those currently being proposed in the market place. This was combined with research through interviews with industry contacts to collect ideas from developers, designers and owners/operators.

The deliverable starts with an installation vessel concept review with related innovative technologies. The evaluation of the ship design is then possible based on various criteria that have been screened by the feedback from interviews of industry experts. Finally, our approach takes into consideration environmental conditions, i.e. metocean data and significant wave height issues, as well as manning implications.

The section "Novel service vessel concept design and access equipment" discusses novel design concepts for maintenance vessels including vessel and turbine access arrangements and equipment which are being proposed and currently used in the market.

The related section presents the results of direct contact and a stakeholder workshop aimed at receiving feedback from developers, designers, owners/operators and other interested parties.

Furthermore, the deliverable section on O&M service vessels also details the present challenges in the European O&M market, as well as the contemporary Operations and Maintenance related technical challenges. Next, the deliverable categorises and classifies O&M vessels, in order to proceed with a preliminary dimension analysis of proposed service vessels per pre-defined use cases for the project:

- Case 0 (South Knock)
- Case 1 (West Gabbard)
- Case 2a (Firth of Forth)
- Case 2b (Moray Firth)
- Case 3 (Belmullet - Atlantic site)

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1. Introduction

The offshore wind industry is striving to make cost savings to move ever closer towards acceptable financing levels for development. Significantly increased costs have been incurred by the wind industry in the move from onshore development to offshore sites. Now these are being further increased by the progression from inshore into deeper waters in search of greater resource and by the pressures of coastal development. While vessel design has become more bespoke with the number of developments, technical innovation is still sought as a means to reduce costs. "LEANWIND" (Logistic Efficiencies and Naval architecture for Wind Installations with Novel Developments) is an EU funded project under FP7 which aims to provide cost reductions across the offshore wind farm lifecycle and supply chain.

This report details the second stage in the design process undertaken as part of the EU LEANWIND FP7 project work package focusing on novel vessel design. This focus is directed towards vessel types used for both offshore wind-farm installation and operations and maintenance phases.

In this project, direct contact with the industry stakeholders is used in order to gather insights and feedback from developers, designers and owners/operators. Additionally, a detailed review was undertaken and documented in a previous report: *WP Framework/Industry Challenges Report – novel vessels and equipment of existing vessels types and innovative concepts being considered.*

Installation has been identified as an area that would benefit from technological innovation. Potential cost reductions are closely linked to reduction of the time needed for the various installation operations extension of the weather windows in which the operations are feasible.
The cost reductions could be achieved by:

- Decreasing use of offshore lifts requiring increased amount of onshore preassembly or increased loading capability for components being lifted to increase number of available weather windows.
- Decrease operating constraints due to meteorological conditions.
- Improved vessel design for less restrictive weather limitations.
- Increased maximum jacking sea state.
- Increased maximum crane operating wind speed.
- Improved weather prediction.
- Improved weather monitoring and decision support system.
- Decreased transit time.
- Increased number of turbines loaded per trip.
- Increased deck payload.
- Increased useable deck area.
- Increased transit speed.
- Decreased offshore operation duration.
- Increased jacking speed.
- Decreased leg-preload duration (by using 4- or 6-legs vessels).

- The use of component feeder vessels.
- The use floating installation vessels.

The current analysis begins with a presentation of novel and existing types of installation vessels and their qualitative evaluation. This is followed by the consideration of installation cranes and lifting operations – including feedback from industry partners. Cost elements are then provided. This analysis finishes with the presentation of the factors impacting the vessel selection, the system requirements and their analysis. The design requirements and design parameters for installation vessels are outlined in Section 3.

The section regarding crane operations and lifting capacity of an installation vessel examines vessel main and secondary cranes. In this respect, the main limitations are the lifting capacity that needs to be based on heaviest possible parts to be lifted, and crane geometry, i.e. minimum clearance in order to avoid clashes. Vessel technical limitations are primarily its main dimensions and the vessel stability, as the positions of heavy cargo items influence the static stability of the vessel in floating condition. Other important limitations regarding the decision making for crane operations and design are related to the jacking capacity of the jack up vessel (JUP), i.e. the maximum elevated weight of JUP vessels, deck strength, size of components, size of seafastening, gangway position for installation, crew accommodation constraints, propulsion package, and safety considerations.

This task is also intended to provide supporting information to project work in "Integrated Logistics" and "Economic and Market Assessment" on the areas of where cost saving can be made and provide improved and more efficient strategies for installation and maintenance of wind turbines by taking into account innovative installation and construction methodologies.

O&M activity accounts for approximately one quarter of the lifetime cost of an offshore wind farm. As part of this, service vessels are required to transfer wind turbine maintenance crew to perform duties on the turbines with significant regularity. Delays in carrying out unplanned maintenance incurs lost revenue and access in sea states higher than the current typical limit of 1.5m significant wave height and 12m/s wind speed is considered necessary to reduce costs in the industry. Vessels and access systems capable of transferring personnel in 3m significant wave height are desired.

The main challenges previously identified for service vessels remain:
- Reducing motion to increase accessibility in larger sea states.
- Increasing fuel efficiency.
- Reducing seasickness and its detrimental effect on maintenance crew.
- Operational efficiency.
- Establishing optimum vessel size and hull form type for varying distances from shore.

Generally, the challenges to be overcome within the next years for new site developments are mainly driven by the marine environment, the further and the more remote a farm is, the more impact metocean parameters have upon O&M activities. For example, wave heights and currents determine whether turbines can be accessed by service boats while visibility affects the accessibility for helicopter operations. Moreover, wind speed creates multiple issues to O&M activity:

- Severe risk of turbine faults due to high wind-state
- Difficult access to the turbine due to wind and wave conditions, leading to increased downtime and lost revenue during the most productive time periods

The overall target is to improve the accessibility of O&M vessels which can be accomplished by larger weather windows (through reduced vessel RAO's thus reducing the vessel heave/roll/pitch response), comfort of crew and higher work efficiency (by reducing sea sickness and staying injury free during an extreme event – thus reduced recovery time for technicians before turbine transfer).

Section 5 presents the results of the industry consultation aimed at receiving feedback from developers, designers, owners/operators and other interested parties. This analysis finishes with the presentation of the factors impacting the vessel selection, the design requirements and design parameters.

At the time of writing the maturity of the project is such that there are many variables affecting vessel design which are not fully defined. As such this report provides the current design parameters, criteria and their anticipated values. Design criteria are expressed in quantitative and/or qualitative form. Quantitative criteria, referred to as design requirements provide the design phase with more specific targets consisting normally of a range of values. Qualitative criteria, however are also important to consider and will help give rise to technical development. It is expected that as the design process progresses, design criteria will be refined and developed as the design iterates to changing project variables in order to deliver the primary goal of cost reduction.

2. Project Common Scenarios

This section explores the common aspects that directly or indirectly affect vessel design.

The LEANWIND project comprises substructure design, vessel design, O&M optimisation, logistics optimisation and cost modelling elements. Integration between these elements has prompted the development of common scenarios which link across these strands of the project. These common scenarios represent a range of offshore wind sites allowing the examination of the effects of time and cost with such issues as water depth its effect on substructure design and installation requirement or distance from shore on O&M strategy and crew vessel design.

In a commercial project, site selection on a consented zone would reveal the intended project configuration of substructure design, turbine selection, based upon the wind resource, site metocean conditions distance to installation port etc. while considering the overall economics of the project. A detailed wind farm project specification is beyond the scope of this project, but where necessary to investigate cost reduction potential, farm project specifications will be developed at certain points in the project design space.

Following feedback from the industry there have been modifications to the scenarios defined in *'WP Framework/Industry Challenges Report – novel vessels and equipment '*

Case	Water depth (m)	Distance to port (km)
0	20	30
1	40	30
2a	60	100
2b	20	100
3	100	30

Table 1 Scenario characteristics modifications

The following design cases were considered:

- Design Case 0 (southern North Sea – South Knock buoy)
- Design Case 1 (southern North Sea – West Gabbard buoy)
- Design Case 2a (northern North Sea – Firth of Forth buoy)
- Design Case 2b (northern North Sea – Moray Firth buoy)
- Design Case 3 (Atlantic site – Belmullet)

It should be noted that parts of the information employed as input parameters to these common scenarios is provided by other parts of the LEANWIND project and so is introduced here with only the necessary background detail. References are provided where reports are in the public domain.

The following information is considered in common with other parts of the project:

- Metocean conditions at site (wind, wave, current)
- Turbine foundation specifications (size, weight, weight distribution)
- Turbine structural properties - blade, nacelle and hub (size, weight)
- Installation configuration, soil conditions and crewing requirements.

2.1 Site selection

Metocean data play an important role in wind farm design for the substructure design, but it is also relevant for the vessel design when considering a lean design process. With the aim of increasing accessibility and reducing time on site, an understanding of the limiting metocean criteria in which the vessel is required to operate becomes necessary.

As a partner in LEANWIND, the University of Edinburgh have compiled the wave, current and wind data collected from resources including POLCOMS [1],[2], WRF[3] and CEFAS[4][1] Wavenet buoys. The results are presented in the below tables.

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	(Of buoy)			Wave data					Current data				Wind data		
Site name	Depth	Latitude	Longitude	Source	Dates	Durat. (years)	Mean Hs (m)	Mean Tp (s)	Source	Dates	Maximum velocity (m/s)	Mean velocity (m/s)	Source	Dates	Mean Speed (m/s)
South Knock	26 m	51,57	1,58	CEFAS Wavenet buoy	1/4/10 - 2/2/14	4	0,82	4,82	POLCOMS	2004	0,6663	0,2029	WRF	2010	8,02
West Gabbard	33 m	51,98	2,08	CEFAS Wavenet buoy	28/8/02 - 28/7/13	9	1,09	5,44	POLCOMS	2004	0,6997	0,1943	WRF	2010	8,12
Firth of Forth	65 m	56,19	-2,5	CEFAS Wavenet buoy	19/8/08 - 5/2/13	5	1,05	6,92	POLCOMS	2004	0,4305	0,135	WRF	2010	7,04
Moray Firth	54 m	57,97	-3,32	CEFAS Wavenet buoy	29/8/08 - 3/9/12	4	1,09	7,34	POLCOMS	2004	0,3445	0,1023	WRF	2010	7,88

Design Case	Site		Depth (m)	Distance (km)	Wave data		Current data		Wind data
					Mean Hs (m)	Mean Tp (s)	Max V (m/s)	Mean V (m/s)	Mean V (m/s)
0	North Sea	South Knock	26	30	0,82	4,82	0,6663	0,2029	8,02
1		West Gabbard	33	30	1,09	5,44	0,6997	0,1943	8,12
2		Moray Firth	65	100	1,05	6,92	0,4305	0,135	7,04
3	Atlantic	Belmullet	50 – 60	5	7,10	11,00	1,03	0,236	8,15
					4,30	8,50	0,78		

Table 2 Wave, current and wind data collected from resources including POLCOM, WRF and CEFAS Wavenet buoys

The wind data (metocean conditions) for the design cases (No 0, 1, and 2) referred to in the tables above is obtained from a mesoscale model ran by the University of Edinburgh. Design case 3, the information pertains to the Belmullet Atlantic site at depths of 50-60 meter, 5 km offshore.

An important aspect is that certain buoy locations such as Moray Firth are actually close to the proposed site for a new development while other locations such as the Firth of Forth might be situated further away from the proposed site to be developed there.

Moreover, the relationship between wind from a mesoscale model and actual measured wave data is spurious, therefore for at least the two sites in the southern North Sea (South Knock and West Gabbard), the University of Edinburgh is creating a SWAN model driven at the boundaries by the mesoscale winds in order to correctly capture the relationship between the wind and waves. A SWAN model is a 3rd generation wave model, developed at Delft University of Technology, that computes random, short crested wind-generated waves in coastal regions and inland waters.

This is critical for the weather window analysis and also important for vessel design considerations. However since this data will not be ready until early 2015, the buoy data is all the data available to base the vessel design requirements on at this stage.

2.2 Selection of wind turbine model for base design cases

The design process of a wind farm involves an initial site selection followed by an assessment of external conditions, selection of wind turbine size, subsurface investigation, assessment of geo-hazards, foundation and support structure selection, development of design load cases, and performing geotechnical and structural analysis.
The flow diagram below details the design algorithm of a typical offshore wind farm:

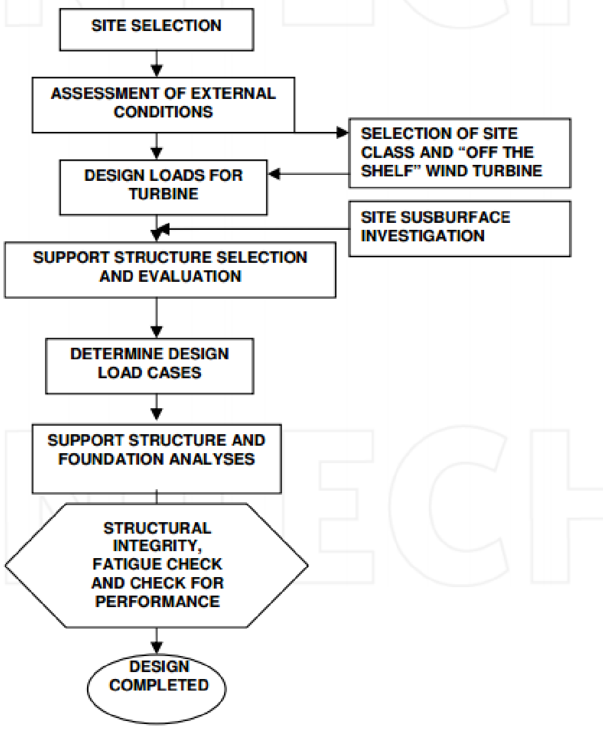


Figure 1 Flow diagram of Design algorithm for a typical offshore wind farm [5]

Consultation with industry stakeholders has pointed out that turbines will, in the future, be larger than the NREL 5MW model, thus an envelope that can accommodate the vessel design requirements must be developed for this range of turbines.

2.2.1 Turbine selection

The design of an offshore wind turbine is a primary driver of vessel design. The weights, dimensions, acceleration limits etc. are needed for the vessel design parameters.

For the purpose of vessel design it has been agreed that a variety of turbines should be considered to address appropriate vessel design requirement ranges and in order to capture the future wind farm development challenges. Therefore this report considers turbines such as the NREL 5MW turbine model, the Siemens 6MW, and the Vestas V164 8MW, Further turbine designs may become available during the course of the project, and these will be considered when credible information becomes available.

For the purpose of achieving economies of scale, wind turbines are mass produced, and available in four predefined classes based on wind speed as defined by the IEC 61400-1 International Standard.

Wind turbine class	I	II	III	S
V_{ref} (m/s)	50	42.5	37.5	Values
A I_{ref} (-)	0.16			specified
B I_{ref} (-)	0.14			By the
C I_{ref} (-)	0.12			designer

Table 3 Turbine classes based on wind speed, as defined by the IEC 61400-1 International Standard [9]

V_{ref} = reference wind speed – This is the basic parameter for the wind speed used for defining wind turbine classes. Other design related climatic parameters are derived from the reference wind speed and other basic wind turbine class parameters.

The annual average wind speed for wind turbine designs according to these classes is given in IEC 61400-1 by the following equation:

$$V_{ave} = 0.2\ V_{ref}$$

Thus a Class I turbine would refer to a 10 m/s average wind speed at hub level, Class II to 8.5 m/s and Class III to 7.5 m/s.

A turbine designed for a wind turbine class with a reference wind speed V_{ref}, is designed to withstand climates for which the extreme 10 min average wind speed with a recurrence period of 50 years at turbine hub height is lower than or equal to V_{ref}.

The Power Law Profile or Wind Shear is the variation of wind speed across a plane perpendicular to the wind direction and can be used to calculate the wind speed at hub height for a range of turbine models:

$$V(z) = V(z_r) * \left(\frac{z}{z_r}\right)^{a}$$

where V(z) is the wind speed at height ‘z’ above the waterline

‘z_r ‘ is a reference height above water level used for fitting the profile

α is the wind shear (or power law) exponent and is considered 0.14 for offshore applications

The logic used at this preliminary stage to assess the basic level of suitability of a particular wind turbine model for our base site cases is based on the minimum blade tip clearance which is set to 22 metres above the mean high water springs (MHWS) to reflect the long standing position of the Royal Yachting Association and the inclusion of this parameter in previous offshore wind farm consents.

Table 4 below display the relevant design cases and turbine data which have been used to inform decision making on key design criteria.

Design Case	Site		Depth (m)	Distance (km)	Wave Data		Current data		Wind data
					Mean H_s (m)	Mean T_p (s)	Max V (m/s)	Mean V (m/s)	Mean V (m/s)
0	*North*	*South Knock*	26	30	0.82	4.82	0.6663	0.2029	8.02
1	*Sea*	*West Gabbard*	33	30	1.09	5.44	0.6997	0.1943	8.12
2a	↓	*Firth of Forth*	65	100	1.05	6.92	0.4305	0.135	7.04
2b		*Moray Firth*	54	27	1.08	7.34	0.3445	0.1023	7.88
3	*Atlantic*	*AMETS Belmullet*	50-60	5	7.10	11.00	1.03	0.236	8.15
					4.30	8.50	0.78		

	NREL 5 MW	Siemens SWT-6.0 MW-154	MHI Vestas V-164-8.0 MW Turbine	Alstom Hallade 150 6 MW	Gamesa G 128 5.0 MW Offshore	Senvion 6.2 MW - 126	Areva 1165 M
Rotor radius [m]	63	75	82	73.5	64	63	58
Wind Turbine Class	IEC 61400-3 (Offshore) Class 1B	IEC - A	IEC - S	I-B IEC 61400-1/IEC 61400 3	IEC I-B	IEC I-B	IEC I-B
Cut-in/Cut-out wind speed		Cut in 3-5 m/s Cut out 25 m/s	Cut in 4 m/s	3 – 25 m/s	3 – 30 m/s	3.5 – 30 m/s	4 – 25 m/s
Operational wind speed (rated)	11.5 m/s	12 – 14 m/s	11 m/s	No OEM info	10 m/s	14 m/s	12.5 m/s

Design Case	Site		Depth [m]	Distance [km]	Wind data Mean V [m/s]		NREL 5 MW	Siemens SWT 6.0 MW-154	MHI Vestas V164-8.0 MW Turbine	Alstom Hallade 150-6MW	Gamesa G128-5.0 MW Offshore	Senvion 6.2MW-126	Areva 116.5M
0	North Sea	South Knock	26	30	8.02	Hub level wind speed [m/s]	10.82	11.02	11.13	11.00	10.84	10.82	10.73
1	↓	West Gabbard	33	30	8.12		10.96	11.16	11.27	11.14	10.97	10.96	10.86
2a		Firth of Fort	65	100	7.04		9.50	9.68	9.77	9.66	9.51	9.50	9.42
2b		Moray Firth	54	22	7.88		10.63	10.83	10.94	10.81	10.65	10.63	10.54
3	Atlantic	AMETS Belmullet	50-60	5	8.15		11.00	11.20	11.31	11.18	11.02	11.00	10.90

Table 4 Wind farm design cases and preliminary turbine suitability assessment

The hub level wind speed for each turbine model at the considered design site location is compared to the turbine rated operational wind speed.

Although a detailed site selection and assessment of external conditions would be a pre-requisite for an 'off-the shelf' turbine selection, these are dependent on economic modelling analysis which is currently under development within the LEANWIND project and not available at this stage.

The preliminary turbine selection for the purpose of reviewing the capabilities of current fleet of TIVs and also novel concept designs is detailed below:

1. Design Case 0 (southern North Sea – South Knock buoy) – MHI Vestas V164 - 8MW

2. Design Case 1 (southern North Sea – West Gabbard buoy) – MHI Vestas V164 – 8MW

3. Design Case 2a (northern North Sea – Firth of Forth buoy) – Gamesa G128 – 5MW

4. Design Case 2b (northern North Sea – Moray Firth buoy) – Gamesa G128 – 5MW

5. Design Case 3 (Atlantic site – Belmullet) – NREL 5MW

The table below has a summary of parameter data for the above identified turbines. This data both directly contributes to the definition of both the vessel and lifting appliance design requirements. As a result we can build a range of values to be used in the vessel concept design phase of the project.

Turbine Parameters	NREL 5MW	Siemens 6MW	Vestas 8 MW	Alstom 6 MW	Gamesa 5 MW	Senvion 5M	Areva 116 5M
Blade Length / Max Width (chord-wise) / Max Depth (thickness wise) (assume as box which twisted blade must fit in)	61.5	75	80	73.5	64.5	74.4	56
Chord	4.65		5.4			4.5	
Thick	1.82			3.2			
Blade weight	17740	25000	35000	33000	15000	25500	16500
Rotor diameter	126						
Hub diameter	3.5	4	4	3.95	3	3.2	4
Hub weight	56780					80000	62500
Nacelle Size	-	width > 6.5m	20x8x8	width > 7.5m	12.5x4x4		
Nacelle weight	240000	200000	390000			350000	233000
Total Weight above yaw bearing	350000	360000	495000			506500	345000
Configuration of turbine components for installation	-						
Turbine Tower Section Parameters							
Section 1 Base and top diameter	5.6						
	4.8						
Weight	128176.6165						350000
Length	32						90
Section 2 Base and top diameter	4.8						
	4			<4m			
Weight	89682.1291						
Length	34						
Increase up to number of sections							

Table 5 Summary of turbine data

Table 5 shows that specific values for which the vessel and/or lifting appliance should be designed to accommodate these suitable turbine designs. The design requirement ranges, other criteria and parameters are summarised at the end the Installation vessel and Service vessel concept design sections.

2.2.2 Substructure Design

In relation to substructure optimisation within the project, LEANWIND partner GDG provided a range of suitable foundation concepts for the three established base case scenarios depending on the water depth, distance from shore and soil conditions as detailed in Table 6 below which subsequently informed the vessel requirements:

Design case	Site conditions		Ground conditions		
	Water depth (m)	Distance to port (km)	Shallow bedrock	Medium dense sand	Note
1	40	30	Gravity base	Gravity base	Generic soil conditions (as outlined in D2.1)
				XL Monopile	
2	60	100	Jacket	Jacket	
			Gravity base	Gravity base	
*3**	100	30		Semi-submersible platform	Site specific soil profile

Table 6 Range of suitable foundation concepts for the three established base case scenarios

In the case of gravity base foundations, two additional site conditions have also been investigated:

- Additional Case 0 at water depth of 20 m and distance to shore of 30 km
- Additional sub-cases 1a / 1b at a water depth of 40m and distance to shore of 30 km

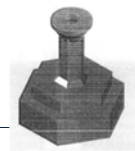
GBF		CASE 0	CASE 1a	CASE 1b
Water Depth	*(m)*	*20*	*40*	*40*
Distance to Shore	*(km)*	*30*	*30*	*30*
Turbine Substructure Design				
	Design Type	Constructed on barge (Karehamn)	Cone (Thornton Bank)	Self Buoyant
	No. of components for installation of substructure			
	Description of components			
	Max Dimensions	ø18 m	ø35 m	32x32 m
	Max Weights	2000 t	3000-5000 t	6000-10000 t
	Likely installation procedure	HLV	HLV	Self Buoyant
	*Component vertical projected surface area (E.g. for untapered monopile is a rectangle of area = diameter*length)*			
	Drag factor of the lifted load or shape - see table to the right			

Table 7 Technical specifications for different gravity base foundations under various use cases [10][11][12][13]

However, it must be emphasised at this stage in the project, the foundation types have been assigned to the base locations based on experience of LEANWIND partners.

Generally the design of foundations is driven by turbine loads, water depth, configuration and site/location assessment in order to achieve the best wind flow and the most optimum energy production. This then drives the feasibility study and financing strategies. For example the financing bank would ask a wind farm developer for a wind resource assessment and to install met-masts to measure wind speeds to assess the feasibility of site development. The measurements from met-masts drive the turbine size which subsequently drives the foundation and substructure.

Table 8 below gives indicative dimensions and weights that need to be considered in the design of the Installation vessel design.

Type	Jacket	Monopile
Dimensions	Jacket -45m to +20m, 20 – 35 m square side at base	2.5 - 6m diameter 6-10 m (in case of XL monopile) estimated length ≈50 – 60 m but can go up to 75 m in case of XL monopiles
No. of sections	Jacket in one section. In case pre-piling is used, then central template is pre-installed as a separate component on seabed	One section
Weight	Piled jacket ≈ 700 – 1000 tonnes Suction-bucket jacket ≈ 700 – 850 tonnes	Monopile 500 – 800 tonnes XL monopiles 800 – 1200 tonnes

Table 8 Indicative weight specifications for various turbine foundation solutions

Based on the assumption that monopile and jacket foundations would be transported on an installation vessel as opposed to be floated out to site, various cranes with broad capacity ranges and ships with different deck space areas, to accommodate the substructures, can be used. However these are analysed within a tighter context in the installation vessel section late in the report.

2.2.3 Innovative substructure designs

Over the last 3 years, a lot of effort has been spent to find "innovative" structures which promise to lower in the overall cost incurred by the wind farm developer. However, bringing innovative concepts to the point of commercialisation is a slow process since investors and insurers like "proven technology". Any new structure by definition is not proven and therefore needs demonstration projects to gain trust in the sector. It is believed that at least 5 years are needed from a first prototype to large-scale industrial application. [14] It is also expensive and time-consuming. At the moment within the offshore wind sector, there are contradictory discussions regarding to whether optimisation and mass-fabrication of already-proven technologies such as monopiles and jackets should take priority in order to reduce the cost of energy rather than new, step-change technologies. [15]

The most technically interesting options in the sector are:

The Keystone "Twisted Jacket". With this innovative design, a slice of the promised cost savings comes from trimming down the tonnage of steel needed by around 5% through the use of a simple tubular construction rather than the complex trellis designs inherited from the offshore oil and gas industry. It is thus cheaper to fabricate in terms of material and, with fewer pieced to assemble and a "simpler geometry" than conventional jackets – faster, and so less costly to build, according to Keystone. [16] Moreover, since the jacket's footprint is lower, more units can be transported simultaneously on a barge, which means lower requirements for free deck space for vessels to transport and/or install such foundations.

Figure 2 Twisted jacket being transported on a barge [17]

The "Universal Foundation" Suction-Bucket that features Suction Installed Caissons to drive the foundation through the seabed based on the principle of pressure differential. This is an interesting concept as it eliminates driving noise. One of the main advantages over the traditional jackets is that there is no requirement for pile hammering tools. Although it is very similar to the monopile concept in the way of driving through the seabed, it does not require upending and gripping devices which would require significant deck space and seafastenings.

Figure 3 Floating structures. Monopile Suction Bucket (left) and Jacket Suction Bucket (right) substructures [18] [19]

Floating technology will not reach commercialisation in the near future, but a great deal of investment is being made in developing the technology. Costs and installation challenges are still a problem but they could be very beneficial for countries such as Japan, with very little shallow coastal waters, should they consider developing their offshore wind sector on a larger scale.

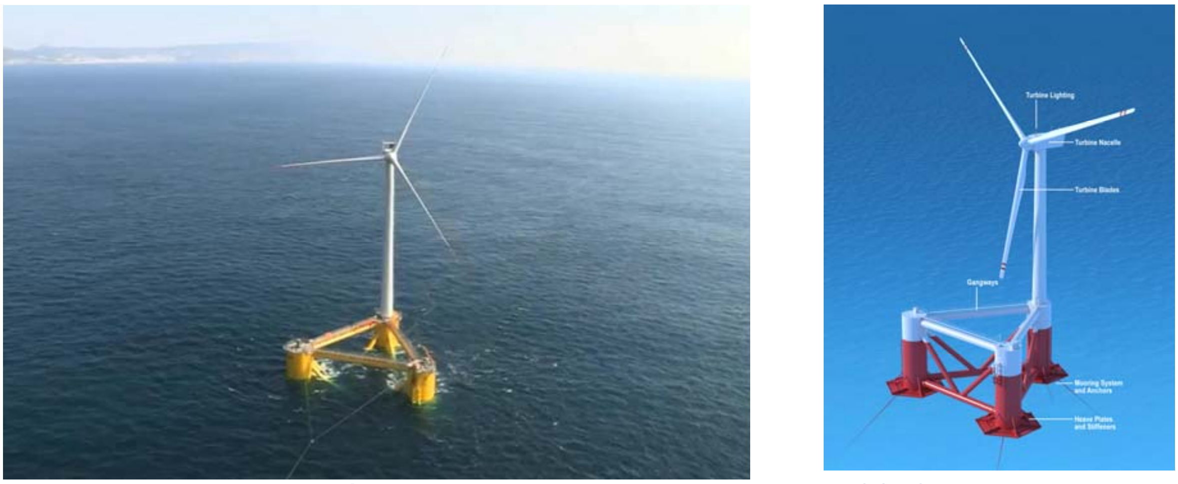


Figure 4 Floating wind turbine substructure [20][21]

2.3 Vessel costs

The cost of a vessel is a significant factor affecting vessel design, and is commonly the overriding factor in the decision process. Therefore it has been considered at this stage of vessel parameter and criteria definition. Cost will play a much more significant role in the next stage of the project when vessel concepts will be selected for the initial design. However here it is worth having a suitable understanding of the cost build-up.

The cost global functions are built up by

- Operational cost + Market forces + Vessel build cost
- Uncertainty in operational cost and length of operation builds in additional cost

Figure 5 below shows idealised supply and demand curves for turbine installation services in the offshore wind market.

Demand is set primarily by the costs of component supply, energy prices and government policy. Installation costs are actually a relatively small driver of overall demand. [22]

Among the factors that shift the supply curve to the right are lower costs of new or operating the vessels (CAPEX & OPEX), technological advancements or optimisations in the installation process.

Factors moving the demand curve to the right include government policies to address climate change, increasing costs of fossil-fuel powered electricity, and reduced costs in other parts of the offshore wind supply chain such as wind turbine manufacturing costs.

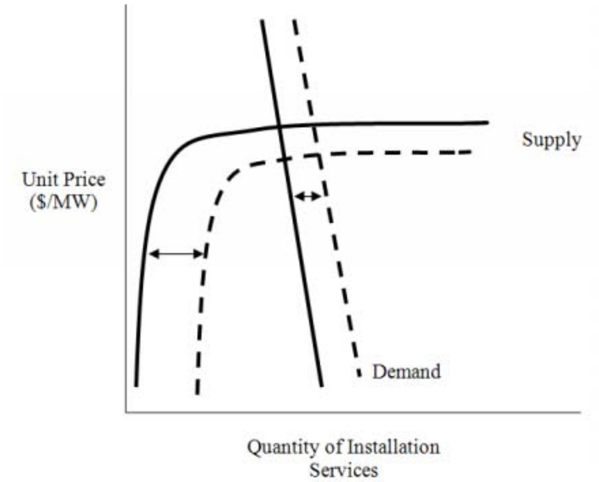


Figure 5 Idealised supply and demand curves for turbine installation services in the offshore wind market [22]

As far as cost reduction issues are concerned, installation costs are driven by:

- Dictated terms by contract
- Price built up by internal cost models by installation contractors and windfarm developers

Theoretical models [23] can be developed, such as:

Cost = time x day rate

$$Time = \frac{N_{turbines\ in\ farm}}{N_{turbines\ carried}}\left(T_{loading} + \frac{2D}{Vel} + N_{turbines\ carried} * T_{install}\right)$$

Issues affected by vessel design:

- $N_{turbines\ carried}$: Number of turbines/substructures carried
- $T_{install}$: Time to install
- V_{el}: vessel transit speed
- D: distance from port to farm

Issues affected by vessel design concern:

- Vessel build cost:
  - Complexity of build
  - Fit out
- Operational cost:
  - Fuel efficiency
  - Manning rates

As can be seen by the above, the costs associated with the design, construction, and operation of all vessels is not only complex but very much influenced by the parameters used to develop the vessel designs. As such costs associated with each design parameter (and through association each design requirement) should be further defined in the next phase of design.

2.4 Design Approach

As mentioned in the introduction, there are a number of variables that feed the design process. These variables have been developed as part of the LEANWIND project or in other work packages. The integration of these packages is therefore critical to maximise the benefits of the project.

Figure 6 below illustrates the typical iterative approach to design. This is known as the 'Design Spiral', with each iteration bringing greater maturity to the vessel design and closer to the realisation of potential cost reductions through innovation best practice.

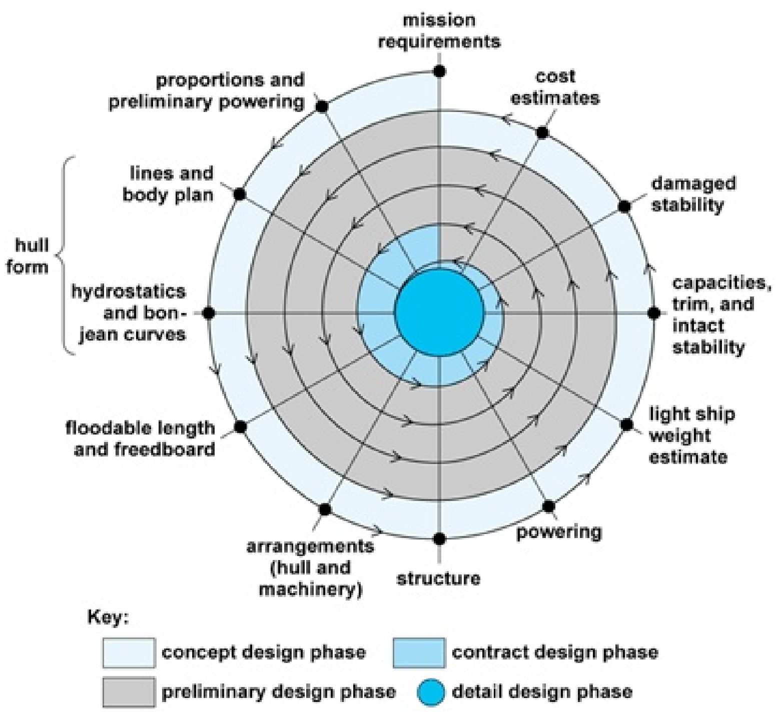


Figure 6 Design phases for a typical installation vessel [24]

It is now common to use a concurrent engineering design process. Based on concurrent design principles (simultaneous engineering/unified life cycle engineering) with a goal of minimisation of costs over the complete life cycle of the system. The focus is on customer's requirements and priorities and a major aspect is that the information flow is bi-directional based on upstream and downstream considerations.

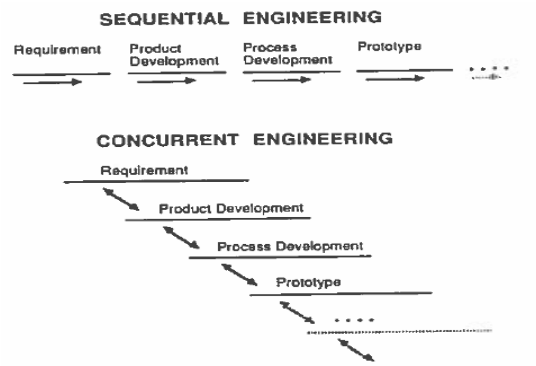


Figure 7 Sequential Engineering vs Concurrent Engineering [12]

2.5 Design Phases

Each successive iteration is a "spin" of the spiral. While the number of spins is highly dependent upon the project and time constraints, there is a general progression of iterations, with some recognised loose milestones.

Phases or cycles are considered once a given level of technical refinement has been achieved. Below is a list of phases of the overall design process :

1) <u>Requirements</u>
As derived in throughout this document, similar to the owner's requirements in a real world scenario that describe the client/owners desires and needs in a vessel.
These requirements can however change over the course of the project as feasibility of design aspects become apparent, supporting documents are developed (eg. geophysical and geotechnical data from site survey and soil investigation reports & extreme environmental conditions described in metocean reports) or as the requirements themselves change over time

2) <u>Concept Design</u>
The concept design only defines envelopes for the most basic of hull form, dimensions, weight, layouts, equipment and capabilities (speed, endurance, FOC, cargo capacity & handling, etc.). It is for the most part a feasibility check. A number of variations will be evaluated, whose varied parameters should be guided by a sensitivity analysis , such as a parametric analysis to compare existing similar ships to develop preliminary specifications for a vessel during the initial stages of design. If very novel concepts will be considered, a parametric analysis may not be appropriate as there are no existing equivalents, however it provides reasonable initial values for ship parameters, and can be continually checked back upon when considering design compromises later in the process.
The concept phase should lead to decisions on major parameters, such as hull and propulsion type.

3) Preliminary Design

The chosen concept design is put through more rigorous analysis. Clashes in major components will identified and corrected in this design cycle.
Capacities are worked out and major parameters have values determined (L, B, D, T etc). Jacking systems, shafting systems, general structural scantlings (midship section used for hull girder calculations and some coefficients of form (block, waterplane coeffs), initial lines plan, general arrangement, specific cargo handling, storage and working deck systems will be conceptualised. In a “real-life” scenario these should be to a suitable level of detail to allow sub-contractors to quote equipment, packages or systems ; in LEANWIND these will be used in order to assess the financial feasibility of the design.
The set up of the LEANWIND project does not allow for many multiple design iterations; the end goal is for concept designs. Also the final stage is detailed design which will not be undertaken in the LEANWIND project but could be envisaged to be a continuation into a further project phase.

4) Contract Design

Preliminary design is further elaborated to create the basis of a shipbuilding contract where technical requirements, general layout, equipment configuration, etc. are well defined. Moreover a preliminary CFD analysis could be done to verify ship’s speed and powering requirements.

5) Functional Design

This phase includes detailed studies of ship which will be divided into structural (hull) blocks and outfitting zones. In functional design phase all design deliverables which are subject for classification approval are prepared and delivered further to an appropriate approval process which may contain revisions on the design and/or design deliverable. Detailed engineering analysis and simulations of the ship are carried out to define ship’s behavior in terms of global/local strength, global/local vibration, noise, seakeeping, maneuvering, etc. (in LEANWIND case, global strength). Such deliverables will be used as key plans for detailed design phase.

6) Detailed Design

The detail design phase is the final phase of development. During this phase, assembly drawings are created, steel plates are nested, pipe spools drawings created, etc.
The detail design phase leads to final production drawings which may be used to build the vessel.

2.6 Design Activities

Follows a list of design activities:

- Concept design drawings (G/A Plan, Lines & Appendages Plan, Tank Plan, etc.)
- 3D Artistic Model
- Hull Structural Drawings and Calculations
- Ship Theory Calculations (stability, long. strength, deadweight, etc.)
- Hydrodynamics Calculations (seakeeping, maneuvring, etc.)
- Engineering Analysis (FEA for structural, CFD for hull form optimization,)
- Engineering Analysis (FEA for structural, CFD for hull form optimization,)

2.7 Design Outcomes

The outcomes of the design phase are the following:

- Functional Requirement Evaluation
- Ship Dimensioning
- Propulsion System Definition
- Preliminary General Arrangement Plan
- Preliminary Hull Form Design, Lines & Appendages Plan
- Preliminary Hull Scantling Calculations
- Preliminary Main Hull Structure Drawings (Midship Section, Longitudinal Sections, Shell Expansion)
- Preliminary Speed, Power & Endurance Analysis
- Preliminary Lightship Weight Estimation
- Preliminary Capacity, Deadweight & Loading Conditions
- Preliminary Intact & Damage Stability Calculations
- Preliminary Longitudinal Strength Calculations
- Preliminary Freeboard Calculation
- Preliminary Tank Arrangement & Capacity Plan
- Preliminary 3D Artistic Model and Views
- Hull Form CFD Analysis Report & Speed-Power Prediction
- Preliminary Seakeeping and Maneuvring Calculations
- Preliminary DP performance assessment
- Global Ship Structural Analysis and Reporting

3. Novel Installation Vessel Concept Design

This section deals with the design parameters and criteria associated with Installation vessels. Installation vessels deal with the installation of turbines and turbine substructures. Although today some installation vessels are used also for some maintenance aspects, the task set by LEANWIND for this type of vessel is to optimise it for the installation activities.

3.1 Review of Existing and Novel Installation Vessels

It is first important to understand what the designs of vessels are and why, in order to improve on both individual design features and the overall design. A detailed review of the current vessel in the market, those under construction, and some concept designs gives a sound basis from where to begin. This data will also be used later in the design phase to help determine the concept designs to be taken into initial design.

3.1.1 Vessel categorisation

Several types of turbine and foundation installation vessels exist and currently operate in the offshore wind market including lift-boats, jack-up barges, self-propelled installation vessels (SPIVs) and heavy-lift vessels (HLVs). Liftboats, jack-up barges and SPIVs are collectively referred to as self-elevating vessels due to their characteristic feature of raising the entire hull above the waterline. SPIV's are also called Turbine Installation Vessels (TIVs) because they are used almost exclusively for these operations.

Primary characteristics for TIVs generally include:

- Principal dimensions
- Operating conditions for jacking
- Accommodation capacity and facilities
- Leg length and jacking speed
- Crane capacity and operating limits for lifting
- Dynamic positioning system
- Cargo area (main deck area and strength)

Liftboats

Liftboats are self-propelled barge-shaped vessels designed with jack-up legs to create a rigid elevating platform. Liftboats traditionally have three long legs which allow them to work at elevated heights with short boomed cranes. The wind industry favours more legs due to the high frequency of jacking procedures.
Liftboats range in size from small vessels capable of transporting a 75 tonne payload with a lifting capacity of 50 tonnes to much larger vessels capable of carrying 750 tonnes and lifting 500 tonnes.
Generally small liftboats are not capable of performing most offshore wind installation operations as even the tower or nacelle of a rather smaller range turbine SWT-3.6-120 can weight in the region of 200 tonnes.

Figure 7. The KS Titan II liftboat. [25[26]

Jack-up barges

Jack-up barges typically have four lattice-structured legs and are intermediate in size between liftboats and SPIV's. Figure 8 shows a large jack-up barge (A2Sea's *Sea Jack*) while Figure 9 shows a smaller jack-up barge (Muhibbah's *MEB-JB1*) .The *Sea Jack* has a crane capacity of 800 tonnes, a free deck area of 2500 m^2 and deck strength of 20t/m^2 while the MEB-JB1 has a crane lift capacity of 272 tonnes, free deck area of 748 m^2 and allowable deck load capacity of 10 t/m^2.

A small jack-up barge may be able to carry two turbines while a large jack-up might carry six to eight turbines.

A critical aspect of this type of vessels is that they are not self-propelled and require to be towed by a tugboat from the load-out harbour to the installation site thus transit speed depends on the tug power and normally ranges between 4 and 8 knots. A towing tug is also involved to help manoeuvre the installation vessel between the various turbine positions.

Figure 8 The Sea Jack jack-up barge. Source A2Sea [27]

Figure 9 Muhibbah Offshore's MEB JB1 jack-up barge. Source Muhibbah & ShipSpotting.com [28]

Self-propelled installation vessels (SPIV's)

Self-propelled installation vessels are large self-elevating vessels with four to six legs that can achieve transit speeds in the region of 7 to 13 knots and have variable payload capacities of 1500 to 8000 tonnes. The majority of SPIVs are ship-shaped, but may also be column-stabilised (rather than fully-elevating) or barge-shaped. They are distinguished from jack-up barges by the presence of self-propulsion and from liftboats by size. Depending on the free deck space and allowable cargo deck load, they usually carry six to eight turbines.

Figure 10 SeaJacks' Kraken (left) – cargo capacity 3350 t and HGO's Innovation - cargo capacity 8000 t (right). [29][30]

Heavy lift vessels (HLVs)

Heavy lift vessels include barge-shaped or semi-submersible hulls with very high lifting capacity and do not employ a hull-elevating system. They may or may not be self-propelled and may also be either dynamically positioned (DP) or conventionally moored.
HLVs include sheerleg cranes, derrick barges and other floating cranes and are widely used in offshore oil and gas construction projects but also mobilised for offshore wind projects.

A sheerleg crane is a barge-shaped crane vessel which is not capable of rotating the crane independently of the ship. Other crane vessels include semi-submersible vessels with heavy lift capabilities such as the *Thialf* of Heerema Marine Contractors. Although they are rarely used to install turbines, they may be used for installing foundations, fully-assembled turbines or substations. Typical transit speed for HLV vessels ranges from 4 to 8 knots. Lifting capability can vary from *Taklift 4*'s1600 tonne (sheerleg) capacity to Thialf's 14,200 tonne capacity (semi-submersible).

Figure 11 SMIT's Taklift 4 (left) sheerleg crane and Heerema's Thialf (right) semi-submersible crane vessel [31][32]

The table below gives a summary of relevant designs and the work that they have undertaken. This not only gives an indication of typical vessel types used for installation activities but also the design requirements for the specific activities to be carried out.

Vessel	Vessel type	Operational water depth (m)	Crane capacity (tonnes)	Wind farms	Payload/Component transported and/or installed
Sea Power	SPIV	24	100	Homs Rev 1, Lillgrund, Homs Rev 2	• 80 Vestas 2MW turbines at Horns Rev 1 • 48 SWT-2.3-93 turbines at Lillgrund • Transport and installation of the 91 x Siemens 2.3 MW turbines at Horns Rev 2
Sea Energy	SPIV	24	100	Kentish Flats, Scroby Sands, Nysted,Princess Amalia wind park	• Installation of 30 x V90 – 3MW turbines at Kentish Flats • Transport and installation of 24 of the 30 Vestas V80 – 2MW at Scroby Sands • Installation of 72 Bonus 2.3MW turbines at Nysted • Sea Energy and Sea Jack installed 60 Vestas 2MW turbines at Princess Amalia
Rambiz	Sheerleg crane	>100	3,300	Beatrice, Thornton Bank, Nysted	• Installed fully assembled turbine on top of jacket at Beatrice Demonstrator • Installation of 6 concrete gravity base foundations at Thornton Bank • Substation Installation (installation of transformer module) at Nysted
Sea Jack	Jack-up barge	30	800	Princess Amalia, Arklow, Scroby Sands, Horns Rev 2	• Installed 92 monopiles and 91 transition pieces at Horns Rev 2 • Sea Energy and Sea Jack installed 60 Vestas 2MW turbines at Princess Amalia • Met Mast grouting at Arklow • Transport and Installation of 24 of the 30 Vestas V80 – 2MW turbines at Scroby Sands
Svanen	HLV	>100	8,700	OWEZ, Rhyl Flats, Gunfleet Sands	• Installation of the 36 monopiles and 36 transition pieces at OWEZ • Installation of 25 monopile foundations and 25 grouted transition pieces (installation charter contract) at Rhyl Flats • Installation of 29 monopile foundations (28 for turbines and 1 for substation) and installation of 28 transition pieces (27 for turbines and 1

					for substation) at Gunfleet Sands
Titan 2	Liftboat	60	400	Rhyl Flats	• Installation of 25 x SWT-3.6-107 turbines
Buzzard	Jack-up barge	45	750	Alpha Ventus, Tornton Bank	• Installed 24 pre-piles the 6 jackets foundations at Alpha Ventus • Installation of 100 pre-piles for 24 turbines and 1 substation foundations • Installation of 24 x 6MW turbines at Thornton Bank
JB 114 and 115	Jack-up barge	50	280	Alpha Ventus	• JB 114 was used to install upper tower sections, nacelle and rotors for the AREVA Multibrid M5000 turbines
Thialf	HLV	>100	14,200	Alpha Ventus	• Thialf was used to install 6 jacket foundations for the RE-power turbines
Eide Barge 5	Sheerleg crane	>100	2,000	Middelgrunden, Nysted, Lillgrund, Sprogo	• Installed the 20 gravity-based foundations at Middelgrunden • Installation of 73 concrete foundations (72 turbines and 1 substation) at Nysted • Installation of 49 concrete foundations (48 turbines and 1 substation) at Lillgrund • Installation of 7 concrete gravity based foundations at Sprogo
Taklift 4	Sheerleg crane	>100	1,600	Alpha Ventus	• Taklift 4 installed the substation • Lowered the substation jacket foundation into position
Kraken and Leviathan	SPIV	40	300	Walney, Greater Gabbard	• Leviathan installed of 46 of the 51 SWT-3.6-107 turbines at Walney • Kraken installed 51 SWT-3.6-120 Siemens turbines on site at Walney • Kraken installed turbines and 9 transition pieces on site at Greater Gabbard
Resolution	SPIV	35	300	Robin Rigg, Barrow, Kentish Flats, North Hoyle	• Was used to install the 60 turbine monopile foundations and the 60 transition pieces at Robin Rigg • Installation of the 30 turbine monopile foundations and 31 transition pieces at Barrow • Installation of 30 x Vestas V90 3MW turbines at Barrow

					• Transport and installation of 30 WTG monopiles and 30 transition pieces at Kentish Flats
Excalibur	Jack-up barge	30	220	North Hoyle	• Installation of 27 turbines between Excalibur Barge and Muhibbah Marine's MEB-JB1 Barge
Lisa A	Jack-up barge	50	600	Rhyl Flats	• Installation of 25 x Siemens 3.6 MW turbines on top of foundations
MEB JB 1	Jack-up barge	40	270	Middelgrunden, North Hoyle	• Performed installation of 20 x Bonus 2MW turbines at Middelgrunden • Installation of 27 turbines between Excalibur Barge and Muhibbah Marine's MEB-JB1 Barge at North Hoyle
Goliath	Jack-up barge	50	1,200	Baltic 2	• Installed the 123 pin piles for the 41 jacket foundations • Was loaded with the first three test piles with a weight of up to 120 tons per pipe • Installed the transition pieces at the site
Sea Worker	Jack-up barge	40	400	Robin Rigg, Gunfleet Sands	• Installation of 60 Vestas V90 3MW turbines at Robin Rigg • Installed 19 of the 48 SWT-3.6-107 turbines at Gunfleet Sands

Table 9 The range of vessels used in offshore wind farm construction in Europe

From the above the following trends have been identified through industry practice with regards to component installation:

Vessel class	Component to install		
	Foundation	Turbine	Substation
Liftboat	Unlikely	Yes	No
Jack-up barge	Yes	Yes	Yes
SPIV	Yes	Yes	Yes
HLV	Yes	Unlikely	Yes

Table 10 Vessel Installation Capabilities

Installation vessel market – trade-offs in vessel selection and availability

Many types of vessel and spreads can be employed for a particular wind farm development during the installation phase, and generally speaking, developers seek for the minimum cost at an acceptable risk from the fleet of installation vessels available in the market and capable of performing the required operations. For this reason, a number of trade-offs and constraints are involved in the selection of the ship, as the cheaper vessels tend to have less transport or lifting capacity, require longer work times and involve a greater vessel spread.

Vessel data was further analysed, utilising the industry experience that exists within LEANWIND specific to vessel installation activities, to identify key areas for optimisation that could hold the potential for cost reduction in vessel design.

Table 11 below summarises a few of the current design features of Jack-up and HLVs in the market.

Vessel Type	Advantages	Disadvantages	Key Design Requirements	Priority for Optimisation
Ship Shaped Self-propelled self-elevating  *[33]*	*can operate in 3 distinct modes : 1) floating crane (weather restricted) with restricted crane loads 2) semi-jack up vessel with reduced loads on legs for operations in harbour and on sites with difficult soil conditions 3) fully jacked-up operations - weather unrestricted mode (only restricted by survival air gap)	*will become limited by the future depths of wind farms	* crane specifications (max. height, capacity) * deck layout and space * length of legs (as dictated site-suitability assessments) will determine the capability of vessel to operate in weather restricted or unrestricted modes (floating/semi-jack-up/full jack-up) * sea fastening design of turbine component to be transported (there is no current standard design, they are tailored to specific operational profile , thus a standard approach could significantly reduce costs) * survival air gap	*High* *High* *High* *Low* *High*
Barge shaped self-propelled self-elevating platforms  *[34]*	*can operate between work sites without recourse to a tug * good manoeuvrability characteristics during load-out, positioning * no vessel displacement due to surface waves and surges	* lower jack-up height than towed barges thus more affected by jack-up positioning planning (assessing suitability for jack-up rig locations) * jacking operation is time-consuming and limited by metocean conditions * lower operational speed than ship-shaped jack-ups * lower wave limit jacking than others	* survival air gap * site-specific assessment must demonstrate that the vessel is capable in elevated position and maintain a minimum air-gap and resist a 50-year extreme storm condition without experiencing additional seabed penetration and stability and structural stresses to remain within defined permissible limits.	*High* *High*
Barge shaped non-propelled self-elevating platforms	*large crane capacity and range * suitable for installation of heavy foundations and large turbine components or pre-	*long transit time * require tug vessel for transit and positioning * long duration of pre-loading and positioning on		

 [35]	assembled turbines * large usable deck space and high allowable deck loading * full jack-up mode allowing operation in areas with high tidal ranges * lower CAPEX and OPEX than ship-shaped jack-ups *tugs are effective for manoeuvrability for positioning at low speeds *capable to work on difficult soil conditions due to lighter hull. Can work in most location as long as legs are long enough for that particular site.	site operations *		
Self-propelled ship-shaped semi jack-up (Leg Stabilised Vessel)  [36]	*short pre-loading time making them very efficient in operations * efficient mobilisation and transit times * can provide a vessel feeder service due to their semi-jack up capability (assuming legs are long enough) * more suitable for shallower water sites * faster loadout, transportation and installation capabilities due to elimination of full jacking up cycle	* limited crane capacity and free deck space * low permissible deck loading * lower payload capacity compared to full jack-ups * operations affected by low limiting significant wave height and peak wave period during jacking operations as fully –elevated mode not possible * hull still partly submerged thus affected by motions		
Floating crane barges (HLV's)	* extremely large crane capacity, able to install very large and heavy structures, foundations even fully	* They are sensitive to environment, so good for one time jobs, but not good productivity	*station keeping ability and manoeuvrability at low speeds governs the initial choice of propulsion system * crane capacity and crane height	*High* *High*

 *[37]*	assembled turbines * not affected by water depth, could be used in the future installation of wind farms in deeper waters, where jack-ups start to be limited by leg length or limited availability of the more capable jack-ups. * However cost will be very high and transit time will become a problem for very remote sites.	* require feeder vessel to load and transport components * require tugs for anchor handling * long mobilisation and transit time for both crane barge and feeder vessel. Also may have problems entering some ports * prone to delays due to synchronisation between mobilisation transit and loadout operations of both crane and feeder vessel * can only undertake weather-restricted operations, highly influenced by sea states and weather windows * low limiting environmental criteria for lifting operations * high chartering rates * market demand and availability as they are used in oil and gas and marine operations as well * very limited usable deck area and payload capacity	* overall dimensions govern the ability to enter some harbours thus could limit the route suitability * overall dimensions govern the ability to enter some harbours thus could limit the route suitability	*High* *High*

Table 11 Design features of Jack-up vessels and HLVs

The feedback on the design features and analysis of current fleet data has helped to inform the design requirements that might be expected from a new design. A table featuring the main characteristics and particulars for a proportion of the current fleet and those under construction can be found in an appendix to this report.

The table below is a specific example refers to the A2SEA's Sea Installer Wind Farm Installation Vessel, information sourced from their contact within the industry [27]

Vessel Name	Sea Installer
Vessel Type	Jack-up vessel
Status	Operational
Owner	A2SEA A/S
Flag	Danish
Yard	COSCO China
Year built	2012
Length [m]	132
Breadth [m]	39
Max. Draft [m]	5.3
Max. Water Depth [m]	6.5 – 60 (depending on tide, penetration)
Cargo Area [m²]	3,350
Payload [tonnes]	5,000
Main Crane Load [t@m]	800 t@ 24 m
Crane Height [m]	102
Speed [knots]	12
Jack-up Legs	4
Accommodation [persons]	60
Dynamic Positioning System	DP2

Table 12 Vessel particulars for A2SEA's Sea Installer TIV [38]

Figure 12 A2SEA's Sea Installer TIV. [38]

3.1.2 Vessel Analysis – Findings and Conclusions

Specific findings on the vessel analysis performed are given in detail in tables 10 – 13. Generally speaking however the basic criteria for the selection of installation vessels are, in close relation to the site employed, the following:

- Principal dimensions
- Operating conditions for jacking
- Accommodation capacity and facilities
- Leg length and jacking speed
- Crane capacity and operating limits for lifting
- Dynamic positioning system
- Cargo area (main deck area and strength)

Cost benefit analysis principles dictate the selection of a suitable vessel at a minimum cost and an acceptable operational risk. But given the fact that such a vessel will not be employed in one single wind farm installation trade-offs between operational capacity, green profile, safety and reliability on the one side and costs on the other have to be carefully examined in each case

In a broad sense above coincides with the feedback from the industry stakeholders, which can be analytically found in the conclusions of this chapter. In view of the project's overall aim of reducing cost and time, they emphasized ambivalent criteria such as reducing risk by heaving and jacking operations, high acceleration capability of drive turbines OEMs, and captive market characteristics of vessel owners. The conservative character of this market as well as the exploitation of novelties regarding deck or crane capacities for new designs, have inevitably led to modifications and retrofitting of existing vessels.

3.1.3 Lifting Operations and Vessel Layout

As seen from industry data design ranges required for the main lifting appliances based on substructures and turbines. This section gives a greater appreciation for what needs to be considered when designing the lifting appliances and vessels on which they will be operating.

Innovative concepts such as telescopic cranes could be the next technology needed as nacelles are becoming increasingly higher. Also a new technique to install offshore wind turbines at higher wind speeds called "Boom Lock" has been developed by High Wind [39]. During installation operations, there are certain phases that are very sensitive to wind speed and thus can cause significant delays. High wind conditions decrease vessel up-time and increase operational delays. The Boom Lock is a smart tool that allows an offshore crane to install wind turbine components at high wind speeds, thus leading to a significant decrease of the weather downtime and results in a full year working possibility. It is basically a purpose built device that can skid along the crane boom and "grab" and hold the hook into position thus preventing the entire component (i.e. blade) from swinging while being lifted.

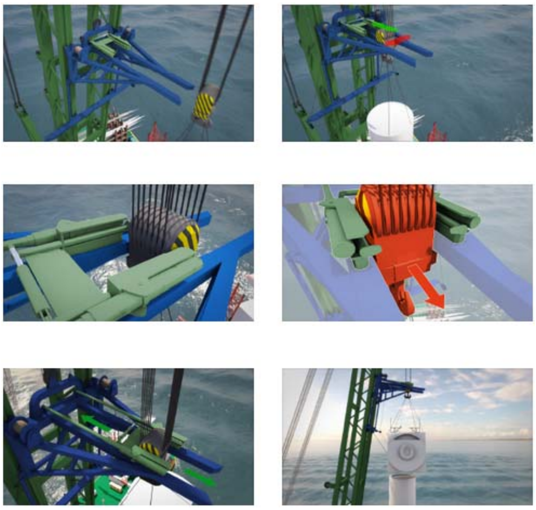


Figure 13 High Wind's Boom Lock system [39]

Vessel main crane(s):

It is necessary to design the main lifting package with respect to both the capacity necessary for handling the components of the WTG in question, but also the geometry of the WTG that has a large impact on the crane geometry. The crane needs to be able to lift all components on and from the deck area, and therefore, geometry is to be considered in respect to the cargoes to be handled and the clashes to be avoided.

Secondary cranes:

To be dimensioned and arranged for supporting the main crane operation.
Lifting capacities create envelopes in which the components can be put on deck.

Project considerations impact/limitations

- Lifting capacity to be based on heaviest possible part.
- Crane geometry to take into consideration the minimum clearance required.

Vessel technical limitations

Vessel main dimensions
The basic dimensions are to be carefully determined in respect of cargo load and area needed, crane requirements and stability.
The intended different cargo loading scenarios are to be considered in respect of size and arrangement of the main deck.

Vessel stability
Positions of heavy cargo items influence the static stability of the vessel in floating condition. To maximize payload of the vessel, the amount of ballast water to get the vessel trimmed and even keeled needs to be minimized. This can be achieved by arranging the cargo in such way, that the total centre of gravity of all cargo and the vessel lightweight (LCG – longitudinal centre of gravity) is aligned with LCB (longitudinal centre of buoyancy) as much as possible since a ship trims due to the couple set up

between LCG and LCB and keeps trimming about the LCF (longitudinal centre of flotation) until LCG and LCB are aligned. Items to account for are e.g. position of the crane and accommodation. In light weight condition the vessel will trim to the side of the crane, so heavy components should be positioned away from the crane.

For WTG installation, heavy components with high CoG's are to be transported e.g. tower sections. From a stability point of view VCG (Vertical Centre of Gravity) limits are applicable to the vessel. If the VCGs of the cargo are too high, the overall VCG of cargo + ship exceeds the allowable VCG. Single tower sections have high VCGs that are unfavourable for vessel stability if carried vertically.

Consultation with A2SEA revealed that following a crane upgrade on the Sea Power jack-up vessel, stability also became an issue due to having a rack for supporting and stowing the turbine blades on the deck. The crane upgrade did not however reduce the weather limits for vessel transit, however having the blade rack did reduce the limiting Hs during transit to 2.5 m.

Jacking capacity of the jack up vessel

The maximum elevated weight of JUP vessels is limited by the jacking system. The total dead weight (= useful cargo + supplies) is thus limited. Not to be overlooked in assessing the jacking limits is weight of the seafastening

Deck strength

Deck strength has limits with heavier components and higher sea states making it more challenging the load spreading towards deck is. The limitation of deck stresses is a main driving factor in designing seafastening frames.

Geometric limitations

Size of components

Components need to physically fit next to each other. Order of loading and installation may need to be considered when positioning different items.
Attention to clashes with the crane boom are to be considered. Additionally, attention to clashes with reference to the crane base are to be considered for lifts at high altitude, e.g. nacelle and blade lifts.

Size of seafastening

Size and weight of the seafastening are driven by the size and weight of the component and by acting loads. These loads are driven by the response of the vessel in the considered wave climate, and the position of the components on the vessel.
Deck strength of the vessel is taken into account for in seafastening design.

Industry feedback stressed that seafastening is always a very important criteria for all installations, and depends on specific projects thus the design of seafastenings is adapted for the operations to be undertaken. Moreover A2SEA pointed out that there is no current standard sea-fastening design for turbines components to be transported as they are tailored to specific operational profiles, thus a standard approach could potentially significantly reduce costs.

Gangway position for installation
Based on lifting capacities, field layouts, etc. a certain position of the vessel w.r.t. the WTG foundation is chosen. From this position the structure must be accessible by a mean of transfer (gangway…). This requirement of access can determine the orientation of the vessel for installation and thus the deck layout.

Accommodation

The shape and size of the accommodation block(s) is to be determined considering size of crew, number of customer's technicians and other personnel.

Propulsion package

The layout of the propulsion system and power generation plant is to be designed with respect to the different operational modes involved.
Further DP-class notation and crane power requirements are key elements when designing the power plant.

Project considerations impact/limitations

- Type of propulsion.
- Number and size of Diesel- Generator sets.

Safety

Safe lifting plans are to be considered both for clearance between the lifted components and surrounding components and vessel structures and w.r.t. personnel on deck. No access zones may need to be considered when lifting components over deck. Lifting over accommodation should be avoided.

3.1.4 Other factors impacting vessel selection

Vessels are chosen for a specific projects based on market availability, economic model and technical factors. Table 9 in the appendix shows the vessel types capable of contributing in each stage of installation at a general level. The operational water depth is critical for all installation stages. Both deep and shallow water can be limiting, for instance in shallow areas, jack-up barges may be required due to their lower draft.

3.2 Design Parameter and Criterion Determination

This section provided further detail on the development of the design criteria and parameters specific to installation vessel design, leading to the summary and ranges of values where possible.

3.2.1 Vessel requirements driven by substructure design

The most critical factors in the specification of a vessel capable of installing offshore wind turbine foundations are:

- Crane capacity – as monopiles can weigh over 500 tonnes and transition pieces over 200 tonnes, this can exceed the lifting capabilities of jack-up barges
- Water depth – important because it drives the turbine substructure design and thus indirectly requirements for vessel's lifting capacity, deck layout, deck free space and maximum allowable cargo

Crane lift height is usually not an important factor because foundations only need to clear the vessel deck, however crane reach is important due to large dimensions of gravity based and jacket substructures.

Transit speed is also not critical as there are alternative methods of transporting foundations to site thus not requiring the installation vessel to move back and forth from load-out port.

3.2.2 Vessel requirements driven by turbine design

Turbines may be installed by any specialised turbine installation vessel, a jack-up barge or SPIV but unlikely to be installed by HLVs due to the required lift height and sensitive nature of the lifts. However heavy-lift vessels are capable of installing completely assembled turbines.

The most important factors driving vessel requirements include:

- Weight of turbine components carried per trip - will determine the required allowable deck payload of the new vessel design
- The number of turbines carried per trip and degree of onshore assembly – will dictate the required free deck space of the vessel
- Weight of turbine components carried per trip and component lifting configuration (influenced by degree of onshore assembly) - will drive the vessel requirement on crane lift capacity
- Crane height and jack-up leg length – determines a vessel's capability to install at a given hub height
- The requirement for the vessel to be capable to install at a given hub height – will drive decisions on crane height and jack-up leg length

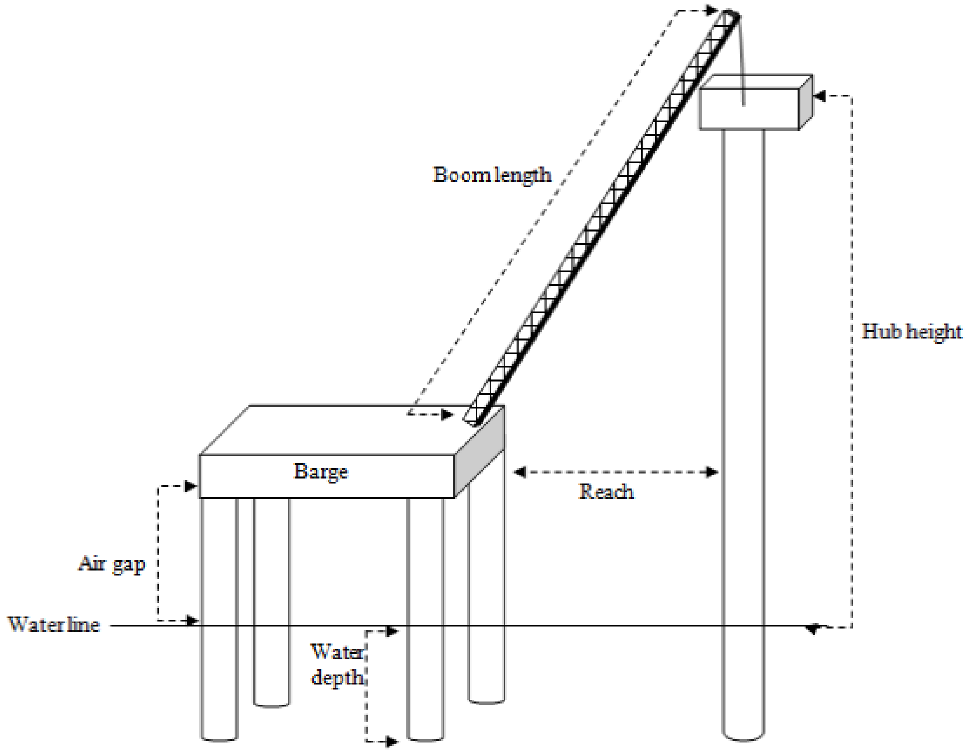


Figure 14 Geometric relationship between the required turbine hub height and vessel requirements

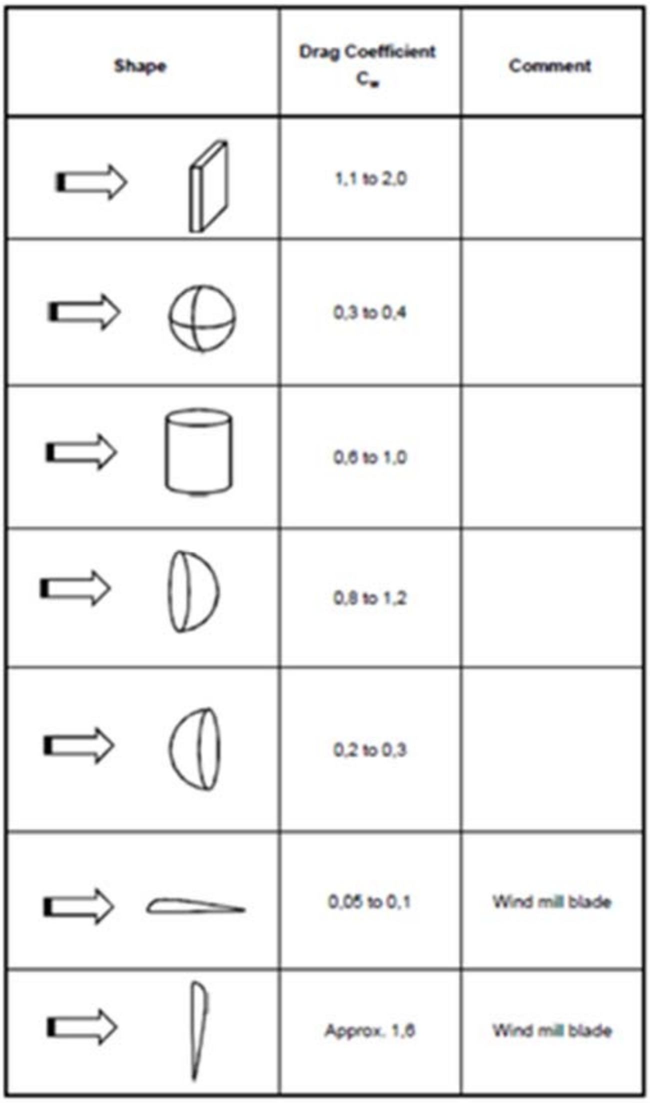
The figure above illustrates the relationship between the required turbine hub height and vessel requirements. The combination of airgap and the vertical component of crane boom length must reach above hub height in order to install the nacelle and rotor with blades.

The crane reach i.e. the horizontal distance from the vessel to the turbine, should be kept to a minimum, since it adversely affects the lifting capacity as well as the lifting height of the crane

Crane lift capacity is dictated by the weight of the component to be lifted plus expected dynamic loads in operation.

The additional loading due to dynamic effects is typically included by taking standardised Dynamic Amplification factors unless model tests or calculations can be shown to prove other values are acceptable.[40]

The attracted wind loading for turbine installation lifts incurring part of the dynamic loading will depend on the size and shape of the component being lifted. Some drag coefficients for typical structures are included in Figure 15.



Shape	Drag Coefficient c_w	Comment
	1,1 to 2,0	
	0,3 to 0,4	
	0,6 to 1,0	
	0,8 to 1,2	
	0,2 to 0,3	
	0,05 to 0,1	Wind mill blade
	Approx. 1,6	Wind mill blade

Figure 15 Typical shapes and corresponding c_W values [40]

Interviews undertaken with industry stakeholders have highlighted that the driving factors behind a crane upgrade on one of their ship-shaped jack-up vessels was specific to the Anholt farm, as the vessel was required to reach further up to place nacelles and turbine blades. Hub height was 81.6 metres and the vessel could be also employed for further maintenance tasks. As a result of this upgrade, compliance with coastal regulations had to be re-assessed for operation in Danish waters and also the design of the modifications approved by a classification society.

Table 13 below shows the different scenarios with relevant turbines as an indication of what could be possible. By defining the given cases it has provided a starting base from which the particulars of substructures and turbines can be estimated and thus in turn the vessel design criteria and ranges to be defined. The ability to meet this design criteria is controlled by varying the associated design parameters.

Installation + Large Maintenance Requirements		Case 1a	Case 1b	Case 2a	Case 2b
Turbine		Vestas V164-8.0 MW	Vestas V164-8.0 MW	Gamesa G128-5MW Offshore	Gamesa G128-5MW Offshore
	Component size	Blade (80 m length x 5.4 m max width chordwise) , Nacelle (20 m long x 8 m tall x 12m wide)	Blade (80 m length x 5.4 m max width chordwise) , Nacelle (20 m long x 8 m tall x 12m wide)	Blade (62.5 m length x 4.2 m max width chordwise) , nacelle (12.5 long x 4 tall x 4 wide)	Blade (62.5 m length x 4.2 m max width chordwise) , nacelle (12.5 long x 4 tall x 4 wide)
	Blade Length	80 m	80 m	62.5 m	62.5 m
	Blade weight	35 t	35 t	15 t	15 t
	Rotor diameter	164 m	164 m	128 m	128 m
	Total height	220 m	220 m	154 m	154 m
	Nacelle weight	390 t	390 t	150 t	150 t
	Hub weight	105 t	105 t	75 t	75 t
	Rotor Weight	210 t	210 t	120 t	120 t
	Total weight above yaw bearing	495 t	495 t	270 t	270 t
	Total Weight (excl.foundation)	695 t	695 t	585 t	585 t
	Turbine Components' Numbers	3 blades/hub/ nacelle/tower - 2 sections/ transition piece/ foundation	3 blades/hub/ nacelle/tower - 2 sections/ transition piece/ foundation	3 blades/hub/ nacelle/tower - 2 sections/ transition piece/ foundation	3 blades/hub/ nacelle/tower - 2 sections/ transition piece/ foundation
Turbine Tower Section					
	Dimensions	24 m long x 7 m diameter	24 m long x 7 m diameter	80 - 94 m long + project specific	80 - 94 m long + project specific

	Weight	200 t	200 t	270 t	270 t
	No. of sections	2	2	2	2
Turbine Substructure Design					
	Type	Gravity-base (cone)	XL Monopile	Jacket (piled)	Jacket (suction caissons)
	Dimensions	35 m diam.	5 m - 10 m diam.	12m base	8 m diam. / suction bucket
	Weight	3000-5000 t	1200 t (5m diam.) for 30m depth	1000 t	850 t (including transition piece - for 50m depth)
	Likely installation procedure	HLV (Crane barge)	Jack-up barge/ship-shaped DP2 vessel	Installation Barge + HLV	Installation Barge + HLV
	No. of sections	1	1	4	3
	Installation components				
Environmental Conditions	*(Needed for transit, jacking & DP, jacking operation, jacking survival conditions)*				
	Water depth	40 m	40 m	60 m	60 m
	Soil Conditions	Shallow bedrock	Medium-dense sand	Shallow bedrock	Medium dense sand
	Soil profile (piles erodible?)				
	Drilling requirement	No requirement	Pile driving (hammer)	Subsea Pile Hammering	Vacuum-assisted-skirts penetrating soil (possibly grouting depending on seabed shape)
	Wind speed (mean)	8.12 m/s	8.12 m/s	7.04 m/s	7.04 m/s
	Wave scatter diagram sea states				
	Current Velocity (max)	0.6997 m/s	0.6997 m/s	0.4305 m/s	0.4305 m/s

	Mean. Significant Wave Height	1.09 m/s	1.09 m/s	1.05 m/s	1.05 m/s
Logistics					
	Installation time (Erections per day)				
	Strategies				
	Cargo weight (not including turbine)				
	Vessel Spread				

Table 13 Wind Turbine characteristics used for the vessel requirements

3.2.3 Accessibility

Once the vessel concept has been selected for development within the project, the accessibility of the vessel has to be considered. Accessibility is primarily dependent on the weather conditions. In order to increase vessel accessibility, reducing time and cost, we must first consider the indicative limits for operational phases as listed in Table 14:

Operating Phases	Wind Speed	Max Sig. Wave Height	Survival Airgap (above LAT)	Current Velocity (at surface)	Tidal Current (surface)	Associated period
Port entry & exit	15.3 m/s	2.8 m @ 0 deg and 45 deg heading)	No limit	0.26 m/s	1 m/s	16.05 s
Transit to/from site	15.3 m/s	2.8 m @ 0 deg and 45 deg heading)	No limit	0.26 m/s	1 m/s	16.05 s
Location approach and positioning	15.3 m/s	2.8 m @ 0 deg and 45 deg heading)	No limit	0.26 m/s	1 m/s	16.05 s
Jacking (operations)	15.3 m/s	2.8 m @ 0 deg and 45 deg heading)	No limit	0.26 m/s	1 m/s	16.05 s
Jacked (survival)	36.1 m/s	10 m	7.8 m	0.61 m/s	1 m/s	16.05 s
Crane operations	16 m/s for 50Te crane or 20 m/s for 600Te crane	10 m	7.8 m	0.61 m/s	1 m/s	16.05 s

Table 14 Definition of concurrent working operational limitations for a typical TIV (MPI's Resolution) [41]

Feedback from interviews with industry contacts [42] highlighted the following main limiting criteria for wind turbine installation vessels which influence the vessel's accessibility to a certain site and constitute critical design requirements:

- Crane capacity, hook height, airgap (in case of jack-up), wind speed while jacked-up
- Certain components are more sensitive in higher sea states. Thus accelerations should be carefully assessed for transit operations with heavy components

Moreover industry suggested the following approximate limiting wind speed for lifting turbine components:

- Limiting wind speed for blade lifting operations: 10 m/s
- Limiting wind speed for nacelle/tower sections lifting operations: 12- 15 m/s
- A simple and safe to operate solution must be found in order to increase the limiting wind speed for component lifting operations, for example dynamically-compensated cranes.

3.2.4 Installation Options and Strategies

Foundation Installation

The foundation type chosen for each base site case dictates the possible methods of installation.

Design case 1b) refers to an XL Monopile foundation with a diameter in the region of 5 – 10 m and a weight of approximately 1200 metric tonnes.

There are a variety of methods in which monopiles can be installed. They may be transported to site by installation vessel, may be barged to the site, using a feeder vessel or may be capped and wet towed.

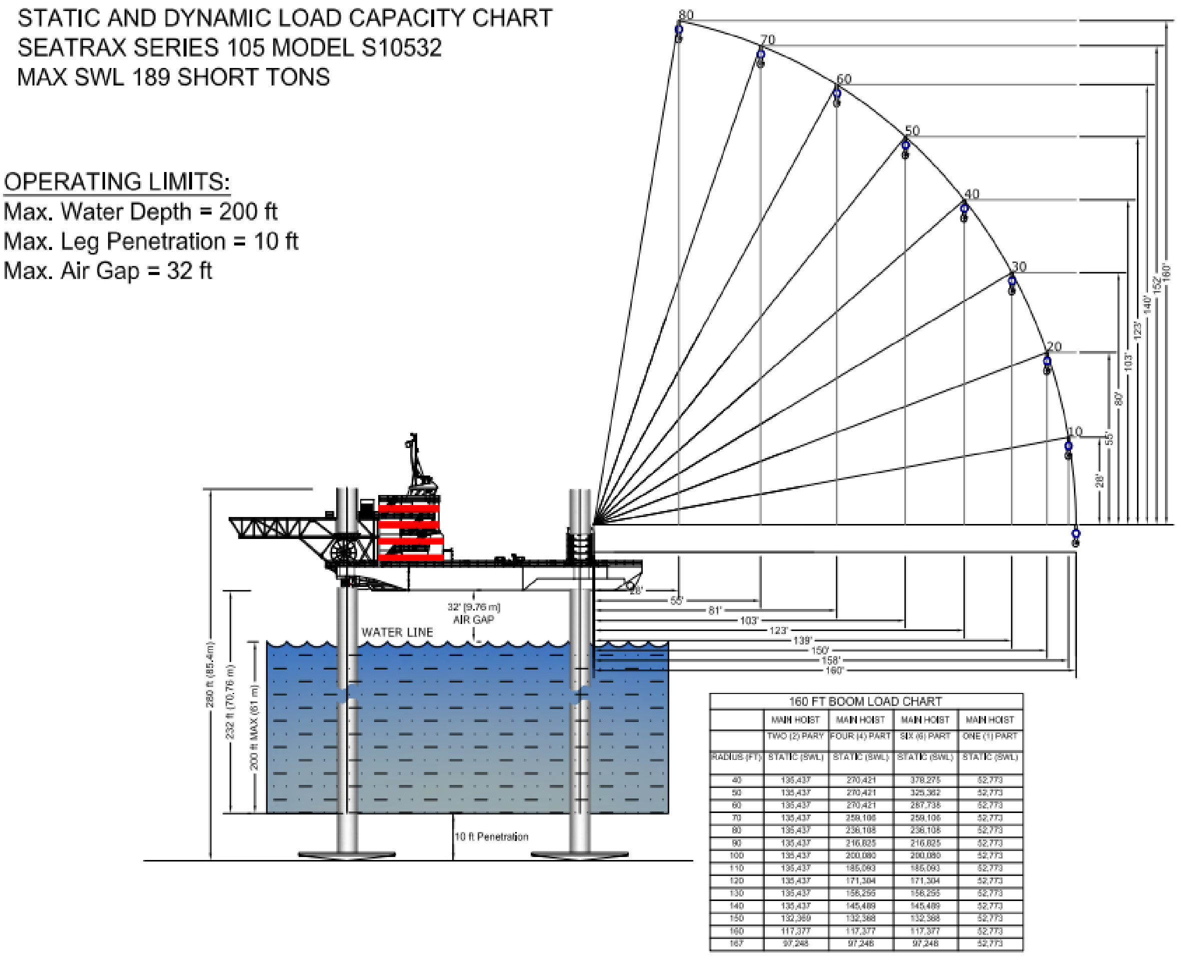
- The choice of the method depends on the following factors :
- Size and weight of monopile
- Variable deck load of installation vessel
- Crane lifting capacity (weight + height) of installation vessel
- Distance from site to shore
- Environmental conditions (metocean + wind + seabed)
- Vessel's transit speed

Large installation vessels with heavy lift cranes and large allowable deck load and free deck space may be capable of carrying several monopiles from load-out port and lift them into position. However vessels with lower crane or cargo deck capacity may not be able of transporting and lifting a monopile clear of the water and may need to use a wet tow or a feeder vessel arrangement.

A key stage in the installation of a monopile is the upending operation once the vessel in positioned at the site, so the monopile can be lowered vertically on the seabed. The pile is lifted using the crane and a special gripping device and this usually dictates the required lifting capacity. In the case of monopiles the crane capacity at a higher outreach is not crucial as the diameter of the monopile chosen is in the region of 5-10 metres compared to a GBF which could also be suitable for the same site that would have a base diameter in the region of 35 metres, however the height at which the crane is capable to lift the target SWL is essential.

Once upended and positioned vertically onto the seabed, the next phase is to drive the monopile into the seabed to a predetermined depth by using a hydraulic hammer attached on top of it. In case of rocky subsurface conditions, drilling through the substrate may be needed, which would significantly increase the overall time of foundation installation. Generally the monopile is driven through the seabed about 30-50% of its total length but this generally depends on the soil type and design loads of the foundation (design loads imposed by turbine and environment).

Once the monopile substructure is securely driven to the required depth through the seabed, a transition piece is lifted by either the same vessel that installed the monopile or another vessel that follows behind. There is also a requirement for a dumping barge or other utility vessel to assist in caring out scour protection by placing rocks around the monopile at mud level to protect against erosion.



160 FT BOOM LOAD CHART				
	MAIN HOIST	MAIN HOIST	MAIN HOIST	MAIN HOIST
	TWO (2) PARY	FOUR (4) PART	SIX (6) PART	ONE (1) PART
RADIUS (FT)	STATIC (SWL)	STATIC (SWL)	STATIC (SWL)	STATIC (SWL)
40	135,437	270,421	378,275	52,773
50	135,437	270,421	325,362	52,773
60	135,437	270,421	287,738	52,773
70	135,437	259,106	259,106	52,773
80	135,437	238,108	238,108	52,773
90	135,437	216,825	216,825	52,773
100	135,437	200,080	200,080	52,773
110	135,437	185,093	185,093	52,773
120	135,437	171,304	171,304	52,773
130	135,437	156,255	156,255	52,773
140	135,437	145,489	145,489	52,773
150	132,369	132,388	132,388	52,773
160	117,377	117,377	117,377	52,773
167	97,248	97,248	97,248	52,773

Figure 16 KS Titan II liftboat's Load Capacity Chart. [43]

Figure 17 Monopile being lifted off the main deck of installation ship. [44]

Design cases 2a) and 2b) both refer to jacket substructure designs, a piled jacket and a suction caissons jacket. The most common method of transport of jacket foundations from the fabrication yard is to be loaded on a barge and then towed to the construction site and lifted into position by a HLV. However, some newbuild self-elevating TIVs do possess the crane capacity to lift these foundations.

In contrast to monopile foundations, jackets can arrive at the installation site with the transition piece already pre-attached which would save an additional lifting operation. Also the piles used to secure jackets to the seafloor are significantly smaller in diameter and length than monopiles because the mass of the jacket and footprint arrangement hold the structure better in place. Additionally scour protection is less critical for jackets than for monopiles.

Figure 18 Heerema Marine's Thialf HLV lifting a jacket foundation at Alpha Ventus site. [32]

Jacket foundations can weigh in the region of 500 – 800 tonnes for water depths of 30 – 50 m. However for the base design cases 2a) and 2b), since the water depth is 60 m, the piled jack up is considered 1000 tonne heavy while the suction caissons jacket 850 tonne heavy.

Factors impacting installation of substructures

The time required for installation of substructures is affected by the following factors:

- Foundation type will impact the time required for installation
- Jackets take longer to install because they are heavier, more complex and more piles must be lifted and driven into position compared to monopiles
- Soil type – if hard rock is present below mud line, piles must be drilled
- If the seabed surface is erodible, scour protection is needed which would increase overall installation time and vessel spread

- Design loads of substructure for that specific site and the soil type dictate the required insertion depth to maintain a stable foundation thus affecting the overall time
- Number of foundations carried per trip by installation vessel, vessel's speed, distance to load-out port determine the loading time and the total transport and installation time
- Vessel spread – if foundations are loaded and transported to installation site on a barge, the installation vessel travel time is significantly reduced
- Season during which installation takes place – determines the weather downtime for various phases of installation breakdown. For example lifting the blades would have different limits than jacking-up, load-out in port or transit to site. Also foundation lifting is not very sensitive to wind speed as opposed to turbine rotor or blade lifting due to the nature of the blade's aerofoil section made to 'catch' wind. Generally work during winter will be associated with weather delays.

Turbine Installation

Once the foundation is fixed at position on the seabed, the turbine is then installed by either the same vessel that installed the foundation or a different vessel depending on the spread arrangement.

Generally a single vessel transports the turbine components and connects the turbine on top of the foundation. However a different vessel spread involving a feeder vessel used to transporting components to the installation site may be used depending on the transit speed, costs of the installation vessel, allowable deck load, free deck space, the size of the turbine components, and the distance to shore should be taken into consideration

As offshore lifts are risky and are susceptible to major weather downtime due to adverse metocean conditions, maximising onshore pre-assembly of components is preferred in order to reduce the number of offshore lifts. However, the degree of pre-assembly will impact vessel selection and installation time in the sense that different lift capacity, permissible deck load, free deck space/layout or vessel motions and metocean conditions will impact the vessel selection and also the overall time for load-out in port, lifting components from deck and connecting to foundation, thus impacting the entire installation time.

The methods used for offshore turbine installation are classified in terms of the number of lifts as shown in Figure 19 below:

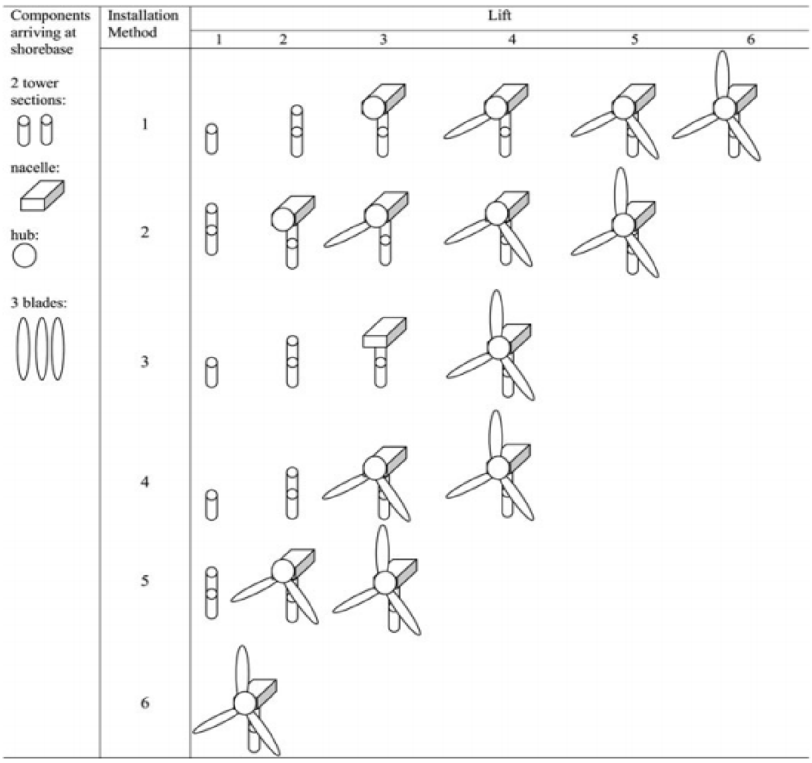


Figure 19 Different methods of wind turbine installation [22]

Method 1) Nacelle and hub pre-joined onshore and transported as one component. In this method, the two tower sections are installed separately in two lifts followed by the nacelle with the rotor hub pre-attached. The blades are then lifted and connected to the hub in three separate lifts. This method involves very little onshore assembly and it allows efficient use of free deck space as a large number of turbine components can be carried in one transport from port to the assembly site.

- Base cases 1a) and 1b)
  - 2 x 100 tonne lifts (tower sections)
  - 1 x 390 tonne lift (nacelle + hub)
  - 3 x 35 tonne lifts (blades)
- Base cases 2a) and 2b)
  - 2 x 135 tonne lifts (tower sections)
  - 1 x 225 tonne lift (nacelle + hub)
  - 3 x 15 tonne lifts (blades)

Method 2) Tower assembled onshore. The tower is assembled onshore and installed in a single lift, followed by the nacelle with the hub pre-attached and finally the blades in separate lifts. The main advantage similar to method 1) is that since the rotor is not assembled, it allows for more blades to be stacked and other components to be transported thus a more efficient use of the vessel's deck space. However, lifting blades one by one has a major disadvantage since naturally the blades long, lightweight aerofoils designed to 'catch' the wind could be influenced by strong prevailing winds during lifting operations could impose significant weather downtime.

Sites where this method was employed include Burbo Bank and Rhyl Flats.

- Base cases 1a) and 1b)
  - 1 x 200 tonne lift (tower section)
  - 1 x 390 tonne lift (nacelle + hub)
  - 3 x 35 tonne lifts (blades)
- Base cases 2a) and 2b)
  - 1 x 270 tonne lifts (tower section)
  - 1 x 225 tonne lift (nacelle + hub)
  - 3 x 15 tonne lifts (blades)

Method 3) Rotor assembled onshore. The tower is loaded onboard the vessel in 2 separate pieces and lifted separately onto the foundation. Nacelle is also loaded onboard the vessel and lifted separately onto the tower. The rotor and all three blades are pre-assembled onshore and loaded onto either a barge or ship-shaped TIV. The advantage of this method is that it reduces the danger of weather downtime for lifting the blades individually due to strong winds and also distributes the weight among the lifts more evenly. Disadvantages include the difficulty of using the deck space for the entire rotor and also the fastening of the rotor during transit.

Wind farms where this method was employed include Horns Rev 2, Middelgrunden, Arklow, Thornton Bank and Lillgrund.

- Base cases 1a) and 1b)
  - 2 x 100 tonne lifts (tower sections)
  - 1 x 390 tonne lift (nacelle + hub)
  - 1 x 210 tonne lift (rotor)
- Base cases 2a) and 2b)
  - 2 x 135 tonne lifts (tower sections)
  - 1 x 225 tonne lift (nacelle + hub)
  - 1 x 120 tonne lift (rotor)

Method 4) Rotor and Nacelle in "bunny ear" configuration. Nacelle, hub and two of the blades are assembled at the port and forms a shape like a bunny's head hence it is called "bunny ear" in the offshore wind industry. The tower is carried in two pieces and the third blade is also loaded separately on the same ship. Thus one turbine requires four offshore lifts at the construction site.

This method has been used at Horns Rev, North Hoyle, Barrow, Scroby Sands and Kentish Flats.

- Base cases 1a) and 1b)
  - 2 x 100 tonne lifts (tower sections)
  - 1 x 460 tonne lift (nacelle + hub + 2 blades)
  - 1 x 35 tonne lift (3rd blade)
- Base cases 2a) and 2b)
  - 2 x 135 tonne lifts (tower sections)
  - 1 x 255 tonne lift (nacelle + hub + 2 blades)

- 1 x 15 tonne lift (3rd blade)

Method 5) Tower pre-assembled onshore + Rotor and Nacelle in "bunny ear" configuration. This method only involves three lifts as the tower sections are assembled onshore and the rotor comes with two blades attached in "bunny ear" configuration.

- Base cases 1a) and 1b)
  - 1 x 200 tonne lifts (complete tower)
  - 1 x 460 tonne lift (nacelle + hub + 2 blades)
  - 1 x 35 tonne lift (3rd blade)
- Base cases 2a) and 2b)
  - 1 x 270 tonne lifts (complete tower)
  - 1 x 255 tonne lift (nacelle + hub + 2 blades)
  - 1 x 15 tonne lift (3rd blade)

Method 6) Entire turbine assembled onshore. All the turbine components are assembled at the dockside or on a barge. The turbine may either be loaded from the dock onboard the installation vessel or loaded on a barge and lifted at site. This method requires a vessel with heavy-lift capabilities with at least

- Base cases 1a) and 1b)
  - 1 x 695 tonne lifts (fully assembled MHI Vestas V164 8MW turbine)
- Base cases 2a) and 2b)
  - 1 x 585 tonne lifts (fully assembled Gamesa G128 5MW Offshore turbine)

Therefore in order to install a fully-assembled turbine, the TIV's lifting capacity must be at least 700 tonnes. The crane capacity of the existing turbine installation fleet ranges from 100 to 1200 tonnes meaning that there are a limited number of vessels out in the market capable of installing using this method.

In conclusion all the methods presented above have both pros and cons which can affect installation performance. Increasing the amount of pre-assembled pieces on the deck decreases the overall offshore installation time, but in fact the increased volume of the assembled structures must be considered as it can lead to a less efficient way of using the available deck space of the vessel. Another consideration is that carrying assembled pieces on the boat requires good sea conditions since the dynamic loads acting on them during the transportation could develop beyond their design parameters. This is also another aspect that makes the project flow more dependent on the prevailing sea conditions.

Wind turbine component sizes and weights vary significantly based on their design. Therefore, choosing the right installation vessel and the optimum transportation and installation procedure according to the specific conditions of the project site is highly essential in order to achieve a flowing installation operation with optimum duration.

3.2.5 Design Criteria Summary

Table 15 represents the design criteria for the installation vessel which will be used in the next step of the design process.

Design Criteria	Case 0	Case 1a	Case 1b	Case 2a	Case 2b
Crane lifting capacity	390 t (nacelle + hub) 460 t ("bunny ear" config.) 2000 t (GBS)	390 t (nacelle + hub) 460 t ("bunny ear" config.) 4000 - 5000 t (GBS)	390 t (nacelle + hub) 460 t ("bunny ear" config.) 800 - 1200 t (XL monopile)	255 t ("bunny ear" config.) 270 t (complete tower) 700 – 1000 t (Jacket-piled)	255 t ("bunny ear" config.) 270 t (complete tower) 700 – 850 t (Jacket-suction buckets)
Crane height , reach	90 m,80 m	90 m, 80 m	120 m,30 m	120 m, 30 m	120 m , 30m
Deck area	Min. 1500 m²	Min. 1500 m²	Min. 3500 m²	Min. 3500 m²	Min. 3500 m²
Additional Deck equipment	-	-	Upending and gripping devices, hydraulic hammer to drive monopile. Sea-fastening may be required.	Piling hydraulic hammer. Seafastening may be required	Purpose-built seafastening may be required
Leg length	Min.70 m	Min. 80 m (leg. Penetration + survival airgap + depth of hull + reserve leg length above main deck)		Min. 100 m	

Table 15 Design criteria for installation vessels

3.2.6 Design Parameters for Installation Vessel and Large Maintenance Vessel

Table 16 represents a full range of potential design parameters that could be used in order to fulfil the relevant design criteria of the vessel design. These are derived from the analysis of design requirements, through industry engagement and naval architecture practice.

Installation + Large Maintenance Parameters	
Vessel Design Parameters	
	Type
	Primary function
	Size (Dimensions)
	Vessel Overall Length, Lpp ,Beam, Draft, Depth (Dimensions)
	Leg length under hull
	Leg Cross Section
	Leg size/dimensions and number (I.e. three, four)
	Leg design

	Unit in elevated position
	Unit in transit conditions
	Lifetime extension
	Ice Class Notation
Hull Structural and General Arrangement parameters	
	Number of legs
	Leg Length
	Accommodation
	Deck area
	Hull depth
	Helicopter Deck
	Helicopter Type
	Upper hull structure
	Lower hull structure
	Columns
	Bracing joints
	Topside structure
	Corrosion protection
	Lifeboat platform
	Extreme limits of the Centre of Gravity (CoG) position
	Weight, Centre of Gravity (CoG) and buoyancy of the legs
	Spud can type: (i) Independent, (ii) Non Independent (bottom mat)
	Jacking mechanism/system and jack-housing
	Upper-Hull shape (triangular, rectangular box)
	Leg type: (i) Shell (tubular), (ii) Lattice
	Leg jacking type: (i) Pin-Hole, (ii) Rack-Pinion
	Leg inclination (due to leg-hull interface clearances)
Lifting appliances parameters	
	Crane height
	Crane Capacity
	Crane Manoeuvrability
	Crane cyclic loads
	Pile gripping device
	Platform Stability (for jacking or crane work)
Operational parameters	
	Jack-up speed
	Preloading time
	Propulsion type
	Positioning (Self-propelled or towing)
	Mobilization speed
	Air Gap
	Manoeuvrability
	Dredging Applications
	Scour protection
	Max Leg Penetration
	Legs in ocean transit conditions
	Legs during installation conditions
	Jack-Up configurations (weight, centre of gravity) for different operational modes and survival mode
	Leg length reserve (leg length contingency factor in the event the actual penetration exceeds that predicted)
Environmental Parameters	

	Areas of operation
	Modes of transport
	Bottom mat
	All-year (annual)/Seasonality for each mode of operation
	Sea water levels (calm sea, waves, tides) and air gap (I.e. Minimum elevated storm air gap)
	Slamming loads: box bottom design (in-place, transit)
Vessel Performance parameters	
	Dive support facilities
	DP capability
	Power
	Endurance or Fuel Capacity
	Crew Number
	Personnel Number
	Fuel Consumption
	Max Deck Load
	Stability in-place
	Engine Cooling System
	P-Delta Effect (lateral displacements, leg load distribution, etc.)
	Overturning stability (ensure against uplift of the windward leg)

Table 16 Design Parameters for Installation Vessel & Large Maintenance Vessel

3.3 Conclusions on Novel Installation Vessel Concept Design

Within the scope of “Novel Installation Vessel Concept Design”, we reviewed available technologies regarding existing and novel Installation Vessels and their layouts.

Several types of turbine and foundation installation vessels can be considered and currently operate in the offshore wind market including lift-boats, jack-up barges, (SPIVs) and heavy-lift vessels (HLVs).

Liftboats, jack-up barges and SPIVs are collectively referred to as self-elevating vessels as they raise the entire hull above the waterline. SPIV’s also known as Turbine Installation Vessels (TIVs) have the following basic specifications:

- Principal dimensions
- Operating conditions for jacking
- Accommodation capacity and facilities
- Leg length and jacking speed
- Crane capacity and operating limits for lifting
- Dynamic positioning system
- Cargo area (main deck area and strength)

Many types of vessel and spreads can be employed for a particular wind farm development during the installation phase and generally speaking, developers seek the minimum cost at an acceptable risk from the fleet of installation vessels available in the market and capable of performing the operations. However in this respect, a number of trade-offs and constraints are involved in the selection. Cheaper vessels tend to have less transport or lifting capacity, require longer work times and involve a greater vessel spread.

As far as vessel chartering costs are concerned, demand is a prime driver, set primarily by the costs of component supply, energy prices and government policy. Installation costs are actually a relatively small driver of overall demand. Factors affected by vessel design are related to vessel build cost (CAPEX), i.e. complexity of construction and outfit, as well as operational costs (OPEX) which are mainly a function of fuel efficiency and manning rates.

When considering lifting capacity of installation cranes, it is necessary to design the main lifting package with respect to both the capacity necessary for handling of the components of the WTG in question, but also the geometry of the WTG has a big impact on the crane geometry. The crane needs to be able to lift all components on and from the deck area, both for loading and installation purposes. Geometry should be considered in respect of cargoes to be handled, while clashes due to the geometry must be avoided. Major project limitations for secondary cranes (dimensioned and arranged for supporting the main crane operation) is the lifting capacity that must be based on heaviest possible part and crane geometry which must take into consideration the minimum clearance in order to avoid clashes.

The most important factors driving vessel requirements include:

- Maximum allowable deck payload – dictates the weight of turbine component carried per trip
- Free deck space – sets limits on the number of turbines carried per trip and degree of onshore assembly
- Crane lifting capacity – governs the number of lifts required per turbine and sets limits on the degree of onshore assembly
- Crane height and jack-up leg length – determines a vessel's capability to install at a given hub height

Moreover, industry contacts have also emphasised on the following important challenges that should be addressed in line with the project's overall aim of reducing cost and time of turbine installation:

- Reduce risk of using heavy lift crane vessels
- Reduce jacking operations as much as possible
- Drive turbine OEMs to be more open to higher accelerations
- Vessel owners have captive market and do not want to change and adapt and this is currently a challenge in the sector
- Vessels went out of specifications, struggling to cope with the required deck or crane capacity for new developments. However most companies will end up modifying a vessel they already possess therefore scope of optimisation might be limited by the reluctance of vessel owners to innovative designs.
- SSE also propose including Dogger Bank as a design case since larger turbines will be installed there which will drive the need for larger capacity TIVs.

4. Novel Service Vessel Design Concept and Access Equipment

This section addresses the same aspects as section 3. Only this time the focus is on the service vessels, which includes both crew transfer vessels and operation and maintenance vessels.

What drives the demand in the offshore wind sector for O&M specialised vessels in Europe? At the time of writing, each turbine in European waters typically requires around six maintenance visits per year. Generally, one planned and five unplanned (corrective maintenance) are required, ranging from manual restarts to major repairs.

In total, there were, as of July 2014, 2304 offshore wind turbines with a combined capacity of 7343 MW fully grid connected in European waters in 73 wind farms across 11 countries, including demonstration sites. [45]

Therefore this means that with at least 2600 turbines installed by the end of 2014, each requiring six visits per year, this means that, in European waters, more than 40 turbines would need to be serviced every day. [45]

The requirements of O&M specialised vessels are thus adapting to new challenges, including more robust access systems for varying foundation designs, improved transit times from shore to site, improved vessel seakeeping response, better fuel economy and vessel spread strategies.

There are a number of strategy issues that the industry faces which directly the effectiveness of operations and therefore cost. Although the development of O&M strategy is not covered in detail, it is within the project scope, and can significant impacts on vessel design.

O&M Operations Challenges

Typically, wind turbines are under warranty for the first 5 years of their lives and manufactures provide full O&M services during this period. After this, the wind farm owner may operate the wind farm itself, contract to a specialist services company or develop and intermediate arrangement.

Operational support is provided 24/7, 365 days a year, including responding to unexpected events and turbine faults, weather monitoring, turbine condition monitoring plus customer and supplier interaction.

Harbour & Facilities

O&M ports dictate many design requirements for service vessels to be employed. Their main function is the provision of facilities from which to operate and monitor the wind farm, plus local services and fuel for vessels. Generally the wind farm operator will establish the nearest port for an O&M base during the installation process in order to minimise time lost due to adverse weather conditions.

O&M facilities need 24/7 access, 365 days a year and uninterrupted access requires the availability of a non-drying harbour.

Typically, a wind farm support vessel needs a 20m berth. A 500 MW farm may require the operation of around 7 vessels, depending on distance to shore.

Moreover, as future wind farm developments will be located further offshore, the use of offshore accommodation and/or mother ships become more attractive.

In general terms, the main factors for deciding the optimal O&M strategy for a particular wind farm development include:

- Distance from site to O&M port and closest safe haven for service vessels
- Metocean conditions at site
- Size/arrangement of farm and number of number of turbines and substations
  However the most influential factor on the cost of offshore wind O&M is the distance from shore facilities. This factor has led more recent focus on possible employment of helicopter services (similarly to oil & gas) as sites further offshore are developed. Obviously economically speaking, the use of helicopters would make sense only if a widespread use for a number of wind farms closely located would be employed in the O&M strategy. Although their response and transit times are short and can operate regardless of sea-conditions (visibility can impact however), helicopter services are very expensive and can carry a limited number of technicians onboard.

4.1 Review of Existing and Novel Operation and Maintenance Vessels

It is first important to understand what the designs of vessels are and why, in order to improve on both individual design features and the overall design. A detailed review of the current vessel in the market, those under construction, and some concept designs gives a sound basis from where to begin. This data will also be used later in the design phase to help determine the concept designs to be taken into initial design.

4.1.1 Vessel categorisation

During the operating phase of a wind farm there are three roles within O&M activity which vessels to fulfil:

Crew Transfer Vessels (CTVs) & Wind Farm Service Vessels (WFSVs)

Fast (20 to 25kn) and rather small vessels with the main purpose of transferring personnel, tools and spare parts to wind farms in case of minor repairs and technical problems which can be solved without heavy equipment. Their payload capacity is in the range of 1 to 2.5 tonnes. CTVs are also required during the installation phase of a wind farm, often with a an even higher demand than in the operating phase.

Monohull

In the early days of offshore wind farms operations, local charter vessels of conventional designs were utilised as CTVs. Today these fast, light monohull vessels are not so common to be found in the offshore wind market as they have gradually been replaced by catamarans, SWATHs or trimarans over the past 5 years. Typical features of these small to medium monohull boats are:

- Very high speed
- Limited passenger capacity (in the region of 6 to 8)
- Limited cargo capacity and no crane capacity
- Uncomfortable for passengers
- Access for transferring technicians to turbine generally limited by significant wave height < 1m
- Suitable for quick intervention during unplanned maintenance

Figure 20 KEM Offshore's M/S Elisabeth M WFSV (Monohull). [46]

Operator	KEM Offshore
Vessel category	Wind farm Crew Transfer vessel
Hull type	Monohull
Year built	2007
Length	20.83 m
Width	4.9 m
Draft	1.1 m
Maximum transit speed	26 knots
Deck crane	None
Load capacity	5 tonnes cargo – 30 m² open deck space
Engines	2 x 1104 kW (1492 HP) Caterpillar, Rolls Royce

	Waterjet FF500

Table 17 Ship particulars of KEM Offshore's M/S Elisabeth M WFSV

Catamaran

Gradually the market developed towards the extensive use of catamarans, as due to their twin-hull design, these medium sized vessels are more stable under rough sea conditions and have the following features:

- Medium speed
- Passenger capacity limited by class (12+)
- Medium cargo capacity (2 – 3 tonnes)
- Comfortable for passengers
- Able to transit at Hs of up to 1.8 m
- Safe access to turbine at Hs > 1.2 m

Figure 21 Gardline Environmental's Gaillion WFSV (Catamaran). [47]

Operator	Gardline Environmental
Vessel Category	Wind Farm Service
Classification	MCA Cat 2
Hull type	Aluminium catamaran
Flag	United Kingdom
LOA	21.3 m
Breadth	6.5 m
Max. Draft	1.6 m
Designer	Global Marine Design
Year built	2011
Engine type	Caterpillar C32 1350
Propulsion	Fixed Pitch Propellers
Max Speed	30 knots

Transit speed	24 knots
Accommodation	15 personnel
Number of crew	3 members
Number of passengers	12
Heli Deck	No

Table 18 Ship particulars of Gardline Environmental

Figure 22 ASP Tyne WFSV (Catamaran). [48]

Operator	ASP Ship Management Group
Vessel Category	Wind Farm Service
Classification	DNV +1A1 HSLC R1 Wind Farm Service 1
Hull type	Aluminium catamaran with skeg and prop tunnel
Flag	United Kingdom
LOA	18.05 m (excl. appendages)
Breadth	7.5 m
Max. Draft	1.45 m
Deck crane	Fwd deck, Palfinger 4501, 4t/m 280kg @ 11 m
Deck strength	3 t/m²
Deck cargo	10 tonnes Aft, 4 tonnes Fwd
Designer	Incat Crowther
Year built	2012
Engine type	2 x Scania D116 42M 'intermediate' rating
Propulsion	2 x 5 blade Fixed Pitch Propellers
Max Speed	26 knots
Transit speed	23 knots
Accommodation	16 personnel
Number of crew	4 members
Number of passengers	12
Heli Deck	No

Table 19 Ship particulars of ASP Tyne WFSV

SWATH

At present in the offshore wind sector, Small Waterplane Area Twin Hull (SWATH) CTVs are increasingly entering the market. These vessels have a similar hull shape above the waterline with catamarans but feature submerged “torpedo” shaped underwater bodies which minimise the wave-making resistance with a small detrimental increase in skin-friction resistance. However due to the increase in depth of the hull the propellers can experience increased efficiencies, and together with the reduced wave-making resistance are known to offset the skin fiction resistance downside. As this hull form concept is based the idea of minimising the hull cross section at the sea’s surface, thus minimising the ship’s volume near the surface where wave energy is located, meaning maximised stability even in high seas and at high speeds. The displacement necessary to keep the vessel afloat is submerged and less affected by wave action as wave excitation drops exponentially as depth increases.

Figure 23 CTruk’s SWATH20 WFSV (SWATH). [49]

Operator	CTruk
Vessel Category	Wind Farm Service
Classification	Structure to BV : HULL Wind Farms Service Ship – S1 Sea Area 3 Full Class to BV: HULL MACH Wind Farms Service Ship – S1 Area 3 MCA SCV Category 2
Hull type	Infused composite material – SWATH hull form
Flag	United Kingdom
LOA	20 m
Breadth	7.5 m
Max. Draft	1.3 m
Designer	Global Marine Design
Displacement	34 tonnes
Engine type	2 x Cummins QSM11 marine engines
Propulsion	2 x Rolls-Royce Kamewa waterjets
Max Speed	24 knots
Transit speed	20 knots
Deck space	Fwd – up to 34 m^2 Aft – up to 10 m^2

Table 20 Ship particulars of CTruk SWATH20 WFSV [49]

A2SEA also operate a fleet of 4 SWATH crew vessels employed in O&M activities. The table below shows the specifications sheet for the SEA BREEZE. [38]

Vessel Name	Sea Breeze
Vessel Type	Wind farm service vessel
Status	Operational
Owner	A2SEA A/S
Flag	Danish
Yard	Danish Yachts A/S
Year built	2013
Length [m]	25
Beam [m]	10.6
Design Draft [m]	1.815/2.525
Classification	DNV + 1A1 HSLC, Passenger, R1,E0,CLEAN,COMF-V(3)
Hull type	SWATH-catamaran
Designer	Hauschildt Marine A/S Denmark
Displacement [tonnes]	105
Engine type	2 x MTU 10V 2000 M72 900kW@2250RPM
Propulsion	2 x CP-propeller with servo gear
Max. speed [knots]	24 (cat-mode)
Deck space [m²]	50
Passenger capacity	24

Table 21 Ship particulars of SEA BREEZE [38]

Figure 24 A2SEA's Sea Breeze Catamaran WFSV [38]

Many of the SWATH WFSVs recently built will have a market impact on operations for Round 1 and Round 2 offshore wind farms, but they are generally designed with Round 3 in mind. For example, CTruk envisage that SWATH20 will be davit launched from mother ships to provide cost effective access to offshore installations in all but the roughest seas.

Consultation with industry stakeholders involved in the O&M market has highlighted that there is a challenge is the station-keeping performance. This is in both head and beam seas, when transferring technicians (the turbine approach phase) to the turbine platform without having to change the vessel heading.

Another important aspect raised by stakeholders is regarding difficulties encountered by operators seeking to employ their vessels in different jurisdictions across Europe as O&M vessels may have been built according to domestic standards which vary by country. Thus, there is a common requirement amongst the flag states for more transparent and uniform regulations in offshore wind O&M segment. Some flag states have indicated that class specifications will become a mandatory requirement for WFSVs in the near future.

Multi-purpose vessels (MPVs)

Employed when damaged wind turbines components have to be replaced and relatively heavy lifting capabilities are required. Depending on the nature of the repair operation to be undertaken on the turbine, different types of MPV's can be used. TIVs could theoretically perform O&M tasks, but the economically feasible is questionable. Moreover industry consultation has stressed that the requirement for O&M jack-up vessels is low.

Service Offshore Vessels (SOVs)

A larger vessel capable of staying out at sea providing accommodation to technicians but also has the ability to transfer personnel to foundations. Some also feature onboard workshops for parts assembly or maintenance as well as storage for spare components.

Figure 25 Jack-up barges which could be employed in an MPV role. [50][51]

In 2013, Siemens signed a chartering agreement with ship-owner Esvagt A/S for two new offshore wind service vessels, which are being commissioned specifically for Siemens' service operations at the Butendiek and Baltic II offshore wind farms in Germany, both of which are scheduled to come online in 2015. Although the SOVs are already equipped with anti-rolling to avoid crew sea-sickness, wellbeing in the often harsh and somewhat unfriendly maritime environment requires more aspects to be considered since the SOV will remain out at sea for several weeks. This could include an adequate infrastructure on the vessels, from washing machines and a gym to an onboard IT infrastructure that enables the crew to stay in touch with their families on the mainland or watch football matches on live TV.

Figure 26 below shows the Esvagt Supporter which is a 41.9 m long ship built in 1989 and rebuilt in Denmark in 2001 and approved by the Danish Maritime Authorities as standby/rescue vessel for 140 survivors and approved by MCA as class B for up to 300 survivors.

Figure 26 ESVAGT's Supporter SOV [52]

4.1.2 Vessel Classification requirements

Vessel coding or classification is a legal requirement to ensure that the safety of the vessel and the crew. The extent of these requirements is dependent on the primarily on the type and size and proposed range of the vessel, At the moment over 50% of WFSVs in Europe are coded MCA Cat 2 meaning they can operate up to 60nm from a safe haven. To work further offshore, an MCA Cat 1 vessel (up to 150nm) or a vessel coded by a Classification society such as Lloyd's Register is required.

As the UK has led the market in offshore wind development so far, most of the future sites considered within LEANWIND include South Knock, West Gabbard, Firth of Forth, Moray Firth, and Hornsea. Additionally, the Belmullet site in the Atlantic is also considered. All the sites are within the 60nm limit, thus MCA Cat 2 vessels are more suitable. However for the Hornsea site, distance to safe haven is in the region of 81nm, therefore fully classed vessels will be in higher demand despite them being more expensive to charter through higher build costs. Also the increase in projects in Germany will result in a higher demand for classed vessels, which are required as standard.
For example the current practice for owners requesting to class their WFSVs with Lloyd's Register, for a vessel operating in Service Area G2, may be assigned the following typical class notation with a descriptive note.

- Hull notation: 100 A1 SSC Workboat G2
- Machinery notation: MCH

- Descriptive note: Wind Farm Service Vessel

It is anticipated that vessels serving offshore wind farms will be assigned Service Area notations G2 or G3.

- G2 Service Group 2 covers craft intended for service in reasonable weather, in waters where the range to refuge is 20nm or less. This group covers cases 0, 1, 2b and 3 within LEANWIND (South Knock, West Gabbard, Mooray Firth and Belmullet sites).
- G3 Service Group 3 covers craft intended for service in waters where the range of refuge is 150nm or less. Case 2a (Firth of Forth) falls within this category.

4.2 Design Parameters and Criteria Determination

This section provided further detail on the development of the design criteria and parameters specific to service vessel design, leading to the summary and ranges of values where possible.

4.2.1 Vessel requirements driven by defined cases

The below table has been compiled using current fleet data and feedback from the industry. This presents a snapshot of the factors that affect vessel design parameters and criteria, as based on the project cases under consideration.

Service Vessels		Case 0 (South Knock)	Case 1 (West Gabbard)	Case 2a (Firth of Forth)	Case 2b (Moray Firth)	Case 3 (Belmullet - Atlantic site)
Turbine Design						
	Maintenance task	1 planned and 5 unplanned (corrective maintenance) are required, from manual restarts to major repairs. Major repairs could include removal of entire generator or nacelle or reconditioning the drivetrain which is required every 5 years.				
	Tower access platform dimensions	Tower access platform about 21 metres above sea level				
	Boat landing design					
	Foundation type	Grounded : Monopile	Grounded : Monopile	Piled jacket / Suction jacket/ Gravity Base	Grounded : Jackets (also some movements regarding GBF)	No data available
	Total Height	147 m	131 m	210 m	204 m	No data available
Environmental Conditions at Site						
	Sea State					
	Water depth	26 m	33 m	65 m	37 - 57 m	50 - 60 m
	Weather window					
	Soil conditions					
	Wind speeds	8.12 m/s	8.12 m/s	7.04 m/s	9.75 m/s (@90m hub height)	7.04 m/s
	Distance between site and closest safe haven	30 km (16 nm)	30 km (16 nm)	100 km (54 nm)	22 km (12 nm)	5 km (approx. 3nm)
Logistics						
	Working Day Length	14 h in any 24-h period / 72 h in any 7-day period (ILO Regulations)				
	Dimensions					

	Transit time		2 h (maximum allowable)			
	Personnel Transfer per day	A team of 5 technicians is likely to be deployed for servicing one wind turbine at a time				
	Expected effective day rates	GBP 130k/day for jack-up MPV used for heavy O&M tasks				
	Shift Rotations	Assumption of a daily work allowance of 8 - 12 hours for personnel (no night shifts)				
	Typical limiting significant wave height	At present Hs = 1.5 m, up to 2 m				
	Tolerable Human Accelerations	For transit passenger (transferring technicians) : Vertical accelerations : 0.05 g / Lateral Accelerations : 0.04 g / Roll motion : 2.5 degrees heel				
	Approach time					
	Wind farm vessel spread					
	Condition monitoring/failure mode assessment systems for wind farms					
Vessel	Maximum Hs as dictated by Availability					

	Transit speed	8 Knots (Min. allowable)	8 Knots (Min. allowable)	27 Knots min. allowable for CTVs / Mother ship more suitable	6 Knots (Min. allowable)	8 Knots (Min. allowable)
	Draft as dictated by farm site/port to operate from	Draft is particularly critical for SWATH hull forms				
	Crew facilities onboard as dictated by crew shift pattern					
	Deck space & load capacity	SWATH: Fwd - up to 34 m² ,aft up to 10 m² ; monohull : up to 30 m² and approx. 5 tonnes load capacity ; catamarans : Fwd up to 37 m² ; Aft up to 34 m² (indicative ranges for sub 24 m WFSVs)				
	Payload capacity	CTV's : 5 tonnes cargo , Catamarans : 10 tonnes aft, 4 tonnes fwd				
	Personnel transfer system as dictated by max Hs ("bump&jump" limited to Hs=1.5m)					
	Vessel classification (MCA Cat 2/Cat 1/coded by Class Society) driven by operational profile (location of closest safe haven)	G2 Service Area Group (up to 20nm) by LR , and MCA Cat - sub 24 m vessel	G2 Service Area Group (up to 20nm) by LR , and MCA Cat - sub 24 m vessel	G3 Service Area Group (up to 150nm) by LR , and MCA Cat - sub 24 m vessel	G2 Service Area Group (up to 20nm) by LR , and MCA Cat - sub 24 m vessel	G2 Service Area Group (up to 20nm) by LR , and MCA Cat - sub 24 m vessel
	Range (determined by fuel capacity and sleeping arrangements)					

	Personnel capacity	If up to 12 , vessel falls under MCA's Small Commercial Vessel (SCV) code , if over 12 passenger vessels needs to be classified				
	Propulsion systems (as driven by balance between required transit speed vs. transfer system and required thrust to maintain contact with foundation)					
	Capability to maintain safe contact with turbine for crew - this also drives fendering design					

Table 22 Preliminary dimension analysis of proposed service vessels per use case

4.2.2 Accessibility

As with installation vessels accessibility is a key requirement for O&M vessels and activities. It is primarily dependent on the weather conditions. In order to increase vessel accessibility, reducing time and cost, we must first consider the indicative limits for operational phases.

Presently the maximum Hs for accessibility are considered to be 1.5m. In order to achieve greater accessibility the vessel design and/or access system should be designed to exceed this 1.5m barrier.

Feedback from interviews with industry contacts [42] highlighted the following main limiting criteria for wind turbine installation vessels which influence the vessel's accessibility to a certain site and constitute critical design requirements:

- Crane capacity, hook height, airgap (in case of jack-up), wind speed while jacked-up
- Certain components are more sensitive in higher sea states. Thus accelerations should be carefully assessed for transit operations with heavy components

The size of service vessels is largely dependent on project, but 15 to 18 m long vessels are still in demand. However in German waters there is a higher demand for 24 m + / 26 m long vessels due to longer wave period compared to UK's East Cast.
26 m long CTV's are practical up to 30 nm, further offshore then 50 m+ long service vessels and accommodation vessels are usually needed.

4.2.3 Vessel Motions, Seakeeping & Station keeping

Vessel motions are naturally linked to the sea conditions, but the vessels design can dictate the response a particular vessel has to those sea conditions. As we have seen in the previous report *'Industry Challenges report – novel vessels and equipment'* the ability and efficiency of service personnel can be heavily impacted by sea sickness, increasing cost of the activity. Therefore a design requirement to be considered is the vessel response accelerations which should be within the following:

- For transit passenger (transferring technicians) : Vertical accelerations : 0.05 g / Lateral Accelerations : 0.04 g / Roll motion : 2.5 degrees heel

The table below indicates limits to be considered for different types of work.

Vertical Acc.	Lateral Acc.	Roll Motion	Description
0.20 g	0.10 g	6.0°	Light Manual Work
0.15 g	0.07 g	4.0°	Heavy Manual Work
0.10 g	0.05 g	3.0°	Intellectual Work
0.05 g	0.04 g	2.5°	Transit Passengers
0.02 g	0.03 g	2.0°	Cruise Liner

Table 23 Seakeeping performance criteria for human effectiveness in RMS [53]

Industry suggests that although a number of 16-18m length vessels are still used, the 24-26m+ length vessels are more desirable for their better seakeeping, station keeping and stability characteristics. New 26 m long CTV's are more capable, being employed in German waters and featuring fixed pitch propeller with good station-keeping performance.

Moreover industry emphasised that as the vessels are now going beyond 50nm from shore, seakeeping is now being taken more seriously. It is also an issue for the transfer too. (i.e. Station-keeping performance). Mr. John Kecsmar from Adhoc Marine Designs pointed out that serious legislation changes materialise only after accidents or loss of life. "Someday soon there shall be a serious accident, and sadly a loss of life may occur. Once this occurs everything shall change. Serious legislation will be enforced."

Industry contacts also stressed that there is very little one can do to improve the seakeeping and/or resistance of such heavy boats for their length, despite what is said in company releases.

4.2.4 Personnel Capacity

Personnel capacity is critical on smaller vessels. In this case is very important to deliver the correct number of personnel in order to efficiently carry out O&M activities whilst also providing the appropriate level of facilities, safety systems and equipment. The more crew and technical personnel a vessel is designed for, generally the slower and more costly the vessel in both constructions and operational cost. Typically a capacity of up to 5 technicians plus crew seems to satisfy the market requirements, based on current work practices and experience to date. Vessel O&M strategies and alternative maintenance programmes such as Turbine Health Monitoring however, could have an impact on this.

4.2.5 Classification and statutory

Service area has a great impact on vessel cost because the requirements for safety and construction of the vessel can increase dramatically. Generally speaking the greater the service area the larger and more complex the vessel. It is understood that increasing a vessel beyond the current 24m length limit for Load Line regulations increases cost by approximately 20%. That's said however, the overriding requirement is to be able to provide service capability to the sites identified in the cases. Therefore the data given in table above suggests that a service vessel with the service areas of G2-G3 is required.

Consultation with industry revealed that at the moment operators and builders within the wind farm O&M sector are trying to fit as much as they can onto a sub-24m vessel as this saves a considerable amount of money and administration and the overall cost of the vessel. Going over 24m is a "killer" for many. Thus the designs are "squeezing" the maximum that is possible out of a sub 24m vessel. This is not conducive to a design that is "best", so to speak. "It is what it is", but making a profit by operating the vessel is all owners are interested in. Their daily charter rate (DCR) allows them to get revenue. Going over 24m would change that. Therefore there is a reluctance to go over 24m, meaning the seakeeping of the vessel is not ideal for offshore applications but a lesser factor than the cost of the vessel.

Moreover once the crew carrying capacity exceeds 12 passengers, as many wish to do at the moment, it becomes a “passenger ship”, and this too drives up the cost and weight. If that was not enough, if a vessel is over 24m and/or 12 passengers and more than 20 knots, the MCA will enforce the HSC 2000 code. This adds roughly 20% to the cost of the vessel too.

Therefore the main drivers currently are keeping below 24m to save money and thus make money with a lesser DCR. If the DCR increases because using for example a 30m vessel it has few takers. Industry contacts also provided an example of an operator who bought a 28m catamaran as a cheap option from a shipyard that used its economies of scale production from other markets. It is now laid up. However it is interesting to note that the same operator has several 24m vessels which produce revenue by doing the same job. Bigger vessels do have higher DCR, however not many operators are willing to pay the higher cost when two smaller boats are cheaper and can do the same job.

4.2.6 Payload Capacity

Payload capacity is dependent on the nature of the O&M activity being performed, particularly the size of the components that are required to be replaced on the turbine. Based on the information gathered we can see that for level of maintenance required to date the range of payload is between 5 and 15 tonnes. However, this would be further driven by turbine development and therefore this requirement could be subject to a technological increase.

4.2.7 Lifting appliances

Industry consultation stressed that the wind farm O&M market is looking for smaller jack-up vessels, in the region of 500 tonnes crane load capacity. Bigger jack-ups can go up to 4200 t crane capacity but are expensive to contract. This could indicate a market gap for an O&M vessel design of around 500 t lifting capacity.

Moreover it has been emphasised that demand exists for jack-up vessels to be employed in O&M activities and is driven by the need to recondition the drivetrain every 5 years. Also for older turbine (Round 2 or smaller turbines), the nacelle may require replacement during the turbine’s lifetime. However later Round 3 farms are not likely to need drivetrain replacement. This means that jack-up vessels could be employed in O&M activities such as removing the entire generator or nacelle with nacelle weight thus driving requirements for crane capacity.

4.2.8 Access Systems

The accessibility of a wind turbine depends on the means of transport used to get technicians from shore to the turbine location, as well as the method of transferring personnel and maintenance tools or parts to the turbine. In the offshore industry two means of transport are being used to reach offshore structures: helicopters and vessels. In the oil and gas industry as long as an offshore structure is equipped with a helicopter landing deck, the helicopter can land on it and passengers safely boards or exit the helicopter. However, this does not easily translate to the offshore wind sector because mounting a helicopter landing deck on an offshore wind turbine would be unpractical due to a variety of reasons. Instead, a hoisting platform can be placed on the nacelle of the turbine and then the transfer of personnel from helicopter to turbine can be achieved by having the helicopter hovering over the turbine and lowering personnel down to the platform on top of the turbine. Although it is fast, this method has major disadvantages including high costs of operation for the helicopter, high probability of casualties in the case of crash, and the fact that only limited spares and tools can be transferred to the turbine. Furthermore high wind speeds and poor visibility can affect the accessibility.

Figure 27 Accessing a wind turbine by helicopter [54]

The most popular access method to transfer personnel and parts onto offshore structures is ship-based access. As a parallel to oil and gas, where crew can be lifted from a vessel onto a platform by having a crane lifting a personnel basket or personnel can use a swing rope to jump from a vessel to a landing platform on the same level, in the offshore wind sector these methods are not suitable due to the requirement for a crane and a crane driver on the turbine or very benign sea conditions for the swing rope method.

Currently the most widely used access method is by creating friction between the service vessel's bow and the turbine's boat landing aiming to have minimal heave motions at the point of contact. The most important downside of this method is that it is limited to moderate wave conditions.

One of this project's main aims is to reduce cost by increasing the accessibility of wind farms. Helicopter access is unlikely to become the preferred method of choice for future developments because of the large cost implication. The conventional "bump and jump" ship-based method only allows access in limited weather conditions, an Hs = 1.5 m being the generally accepted limit maximum sea state for safe access. Industry feedback further suggests that this 1.5 m limitation will remain and thus the project will target operational phases that are prone to downtime due to weather in order to reduce overall duration in O&M activities.

Therefore in order to increase accessibility of future offshore wind farms and also safety of personnel to be transferred, reduce downtime and induced revenue losses, a number of improved access systems have been under development and refinement recently.

Requirements of such enhanced access systems mainly include:

- Safety – the main concern for ship-based access is avoiding injuries of personnel being transferred. For the current “bump and jump” access methods the most critical moment is when a technician steps from the vessel onto the ladder mounted on the turbine. In high sea states, the vertical force induced by the vessel’s heave motion could be higher than the friction between the ship’s fenders and the boat landing and thus cause sudden displacement when personnel are transferring.
- No need for special provisions on the turbine. As the future wind farms will be of larger scales, any costly adaptation required to enable use of an access system would result in a significant increase of the total wind farm installation cost. An example would be the Offshore Access System (OAS) that connects a ship-based gangway to a vertical pole on a dedicated platform, thus meaning that this would be required on the turbine’s boat landing platform if such systems were considered and the O&M strategy for the farm would have to be tailored around the requirement for such provision.
- Applicable on different types of vessel types and hull forms
- High accessibility: up to sea states with Hs = 2.5 m.

One of the most developed access systems used in the offshore wind industry today is the Ampelmann System which features active motion compensation in six degrees of freedom. This system is very safe as it compensates for the vessel’s motions to make the gangway between the transfer platform on the vessel and the boat landing platform on the turbine very stable to enable personnel to walk safely.

The decision of whether to use a motion compensating access system would be the result of a cost-benefit analysis on the potential improvement of total accessibility due to a further increase in the operational limit closer to Hs = 2.5 m, considering the probability of occurrence/exceedance of Hs=2.5 m, at the site under consideration.

Figure 28 Accessing a wind turbine by motion compensating access system [55]

To design a motion compensated access system, the first input needed is the wave spectra derived from a wave scatter diagram for the sites considered. Once that data is available, then the vessel's RAOs are required so the response spectra for the vessel motion in a particular sea state can be calculated. The next step would be the transformation of the response spectra to the time domain through inverse fast Fourier transform (IFFT) in order to generate time signals of the vessel motions. These vessel motions could then be transferred to any location on the vessel's deck to acquire the envelope of motions of that particular point in the sea state under consideration. As the access system would need to counteract the motions of the deck, the inverse of the vessel's motion envelope would be the envelope the access system must reach.

Regarding the vessel to host an access system, the requirements that the vessel design would have to address include the following:

- Deck space – to accommodate the mounting of the access system's platform and additional equipment such as hydraulic power units and control system.
- Vessel strengthening - an access system would require strengthening the under-deck structure supporting the platform, and also dedicated seafastening elements.
- Station keeping assistance or dynamic positioning system (DP)
- Extra cargo carrying capacity and powering to accommodate the installation of an access system on the deck

4.2.9 Vessel Layout

Industry feedback better suggests that a number of improvements can be made to the vessel layout to improve efficiency in particular:

- Increased deck storage for parts and equipment, better storage for waste oil and technicians' belongings.
- Easier access to engines.
- Improved visibility from wheel house
- Improved design of bow fenders and shock absorption

These requirements are more qualitative and can be developed in the initial design phases of the project.

4.2.10 Design Criteria Summary

The table below represents the design criteria for the service vessel which will be used in the next step of the design process.

Design Criteria	Case 0	Case 1a	Case 1b	Case 2a	Case 2b
Vessel Speed	Min. 8 kts	Min. 8 kts	Min. 27 kts	Min. 6 kts	Min. 8 kts
Personnel carrying capacity	Quantitative requirement. Will be further defined in T4.2/T4.5				
Motions response & accelerations + manoeuvrability (seakeeping and station-keeping)	As lower as possible compared to tolerable human accelerations : Heave acceleration – 0.05g Surge/Sway acceleration – 0.04g Roll heel angle – 2.5°				
Classification	G2 Service Area	G2 Service Area	G3 Service Area	G2 Service Area	G2 Service Area
Access System	Qualitative requirement. Decision driven by cost-benefit comparison between potential increased turbine accessibility (by increasing limit closer to Hs=2.5m) and probability of occurrence of Hs=2.5 m at site. Input required from T5.4a on wave spectra derived from a wave scatter diagram for the sites.				

Table 24 Vessel design criteria

4.2.11 Design Parameters for O&M Vessels

Service Vessels	.
Vessel Design parameters	
	Type
	Hull form
	Vessel Length
	Beam
	Draft
	Hull Depth
	Max. Deadweight
	Ice Class Notation
Hull Structural and General Arrangement parameters	
	Motion compensating platform
	Corrosion protection
	Aft deck area
	Deck area
	Max Deck Load
	Helicopter Deck

	Lifeboat platform
	Accommodation superstructure
Lifting appliances parameters	
	Crane Manoeuvrability
	Crane Capacity
	Crane cyclic loads
Operational parameters	
	Areas of operation
	Modes of transport
	No. of technicians
	Mobilisation speed
Environmental Parameters	
	Limiting wave length
	Helicopter Type
	All-year (annual)/Seasonality for each mode of
	Typical limiting significant wave height for vessel to
Vessel Performance parameters	
	Vessel Speed
	Passenger/Crew number
	Powering
	Propulsion type
	Auxiliary propulsion
	Seakeeping
	Stability in-place
	Dive support facilities
	DP capability
	Range
	Mobilisation speed
	Manoeuvrability
	Fuel Capacity
	Fuel Consumption
	Endurance
	Engine Cooling System
	Fresh water capacity
	Spare part capacity
Access System	
	Bow Height
	Vessel Thrust
	Bow Strength
	Bow fendering design
	Personnel Transfer system
	Boat landing clearance

Table 25 Design parameters for O&M vessels

4.3 Conclusions on Novel Service Vessel Concept Design and Access Equipment

In the early days of the sector, non-specialist vessels such as monohull fishing boats were used before it became apparent that these vessels were not suitable. As a result, the size, ability and design of WFSVs have evolved dramatically over the last five years. At the moment, catamarans of up to 20 metres in length are being used by crew transfer operators to service offshore wind farms. These current designs are suitable for sites relatively close to shore, where the limiting sea states and transit times from the closest safe haven to farm are not hard to meet.

As sites are being developed further offshore in more harsh environments, the requirement to widen the access window to offshore installations is becoming particularly crucial. Investments have been made by vessel designers, owners and operators in order to adapt existing vessels or develop innovative vessels to improve the weather windows in which the vessel can safely transfer technicians to the turbine.

The “bump and jump” method is becoming increasingly unsuitable especially when considering farms further offshore as transferring technicians to the turbine is currently the activity of most risk as a sudden rise or drop in wave height could potentially cause human injury or fatality thus this access method is gradually being phased out and replaced with dedicated transfer systems.

The overall target is to improve the accessibility of O&M vessels which can be accomplished by larger weather windows (through improved vessel RAO’s thus reducing the vessel heave/roll/pitch response), comfort of crew and higher work efficiency (by reducing sea sickness and staying injury free during an extreme event – thus reduced recovery time for technicians before turbine transfer).

Generally the factors to be taken into account regarding the utilisation of O&M vessels include:

- The weather conditions, more precisely metocean data, wave height, wind speed, current speed which influence the operability of a vessel, personnel safety and accessibility of offshore wind turbines
- The distance of the wind farm site to the O&M port determines in conjunction with the vessel’s transit speed the required journey time and therefore the working time on site (“technician time on turbine”)
- The water depth in the working area limits the suitability of MPVs than can be utilised in case jack-up MPVs are considered.

In conclusion speed and operability under rough sea conditions are critical for CTVs.

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5.1.3 Installation vessel fleet characteristics and particulars

Owner	Vessel Name	Vessel Type	Status	Flag	Yard	Year built	Length [m]	Breadth [m]	Draft [m]	Water Depth [m]	Cargo Area [m²]	Pay Load [t]	Main Crane Load	Crane Height [m]	Speed [knots]	Legs	Accommodation (people)	Dynamic positioning
A2Sea	Sea Power	Semi-Jackup	Operational	Denmark	-	1991/ 2002	92	22	4,3	24	1.020	2386	230 t@15m	-	7,8	4	16	None
A2Sea	Sea Energy	Semi-Jackup	Operational	Denmark	-	1990/ 2002	92	22	4,3	24	1020	2386	110 t@20m	-	7,8	4	16	None
A2Sea	Sea Jack	Jack-up Barge	Operational	Denmark	-	2003	91	33	5,5	30	2500	2500	800 t	-	-	4	23	None
A2Sea	Sea Worker	Jack-up barge	Operational	Denmark	-	2008	56	33	3,6	40	750	1100	400 t@17 m	-	-	4	22	None
A2Sea	Sea Installer	TIV	Operational	Denmark	Cosco (China)	2012	132	39	5,3	45	3350	5000	800 t@24 m	102	12	4	60	DP 2
A2SEA	Sea Challenger	TIV	Operational	Denmark	COSCO (China)	2014	132	39	5.3	45	3350	5000	900 t@24 m	102	12	4	60	DP 2
Bard	Wind Lift 1	Jack-up Barge	Operational	Germany	Western Shipyard (Lithuania)	2010	102	36	3,5	45	-	2600	500 t@31 m	121	-	4	50	DP 1
Besix	Pauline	Jack-up Barge	Operational	St. Vincent & G.	IHC Merwede (Netherlands)	2002	48	24	2,5	30	-	1500	200 t	-	-	4	-	-
DBB Jack-up Services	MV Wind	Jack-up Barge	Operational	Denmark	Rupelmonde (Belgium)	1995/ 2010	55	18	2,4	25	-	-	1200 t	100	0	4	0	DP 2
Geosea	Neptune	Jack-up Barge	Operational	Luxembourg	IHC Merwede (Netherlands)	2012	60	38	3,9	52	1600	1600	600 t@26 m	-	7,7	4	60	DP 2
Geosea	Goliath	Jack-up Barge	Operational	Luxembourg	Lemands (Belgium)	2008	56	32	3,6	40	1080	1600	400 t@15 m	-	-	4	12	DP 2
Geosea	Vagant	Jack-up Barge	Operational	Netherlands	IHC Merwede (Netherlands)	2002	44	23	4,2	30	-	1000	-	-	-	4	10	None
Geosea	Buzzard	Jack-up Barge	Operational	St. Vincent & G.	De Biesbosch (Netherlands)	1982	43	30	3	40	-	1300	-	-	-	4	8	None
Gulf Marine Services	GMS Endeavour	Jack-up Barge	Operational	Panama	Gulf Marine Services WLL(UAE)	2010	76	36	6	65	1035	1600	300 t	-	8	4	150	DP 2
Fugro Seacore	Excalibur	Jack-up	Operational	Vanuatu	HDW Kiel (Germany)	1978	60	32	2,8	40	-	1352	220 t@14 m	64	-	8	50	None
HGO InfraSea Solutions	Innovation	TIV	Operational	Germany	Crist Gdyna (Poland)	2012	147	42	7,3	50	-	8000	1500 t@32 m	120	12	4	100	DP 2
Hochtief	Thor	Jack-up Barge	Operational	Germany	Gdansk (Poland)	2010	70	40	8,3	50	1850	3300	500 t@20 m	-	-	4	48	None
Hochtief	Odin	Jack-up Barge	Operational	Germany	Crist Gdyna (Poland)	2004	46	30	5,5	35	-	900	300 t@15 m	-	-	4	40	None
Jack-Up barge B.V.	JB-114	Jack-up HLV	Operational	Bahamas	Labroy Shipping (Singapore)	2009	56	32	3	40	-	1250	300 t@16 m	-	-	4	-	None
Jack-Up barge B.V.	JB-115	Jack-up HLV	Operational	Bahamas	Labroy Shipping (Singapore)	2009	56	32	3	40	-	1250	300 t@16 m	-	-	4	-	None
Jack-Up barge B.V.	JB-117	Jack-up HLV	Operational	Bahamas	Labroy Shipping (Singapore)	2011	76	40	3,9	45	-	2250	100 t@22 m	-	-	4	-	None
KS Drilling	Titan 2	Jackup Barge	Operational	Panama	Semco Shipyard Lafitte, LA(US)	2007	52	35	2,9	40	-	-	176 t@12m	-	7	3	-	-
MCI	LISA A	Jackup	Operational	Panama	Kaiser Swan, Portland(US)	1977/ 2007	73	40	4	33	1000	950	425 t@18m	80	-	4	40	None

Owner	Vessel Name	Vessel Type	Status	Flag	Yard	Year built	Length [m]	Breadth [m]	Draft [m]	Water Depth [m]	Cargo Area [m^2]	Pay Load [t]	Main Crane Load	Crane Height [m]	Speed [knots]	Legs	Accommodation (people)	Dynamic positioning
Master Marine	NORA	Jackup	Operational	Cyprus	Drydocks World Graha (Indonesia)	2012	118	50	7,4	50	2500	7200	750 t@29m	-	8	4	260	DP 2
Muhibbah Marine	MEB JB1	Jackup Barge	Operational	Germany	HDW Howaldswerke (Germany)	1960/ 1995	49	31	3	30	748	-	272 t @14m	-	-	8	20/60	GPS
RWE Innogy	Victoria Mathias	TIV	Operational	Germany	Daewoo (South Korea)	2011	100	40	4,5	40	-	4200	1000 t@21m	110	7,5	4	60	DP 2
RWE Innogy	Friedrich-Emestine	TIV	Operational	Germany	Daewoo (South Korea)	2012	109	40	-	40	-	4200	100 t@21m	110	6,4	4	60	DP 2
Sea Jacks	SeaJacks Kraken	TIV	Operational	Panama	Lamprell (UAE)	2009	76	36	3,7	41	900	1550	300 t@16m	-	8	4	90	DP 2
Sea Jacks	SeaJacks Leviathan	TIV	Operational	Panama	Lamprell (UAE)	2009	76	36	3,7	41	900	1550	300 t@16m	-	8	4	90	DP 2
Sea Jacks	SeaJacks Zaratan	TIV	Operational	Panama	Lamprell (UAE)	2012	81	41	5,3	55	2000	3350	800 t@24m	-	9,1	4	90	DP 2
Swire Blue Ocean	Pacific Orca	TIV	Operational	Cyprus	Samsung H.I. (South Korea)	2012	161	49	6	70	4300	6600	1200 t@31m	118	13	6	111	DP 2
Swire Blue Ocean	Pacific Osprey	TIV	Operational	Cyprus	Samsung H.I. (South Korea)	2012	161	49	5,5	70	4300	6600	1200 t@31 m	118	13	6	111	DP 2
Workfox	Seafox 7	TIV	Operational	Isle of Man	Labroy Shipping (Singapore)	2008	75	32	3,4	40	700	1120	280 t@22m	-	-	4	113	None
Workfox	Seafox 5	TIV	Operational	Isle of Man	Keppel Fels (Singapore)	2012	151	50	10,9	65	3750	6500	1200 t@25m	-	10	4	150	DP 2
MPI/Vroon	MPI Resolution	TIV	Operational	Netherlands	Shanhaiguan (China)	2003	130	38	4,3	35	3200	4875	600 t@25 m	95	11	6	70	SDP-11
MPI/Vroon	MPI Adventure	TIV	Operational	Netherlands	Cosco (China)	2011	139	41	5,5	40	3600	6000	1000 t@26m	105	12,5	6	112	DP 2
MPI/Vroon	MPI Discovery	TIV	Operational	Netherlands	Cosco (China)	2011	139	41	5,5	40	3600	6000	1000 t@26 m	105	12,5	6	112	DP 2
Weeks Marine	RD MacDonald	Jackup Barge	Operational	US	Jacksonville, FL	2012	79	24	4,4	22	955	2300	680 t@43m	46	-	8	-	-
Fred. Olsen Windcarrier	Brave Tern	TIV	Operational	Malta	Lamprell (UAE)	2012	132	39	6	45	3200	5300	800 t@24m	102	12	4	80	DP 2
Fred. Olsen Windcarrier	Bold Tern	TIV	Under construction	Malta	Lamprell (UAE)	2013	132	39	6	45	3200	5300	800 t@24m	102	12	4	80	DP 2
Hochtief	Vidar	TIV	Under construction	Germany	Crist Gdyna (Poland)	2013	137	41	6,3	50	3400	6500	1200t @28m	-	10	4	90	DP 2
Van Oord	Aeolus	TIV	Under construction	Netherlands	Sietas (Germany)	2013	139	38	5,7	45	-	6500	900 t@30m	120	12	4	74	DP 2
SeaJacks	Seajacks Hydra	TIV	Under construction	-	Lamprell (UAE)	2014	-	-	-	48	900	3350	400 t	-	-	4	90	DP 2
DBB Jack-Up Services	Wind II	TIV	Under construction	-	Nordic Yards (Germany)	2014	80	32	-	45	-	-	-	-	-	4	-	DP 2
Inwind	INWIND Installer	TIV	Concept	-	-	-	101	68	4,5	65	3500	4500	1200 t@25m	105	-	3	90	DP 2
Gaoh Offshore	Deepwater Installer	TIV	Concept	-	STX (South Korea)	-	140	40	6,5	50	6000	10450	1600 t@20m	105	10	4	120	DP 2
Scaldis Salvage & Marine Contractors N.V.	Rambiz 4000	HLV	Under construction	Belgian	STX Qidong and Xiamen yards in China	2014	108	49	4.9	No jacking	-	3000	4000 @ 78.5 m	90	7	None	78	DP2

5.1.4 Feedback From Industry Stakeholders that informed the definition of design requirements for Installation vessels.

Interview and Workshop between LR and A2Sea

<u>Questions and Feedback</u>

- What were the driving factors behind Sea Power's upgrade in 2012? Were higher lifting height and crane capacity increased in order to make the vessel more suitable for installing larger turbine components or pre-assembled parts (i.e. complete rotor) in one single lift operation?
- Driving reasons were the Anholt farm, as the vessel had to reach further up to place? nacelle and blades. Hub height was 81.6 metres. Crane boom would be required if a higher lifting capacity was the target. The shipbuilder was asked to increase crane capacity. The upgrade was specific for this project and the vessel could also be employed for further maintenance tasks. This vessel has installed most of the turbines in this site.

- How was Sea Power's suitability assessed for transit after upgrade?
- The developer carried out a soil analysis for the full range of turbines that they had installed previously with that vessel to ensure suitability.

- What are the timescales for a typical installation operation and where could time reduction be achieved easier?
- Timescales are very difficult to estimate. Transit times cannot easily be optimised. Turbine installation takes typically up to a day, depending on the weather window.

- Have afloat intact and damage stability performance and jack-up elevated loads been re-assessed following the upgrade?
- Compliance with coastal regulations had to be undertaken for operation in Danish water. Also design approval had to be approved by DNV.

- Has the limiting sea state for transit afloat been re-defined or remained un-changed?
- Transit limits reduced to wave height of 2.5 m due to having a side blade rack. Stability became an issue but only due to the blade rack.

- When is the floating mode used for TIVs?
- Floating is normally used only in harbour and sheltered areas, it would not be used in installation activities.

- What were the driving factors behind Sea Jack's leg extension? Was the increasing of the jacking wave limit or the ability to access deeper waters the targets?
- Yes, the driving reasons were to access deeper waters.

- Have the payload capacity and allowable deck load seen any significant drops after the upgrade? If yes, how have they been counter-acted?

- No significant drops in payload capacity or deck strength however more focus needs to be on lifetime extension and fatigue.

5.1.5 Feedback From Industry Stakeholders that informed the definition of design requirements for Service vessels.

Arklow Marine Services (AMS)

Feedback provided by AMS is extremely beneficial to LEANWIND, especially interviews carried out with skippers and other relevant industry contacts that currently operate O&M vessels. This allowed the design requirements to be informed by "real-world" data and also the future optimisation of vessels selected through TRL to be based on critical issues experienced over years of operating service vessels.

Critical outputs from the interviews that impact the O&M vessels requirements include:

- Regarding crew transfer to turbine: experience of skippers and training is essential.
- Organisation from shore is quite often poor and leads to the vessel having to transfer in bad weather. A lot more shore cooperation and planning is essential.
- Vessel design: better vessel layout is required especially regarding bow fenders and shock absorption, more deck storage for parts and equipment, better storage for waste oil and easier access to engines. Also visibility from wheel house and stowage for technicians' belongings has been highlighted as aspects to affect the efficiency of the crew operating the vessels.

Therefore highlighted key requirements that will be considered as part of the vessel design optimisation or concept designs later on within the project will include:

- Bow fendering is essential and choice is critical; reliability and vessel strength
- Improved crew training for skippers.
- Vessel weight to be considered as it impacts the cargo capacity and manoeuvrability.
- Better organisation from shore and planning.
- Better facilities for vessels when in port.
- Fuel consumption is increasingly becoming an issue of concern for service vessels recently.

Table A1 Feedback from Vessel skippers

	Areas of your work you think work well.				Areas for improvement		Far offshore wind farms			Cost reduction		Requirements
Base	Crew transportation	Work Schedule	Tools	Parts/ Equipment	Crew transportation	Tools/ plant	Work patterns for technicians	Shift time	Problems	Time waste	Cost waste	
Ramsgate Lon. Array	Good skipper with existing systems. Nothing else required	Safety issues & vessels being forced to sea. Team leader. some 5 minute & some all day.	Working with cable layers a lot of gear on deck. 2/3 tons.	More through from shore side. More communication with skippers. Cages on deck for carrying bottles etc. fuel.	Skipper experience and control.	Planning & organization by shore control. DP in bigger boats over 30mtrs but time constraint	Must be mother after 40 mls.	12 hours. with accommodation onboard. 12 hours. with max 7 days out on mother ship.	crew changes & not being able to rotate on 12 hrs. to mother ships.	weather? Not having Again bad organization	fuel consumption Hull design.	Fendering, reliability, vessel strength.
All over.	Fender and more protect Shock absorption	Seasick. Bad shore Organization	Storage and more storage 2 tonnes minimum	Organizing ashore	fender bigger fridge	S/S on front face of pipes	will revert			Org & wealth	planning ashore	Better crew training for skippers. Skippers with yachtmaster tickets driving boats with 3000 hp - not on.
All over.	A good skip again with existing systems	Shore co-ord	More stowage Lashing pts. Gear boxes.	Better plan from shore.	Gummy fender. More expert skippers & boat handling	Better vessel lay out. Visibility from wheelhouse.	no idea - but DP will not work - too much time.	12 hours - with mother ship.	Weather. Reliability.	More org. ashore. techs not with right gear	Driving boats too hard. Vessel design.	Vessel weight, more org from shore and not forcing vessels to sea just to look good.

All over	Experience in skippers is essential.	Told to go in bad weather. Work allocation to techs. A lot more shore co-ord.	HP washing. Fuel transfer. Deck crane not required More stowage. space.	More communication with skippers from shore co-ord.	Better bow fenders with shock resist.	Maybe vessels should have tool store on board to suit contract.	Cannot see how it will work. Mother ships - but then how to transfer.			Organizing ashore of day schedules	planning vessels speeding	
All over & at present in Germany.	Experienced skippers with the right boat.	Some O&M very good others are a disaster.	Co-ord as to what tools for the work they are going to - again shore co-ordination.	Needs more consideration from shore personnel.	Crew training	Waste oil Oil storage. Easier access to engines. Stowage for tech. bags.	Over 40 miles mother vessel. Tech sea sick	12 hrs. max for techs	Weather. Crew change.	Better coordination ashore. Techs bring correct gear.	Planning ashore. Vessel speed	Better facilities for vessels when in port. Bow fender is very important and choice is critical. Technicians bring with them all necessary gear after toolbox talk each shift start. Crew who will look after their boat & maintenance.

Feedback from LR

Certain concerns raised by the skippers such as better facilities for vessels in port and better shore organisation could be generally addressed for service ships operating from various ports to various wind farm sites therefore they are not viewed as basic design driving criteria. Improving these aspects would not have a visible direct reduction in LCOE and could incur higher build costs but on the other hand could in fact increase work efficiency of turbine maintenance personnel.

However comments including: need for more storage, vessel speed, “driving boats too hard”, fuel consumption, deck arrangement and hull strength could be better materialised into basic design requirements if they could be linked to operational profiles. For example, fuel consumption could become a driving criterion especially for fast service/emergency response vessels only if common breakdown activities can be identified against operations a vessel must perform for a farm location/port to operate from/to (i.e. Long waiting times idling the engine, transit trips back to port for parts/tools where a fuel efficiency optimisation could make a tangible impact).

Relevant feedback from interview with Mr. Hernan Vargas (O&M Engineer) , Vattenfall Wind Power

- Availability is low in the UK, high presence of O&M fleet in Germany at the moment
- UK Round 3 was expected between 2017-2019, however now it is expected around 2019 onwards to ramp up
- Concerns for Vattenfall: weather windows are important, it is recommended ideally to select a summer weather window as this would provide significant benefits to O&M costs
- Water depth is increasing due to wind farms located further offshore
- At present 1.5 m is the limit for Hs (health and safety limitation). Can go up to Hs = 2 m.
- Service vessels need to operate in shallower waters on UK farms, thus jet propulsors are more appropriate as they provide better manoeuvrability but as a downside they lose bollard pull compared to FPP’s (fixed pitch propeller).
- Turbine spare logistics is the responsibility of wind turbine suppliers, as part of warranty (normally 5 years)
- Site developer covers Balance of Plant (e.g. – transporting of cargo for accommodation platform) then Vattenfall charter the vessels on a yearly-basis.
- There is currently a gap for vessels capable to carry more spare parts, around 20 tonne payload capacity at the moment. Demand for vessels featuring 30-40 tonne cargo capacity plus personnel is high.
- PSV’s (platform supply vessels) could fill this gap as they could carry spares, waste, perform balance of plant jobs, survey work but ideally around 30 m length as they would need to push against turbine and cope with weather in German waters. Also DP2 capability with access systems on PSV’s would be highly beneficial.
- PSV’s are normally available in the spot market, if they are smaller vessels and not on the spot market, then they could be chartered on yearly-basis.

- CTV's work 12h shift at the moment, no night operations. Possibility of night operations should be explored.
- Carbon Trust O&M CTV's performance plot could be beneficial, as it utilises multi-dimensional inputs, rather than rely only on Hs.
- Site developers are more likely to subcontract O&M in longer term perhaps
- In terms of logistics, contracts state that spare parts must be ready for jack-up vessels at Load-out

Relevant feedback from interview with Mr. Sol Judah ,Senior Technical Lead, Global Maritime, formerly SSE

- Regarding turbine repairs, a contract between the farm operator and turbine manufacturer supplies a 5-year warranty. Turbine manufacturers are now asked to provide reliability data for the first 5 years.
- SSE are planning to use bigger DP2 vessels for maintenance campaigns. Vessels will keep station on DP with a dozen technicians onboard.
- For large maintenance operations (e.g. Drivetrain/Bearings failure) large jack-up vessels would normally be employed.

Relevant feedback from interview with RES Offshore

- Do you have knowledge of typical transit times to/from home harbour/load-out port to wind farm site for self-propelled ships, self-propelled barges, towed barges and service small craft performing O&M operations?

– Self-propelled ships – 10 Knots
– Self-propelled barges – 7 Knots
– Towed barges – 4 Knots
– CTV's – 20 Knots

Obviously this depends on how far from the operational ports the wind farm is – the above are suggested transit speeds only.

Transit times depend on the site, then speed is very important. CTV's average is 20 Kn but can do 25 Kn in very calm seas.

– Jack-up barges – 12-14 Knots
– Heavy lift vessels – 4 Knots

Industry has been trying to use smaller vessels for component lifting. For example: Rambiz sheerleg crane vessel has a limiting Hs = 1.2 m on crane curves. Downtime can be very long.
Therefore cheapest vessels are not necessarily cheapest to operate due to downtime.

- What is the typical lead time to prepare a vessel for O&M operations once a suitable vessel has been identified (i.e. for logistics/turbine components/spare parts supply planning, site-assessments prior to mobilisation)?

– Depends on the type of vessel and the job at hand.
– A jack-up, given availability, could be ready for O&M repair in 5 days at base port. However, should there be a need for specialised equipment and/or special design sea fastening it could take several weeks.
– The method statements and associated paperwork approval can be covered in a couple of weeks if it is a failure, but generally can take several weeks to go through the review systems of companies and MWS

- What are the typical charter rates for a jack-up vessel to be used on O&M phase if long-term charter agreements are not used?

– Would work on £130k/day manned and equipped for turbine repair.

- Could you provide approximate deployment costs for O&M operations for example between the North Sea and West Coast of the UK ? How long would the transit route take, what would the operational costs (fuel, port fees, sea fastenings, site-assessments)?

– Mobilisation to English east coast is generally 2 days from say Vlissingen in the Netherlands and 6 days to west coast at the day rate quoted above

- What availability will help reduce costs in industry?

– Any. Availability is affected by marine companies willing to build this type of vessels.

- Are short-term contracts using spot market rates favoured over long-term chartering at the moment?

– For O&M long-term charter is not a viable option until the farms become much bigger.

- How is the lost production revenue (through any turbine downtime) balanced with the market state (spot rates vs. long-term charter rates which would rive mobilisation costs)?

– Generally the speed of repair is the vital issue – if a turbine has gone down there could well be possible failure of others to be considered – turbines locked for long periods have issues.

- How does the industry assess and mitigate risks arising from the use of heavy-lift jack-up vessels during O&M phase (i.e. mobilisation/deployment costs and weather delay risk)? How is a single turbine repair tackled?

– Maintenance programmes – prevention is better than cure. Some operators have call-off agreement with contractors ensuring quick response times.

- How is the suitability for a jack-up vessel assessed? Is a site-specific assessment carried out?

– Yes, an assessment is made for the best resource for each repair.

Relevant feedback from interview with IBERDROLA

- What are the operational limits in terms of sea state (wind speed, significant wave height and peak period) would be ideal in order to access the turbine for preventive, minor corrective actions activities?
- – As per IBERDROLA's understanding, the main parameter that leads transit operation by Crew Transfer Vessels or workboats is the wave height. In this sense, we can suggest 1.5 m for monohull and up to 2.5 for catamarans, although there are several studies trying to increase (or reach) these limiting wave heights.
- – Acceptable transit time is normally around 60 up to 80-120 minutes, so transit speed has to be also considered.

Relevant feedback from interview with Mr. John Kecsmar , CEng Naval Architect, Ad Hoc Marine Designs Ltd

Questions and points raised by LR :

- The main requirements for wind farm O&M vessels we have identified so far are the maximum Hs, Transit Speed, Deck space and Strength, Payload capacity, Max. lifting capacity if crane fitted and personnel Transfer and Access System. Researching Adhoc Marine's website has shown that serious emphasis has been on catamaran and SWATH hull forms, thus Mr. Kecsmar's expert opinions on how these concepts fulfil the new challenges faced by future/further site developments have greatly informed design requirements within LEANWIND.

- The main challenges for service vessels identified are :

- – Reducing motion to increase accessibility in larger sea states (through optimised vessel RAO and motion compensating access systems)
- – Increased fuel efficiency
- – Reducing sea sickness and its detrimental effect on maintenance crew's work efficiency
- – Establishing optimum vessel size and hull form type for varying distances from shore

- Does the 'Autobrow' concept allow for roll motion compensation or is the vessel usually positioned in head seas and then the Autobrow platform rotated? Also does the vessel's underdeck structure require significant strengthening to accommodate the Autobrow?

- Do you have knowledge of the required weather windows and also expected effective day rates?

Feedback from AdHoc Marine Designs:

- The wind farm industry has been evolved a lot over the past 3-5 years. Initially any boat, literally, would do. A boat could go from A to B and carry a few passengers with a bow that allows the technicians to do basic maintenance of turbine towers. These towers were all inshore just around 5-15nm from shore. Thus any workboat "fit the bill". As the fields grew they also started going further from the shore up to 20-50nm. Therefore the requirements of the vessel also changed from just a simple in and out to traversing a greater distance and several times between each tower and with going further offshore the sea states started to play a factor. Therefore, the role of vessel, also changes from one that just carries passengers with "some tools", to one that performs heavy maintenance remaining several hours on the spot. Spare generators being carried, ISO containers carried, large cranes fitted with more kit and also what has now become the norm, multi-functionality.

- The days of "just" a workboat no longer apply as the vessels are required to perform many different tasks now. It helps to widen the appeal of the operator rather than being just a "one trick pony"! Thus the design of the vessels have changed to suit this every changing roll, now also with cabins for sleeping for the crew, owning to the distances and long working days.

- To make matters more complicated the "design" of the boat has shifted. The typical workboat and the companies that supplied such (like the old South Boats before it changed hands) have been swamped by the companies that have been desperate for work since the global downturn of 2008/2009. Large companies that used to build/design plenty of fast ferries and/or patrol boats have been struggling for orders. Thus they have muscled into the wind farm market. They, just like supermarkets dictating to their client what they can or cannot buy, have shifted the designs more to suit the yard's production to maximise their profit than a "tailor made design" for the client in reality, since the profit margins on small boats is not large. Thus the best way to maximise this is to simplify the designs and construction used by the larger boat markets which has yet to take hold in the smaller workboat markets.

- The operators are also subsidised by the Government with their fuel, thus their fuel running is oddly enough not a major concern.

- At the moment the designs being offered are centred around maximising the profitable DCR on a sub 24m boat.

- Regarding the Autobrow system, it was designed back in the days when the vessels were simple and had only 1 or 2 functions. It followed on from several brow designs Adhoc Marine have done in the past from the first in 1997/8. The main issue now is that with these still sub 24m vessels, they all carry generators and/or ISO containers on the fore decks and some on the aft too. Thus there is no space for the Autobrow on a multifunction vessel these days – the access platform height is also high(for the hydraulics) which renders line of sight issues for the Captain too. It is fine for larger vessels but now it is a hindrance for smaller vessels which we were not anticipated some 4-5 years ago. There is not simply the space. These vessels push up hard onto the tower and with a special shaped fender with a nib "fit" into a small space between small tubes on the tower. This "holds" the vessel to an extent. Thus any beam seas to be either minor effect as the nib holds the boat or can actually be major as the bigger beam seas move the boat too much. Thus roll is either minor or major. The Autobrow is not really designed for major rolling, the system becomes a bit more complex then. The first brows Adhoc Marine designed were sited on the bean-side of the boat, not on the bow. Thus roll, pitch and heave is experienced as pure vertical motion, an easier proposition.

– SWATH's are in Mr. Kecsmar's opinion the only type of vessel that will eventually work in such harsh offshore farms too. They can carry the same payload as catamarans but to do so they need to be a bit bigger, which presently most clients are reluctant to pay for, for the above said reasons. But going further offshore a higher DCR can be found which would allow SWATH's to be viable. Technically it is not difficult at all, it is just a willingness to accept the change.

6. References

[1] Data supplied by the Natural Environment Research Council via the BODC (https://www.bodc.ac.uk)
[2]http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.]Accessed April 2015]
[3] S. Hawkings, "A High Resolution Reanalysis of Wind Speeds over the British Isles for Wind Energy Integration," University of Edinburgh, 2012
[4] © Crown copyright, 2014. Available from www.cefas.defra.gov.uk. Accessed July 2014
[5]Sanjeev Malhotra, Parsons Brinckerhoff Inc., USA – "Selection, Design and Construction of Offshore Wind Turbine Foundations" http://cdn.intechopen.com/pdfs-wm/14804.pdf
[6] http://orbit.dtu.dk/ws/files/55645274/The_DTU_10MW_Reference_Turbine_Christian_Bak.pdf [Accessed 04/03/15]
[7]http://www.swayturbine.no/ [Accessed 04/03/15]
[8]http://www.diva-portal.org/smash/get/diva2:648694/FULLTEXT01.pdf [Accessed 27/02/15]
[9]IEC 61400-3 – "Wind turbines – part 3, Design requirements for offshore wind turbines" (11 Feb 09)
[10] Ms. Elena Reig Amoros, ACCIONA (2015) – "Correspondence regarding the preliminary parameter estimation of gravity-base foundations" [E-mail correspondence]. Personal communication (24 Apr 2015)
[11]"Offshore Foundations – KAREHAMN Offshore Windfarm Foundations" – Presentation , Offshore Wind Power Workshop (Sweden), Carl HEIREMANS, Madrid 2014
[12] "Gravity Based Foundations for the Thornton Bank offshore wind farm" – Presentation, Kenneth PEIRE, Hendrik NONNEMAN and ERIC BOSSCHEM, Terra et Aqua, No. 115, June 2009
[13] "Kriegers Flak offshore wind farm. Gravity based"- Conceptual Design report, COWI March 2009.
[14]Dr.Marc Seidel, Senvion SE, Germany – "Substructures for offshore wind turbines – Current trends and developments", Hannover 2014 http://www.marc-seidel.de/Papers/Seidel_Festschrift_Schaumann2014.pdf [Accessed 04/03/15]
[15] Wind Energy Update – "Substructure Trends and Developments" http://www.windenergyupdate.com/offshore-wind-structures/ [Accessed 04/03/15]
[16] http://www.rechargenews.com/news/technology/article1298441.ece [Accessed 04/03/15]
[17] http://www.smartwind.co.uk/gallery-item.aspx?phst=72157629489880150 [Accessed 04/03/15]
[18]http://www.offshorewind.biz/2013/04/25/scotland-launches-gbp-15-million-fund-for-innovative-offshore-wind-foundation-projects/scotland-launches-gbp-15-million-fund-for-innovative-offshore-wind-foundation-projects/ [Accessed 04/03/15]
[19]http://www.theengineer.co.uk/energy/news/offshore-windfarms-look-to-suction-buckets-for-easier-installation/1019167.article [Accessed 04/03/15]
[20]http://www.offshorewind.biz/2014/04/30/first-floating-wind-turbine-in-germany-to-get-eur-5-25-mln/ [Accessed 04/03/15]
[21]http://www.coriolisenergy.pl/en/news/the-succes-of-floating-turbine-wind-plus

[22]Mark J. Kaiser, Brian F. Snyder – "Offshore Wind Energy Cost Modelling – Installation and Decommissioning", 2012
[23]S.Zhang & J.Ding, State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University – "Comparison and Analysis of Economy of Wind Turbine Installation Vessels",
[24]http://www.marinewiki.org/index.php/SHIP_DESIGN_PROCESS [Accessed 15/04/15]
[25]http://www.vesseltracker.com/cn/ShipPhotos/296263-BULL%20RAY-296263.html [Accessed 10/02/15]
[26]http://www.seatrax.com/news.html [Accessed 10/02/15]
[27]http://www.maritimejournal.com/news101/marine-renewable-energy/operators-respond-to-wind-farm-demand [Accessed 10/02/15]
[28]http://www.shipspotting.com/gallery/photo.php?lid=271898 [Accessed 10/02/15]
[29]http://www.offshorewind.biz/2013/11/12/germany-seajacks-nearing-completion-of-meerwind-owf/ [Accessed 10/02/15]
[30]http://www.hgo-infrasea-solutions.de/assets/pdf/Fact-Sheet.pdf
[31]http://www.shipspotting.com/gallery/photo.php?lid=1460354 [Accessed 10/02/15]
[32] http://www.semar.no/sider/tekst.asp?side=127&submeny=ingen&niv2=
[33] http://www.offshorewind.biz/2014/06/24/a2sea-celebrates-sea-challenger/ [Accessed 24/04/15]
[34] http://paulduann.com/blog/2010/06/seajacks-kraken/ [Accessed 24/05/15]
[35] http://www.scheepvaartwest.be/CMS/index.php/dredgers-workboats/1156-buzzard [Accessed 24/05/15]
[36]http://www.shipspotting.com/gallery/photo.php?lid=1257055 [Accessed 24/05/15]
[37] http://www.heavyliftspecialist.com/tag/offshore-wind/ [Accessed 24/05/15]
[38]Mr. Jens Moller Christensen, A2SEA (2015) – "Discussion on specifications of vessels in A2SEA's fleet" [Conversation]. Personal Communication and data exchange (10 Feb 2015)
[39]http://www.high-wind.eu/boomlock/ [Accessed 04/03/15]
[40] Federation Europeenne de la Manutention – Guideline on "Safety issues in Wind Turbine Installation and Transportation" (25 Oct 12)
http://www.vertikal.net/uploads/tx_filelinks/fem_5_016_121112.pdf
[41]http://www.vroon.nl/Files/VesselParticulars/MPI%20RESOLUTION20130507100532.pdf
[42]Mr. Sol Judah , Global Maritime (2014) – "Discussion on installation vessel design requirements" [Conversation]. Personal Communication (06 Oct 2014)
[43]http://www.herculesoffshore.com/documents/BULLRAYSpec131306.pdf [Accessed 10/02/15]
[44]http://www.laurensphotos.com/Windfarm%20Gallery/pages/Monopile%200149.htm
[45]EWEA – "The European offshore wind industry – key trends and statistics 2013", January 2014
[46]http://www.kem-offshore.dk/forside_s1.html [Accessed 04/03/15]
[47]http://www.4coffshore.com/windfarms/vessel-gaillion-fvid1001.html [Accessed 04/03/15]
[48]http://www.nauticexpo.com/prod/incat-crowther/logistics-transport-boats-34070-379795.html [Accessed 25/02/15]
[49]http://www.ctruk.com/products-and-systems/SWATH20 [Accessed 25/02/15]

[50]http://www.dredgingtoday.com/2012/06/29/belgium-deme-subsidiary-inks-northwind-contract/ [Accessed 25/02/15]
[51]http://www.maritimejournal.com/news101/marine-renewable-energy/activity-gathers-pace-at-london-array [Accessed 25/02/15]
[52]http://www.esvagt.com/fleet/wind-service-operations-vessels/esvagt-supporter/ [Accessed 25/02/15]
[53]FAROS project, Human Factors in Risk-Based Ship Design Methodology – "Quantitative models of crew performance linked to ship motions", Deliverables D3.2 and D3.3
[54]http://www.windpoweroffshore.com/article/1190930/clever-concept-arevas-wind-service-model-adapts-varying-offshore-demands [Accessed 25/02/15]
[55]http://www.ulstein.com/Kunder/ulstein/cms66.nsf/pages/newslista.htm?open&disp_key=b770d8f302689e7fc125777e00317708&dato_start=196 [Accessed 26/02/15]