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Preface

This is a 30-credit point Master thesis written as part of the pre-requisite for the award of Master of Maritime Operations degree (Offshore and Subsea Operations Specialization) at the Western Norway University of Applied Science, Haugesund, Norway. The thesis research was conducted as part of the DECOM Tools project for Wind turbine decommissioning. DECOM Tools is funded by EU and is part of the *"Interreg VB North Sea Region programme".*

A novel conceptual design of vessels for offshore wind turbines decommissioning was presented. The design concept used was the System-Based Ship Design and it address the need to sustain the Offshore wind turbines (OWTs) DECOM tasks through reduction of vessel cost, safety and efficient operations. There are two proposed model of vessels in this thesis; the floating, processing, storage vessel (FPSV) and a jack-up, processing, storage vessel (JPSV) respectively. The two models operate based on the principles of recycling or mechanical deformation/compression of wind turbine components into sheets, plates or scrap bale prior to storage. This technique will ensure effective space utilization. Therefore, transit time and cost are minimized. It is my hope that the wind turbines decommissioning industry would find the concept in this report useful and economically viable to invest.

The support of my internal supervisor, Professor Jens Christian Lindaas is highly appreciated for linking me with DECOM Tools community and scholarly guidance. I also thank Professor Andreas Olivares Lopez for giving me an insight into the project scope.

Finally, many thanks to the local and international companies whom despite their tight schedule and the pandemic situations responded to my research interview questions. I sincerely appreciate the supports of Mr. Andries Ferla (DEEPOCEAN, Haugesund, Norway) and Mr. Tony Ferns (HEEREMA Group, Leiden, Netherlands).

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Abstract

Offshore wind energy is an important source of power and has an abundant volume of reliable clean energy. The installation and decommissioning of offshore wind parks do require elaborate project planning for safety and cost implications. Meanwhile, the research under investigation was on the vessels required for offshore wind parks decommissioning. A conceptual design of the decommissioning vessels was proposed to ensure sustainability, efficient, safe, and economically viable offshore wind park operations. The concept was referenced in line with the existing wind turbine installation vessels (MPI resolution) i.e. the jack-up vessels and the Floating production storage and offloading (FPSO) vessels used in the oil and gas industry. The decommissioned turbines would be plastically deformed or processed mechanically into metal sheets or plates (i.e. increased surface area) then store in the storage chamber. These unique methodologies would ensure maximal usage of deck space, the volume of the chamber and reduce vessel logistic cost especially when decommissioning offshore wind parks with a large number of turbines of at least 100 units

Furthermore, the Thanet offshore wind park decommissioning project was taken as a case study and references made to the specific turbine parameters e.g. weight, height, and configuration of components, field characteristics i.e. (weather condition), vessel requirements, operations sequence, etc. The proposed conceptual vessel design for decommissioning tasks has a capacity to remove, lift, store and transport at least 20 wind turbines to the port after the components have been processed to sheets or scrap plates for vessel space management. The main advantage of this vessel is the reduction in project or operations time and cost. The two models of vessels suggested for the decommissioning operations were the floating, processing, and storage vessels (FPSV) and jack-up, processing, and storage vessels (JPSV) respectively.
It is envisaged that the two models met up with the technical, functional, and operational requirements in an efficient and sustainable manner.

Acknowledgement

I want to acknowledge the support of my supervisor, Professor Jens Christian Lindaas for his guidance, a wealth of experience on the researched topic, warm reception, supports, and understanding all through the period of writing this thesis. His unflinching motivation, advice, and feedback have sharpened my thought and widen my horizon in the field of offshore wind energy operations.

Furthermore, I appreciate the support of my beloved better half and children for their understanding especially at challenging and critical times. Finally, I thank my extended family and in-laws for supporting my dream and ensuring it becomes a reality.

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Abbreviation

ABS	American Bureau of Shipping
AHTV	Anchor Handling Tug Supply Vessel
API	American Petroleum Institute
ATB	Articulated Tug Barge
AIS	Automatic Identification System
AUV	Autonomous Underwater Vehicles
CAPEX	Capital Expenditure
CB	Construction Barges
COVID-19	Corona Virus Disease 2019
DSV	Diving Support Vessel
DNV	Det Norske Veritas
DP	Dynamic Positioning
DT	Dynamic Tracking
ECDIS	Electronic Chart Display and Information Systems
EIA	Environmental Impact Assessment
EU	European Union
EWEA	European Wind Energy Association
FSV	Field Support Vessel
FPSV	Floating Processing and Storage Vessel
FPSO	Floating Production Storage and Offloading
HLV	Heavy Lift Vessels
ITB	Integrated Tug Barge
IACS	International Association of Classification Societies
IMO	International Maritime Organization

JPSV	Jack-Up, Processing and Storage Vessel
KPI	Key Performance Indicators
MVA	Mega Volt Amp
NDT	Nondestructive testing
NEA	Norwegian Environmental Agency
MPE	Norwegian Ministry of Petroleum and Energy
NPD	Norwegian Petroleum Directorate
OSV	Offshore Support Vessels
OWT	Offshore Wind Turbine Decommissioning
PTV	Personnel Transfer Vessel
PSA	Petroleum Safety Authority
PLEM	Pipeline End Manifold
PLET	Pipeline End Termination
PLC	Programmable Controller
RAO	Response Amplitude Operators
ROV	Remotely Operated Vehicle
SDU	Subsea Distribution Unit
SV	Supply Vessel
TIV	Turbine Installations Vessel
UTA	Umbilical Termination Assembly
WTIV	Wind Turbine Installations Vessel
Xmas Tree	Christmas Tree

Nomenclatures

$	Dollars
h	hour
mm	millimeters
kn	Knot
nm	Nautical mile
ADJTRIP, h	Weather adjusted time per trip;
ADJTURB	Weather adjusted time per turbine
COST, $	Total project cost ($)
CUT, h/m	Time to cut the foundation
D, m	Pile diameter
D, nm	Distance to port
F_n	Froude number
JACK-UP, h	Time to stabilize on site
L_{pp}	Length between perpendiculars [m]
L, h	Off-loading
LIFT, h	Time to lift the foundation and place on a barge
LOAD, h	Total off-loading time
M	Move to another field location
M, h	Intra-field movement times per turbine
MOVE, h	Time to jack the vessel down and move to the next foundation
MOVE, h	Total per-trip intra-field movement time
NUMFOUND	Number of foundations

NUMTRIP	Number of trips
NUMTURB	Number of turbines
PUMP, h	Time to pump mud from the foundation
R	Time to remove a turbine
R, h	Removal
REMOVE, h	Total per-trip removal time
REMTIME, h	Removal time
S, kn	Speed of vessel
SDR	Spread day rate
SDR, $/day	Spread dayrate
STABILIZE, h	Time to stabilize at the foundation and move to the next foundation
TDC, $/day	Total daily cost
TDC, $/day	Total daily cost
TPF, h	Total time per foundation
TPFo, h	Time required to cut the monopile
TPFr, h	Time per foundation for the removal vessel
TRAVEL, h	Total travel time
TRIP, h	Total time per trip
TURB, h	Total turbine removal time per turbine
VC	Vessel capacity (number turbines)
VDR	Vessel day rate
VDR, $/day	Vessel day rate
W	Duration of time that vessels are unable to travel
Δ	Displacement [t]
V	Speed [kn]

1.0 Introduction

The most abundant source of renewable energy resources available both onshore and offshore is wind. At present, the focus on wind energy is on the increase due to the recent global climate and environmental changes. Aside from the fact that wind energy is renewable and cheap, it is equally sustainable and environmentally friendly (Hameed, Vatn, & Heggset, 2011). Investment in offshore wind energy generation has increased spontaneously in recent years. The reason is that winds are more stable, abundant, stronger motion, and reliable in the offshore locations than in onshore regions. It was estimated that over 90% of the global offshore wind farms were installed on the European waters in the Irish, Baltic, and North seas respectively (Kerkvliet & Polatidis, 2016).

Offshore wind energy is also the most promising alternative energy source. The installation, operation, and maintenance stages of this form of energy generation are most often given wide attention while the decommissioning aspect has received little or no attention to date. However, the decommissioning stage is the crucial aspect of most projects and must be given serious preference while at the initial design stage to avoid the cost, logistics, safety, and environmental implications (Topham & McMillan, 2017). The maritime operations play an important role in all the stages of wind farm life cycle. Furthermore, the uncertainties in weather condition in remote locations increases the degree of marine operations complexity and therefore, make adequate project planning and vessel selection unnegotiable. As water depth increases, severity in weather conditions is high and operational logistics becomes complex. The vessel capacity, equipment, vessel behavior in rough sea conditions, and cost are important factors required for a sustainable offshore wind farm decommissioning operation (Paterson et al.,2018).

Sometimes the vessels used for offshore work-over operations like decommissioning are usually acquainted with challenges and this can cause an avoidable delay in project completion time. Also, the lack of specialized vessels and vessel daily rate charges can equally pose a severe threat to decommissioning tasks. In some instances, the mobilized vessels might not ideally suit the tasks or were oversized, or charter rates overinflated. Therefore, the company is forced to design and construct purposely built offshore wind vessels that can withstand more severe weather conditions, offer more deck space, and reduce overall operations durations (Paterson et al., 2018).

The main challenge to offshore business is the cost of installation and maintenance. The bulk of the project cost often accrues to vessel mobilization, ROVs and tooling, other equipment, and logistics. Reducing the cost of vessels for OWTs Installation, maintenance, and decommissioning is essential for the sustainability of the industry.

1.1 Research Question

Several offshore wind parks will reach their end of life in a few years to come. In situations where the offshore turbines are no longer economically sustainable to extend their life cycle through repowering, then decommissioning of the installed offshore structures becomes a viable solution. Although, the decommissioning of offshore assets is surrounded by a lot of uncertainties and complexities, but the decision-making process required to manage the project need to be properly understood to achieve success. According to Topham, Gonzalez, McMillan, and João, (2019), the inability to explore the opportunities in offshore wind farm decommissioning was due to the lack of sufficient knowledge or expertise in the field. The four main challenges facing the decommissioning industry in Europe are as follows (Topham et al., 2019):

a) Lack of regulatory framework
b) Unavailability of specialized vessels to carry out the tasks at the required time

c) Lack of standardized procedure for planning decommissioning tasks
d) The environmental impact set back

From the above-stated challenges, it is observed that vessels play a crucial role in maritime operations. The unavailability and huge chartering cost of vessels for offshore renewable energy tasks can also be attributed to the high demand by the oil and gas industry. The proposed designs are expected to reduce the cost of vessel lease for offshore wind turbine decommissioning (OWT) and will enhance the sustainability of the wind energy industry. This research would answer the question raised on how the Offshore Wind park decommissioning activities can be made sustainable and more efficient through effective vessel design.

1.2 Aim

The aim of this research is to propose a conceptual design of vessels for efficient and sustainable offshore wind parks decommissioning in Europe.

1.3 Objectives

- To conduct an extensive review of literatures and market survey of offshore vessels used for oil and gas
- To conduct an extensive review of literatures and market survey of offshore vessels used for wind turbine Installations
- To conduct an extensive review of literatures and market survey of offshore vessels used for oil and gas.
- To conduct an extensive review of literatures and market survey of offshore vessels used for wind turbine decommissioning
- To develop a conceptual design of vessels for wind park decommissioning
- To examine the proposed design for efficient and sustainable decommissioning tasks

1.4 Research Methodology

A comprehensive study and technical review of different surface vessels for windfarm decommissioning would be studied. This will entail a comparative overview of what is obtainable in the oil and gas and wind energy industry. A qualitative approach would be used for data collection and analysis. The methodology was adopted formed the basis of formulating the research questions, research methods, aim and objectives.

Also, interviews with offshore project engineers, vessel managers, vessel design specialist, etc. and site visitations in Norway would form part of the research scope. Discussions and analysis of vessel design for offshore wind turbine decommissioning as it relates to maritime operations with little or no emphasis on technology and engineering aspect.

Finally, the review of research work on decommissioning, an in-depth evaluation of peer-reviewed journal articles, online videos, and references to selected European Union (EU) decommissioning projects.

Vessels Review Guidelines

- Vessel type, Equipment, Vessel capacity, Vessel layout.
- Operations information – number of crew, vessel day rate, fuel consumption, etc.

Vessel Design Framework

- An innovative vessel design to enhance offshore decommissioning operations
- The future vessels for offshore windfarm decommissioning
- Functional and operational requirements

1.4.1 Literature Review

The first research method adopted in this report was a detailed evaluation of previous research articles and publications on the topic to identify the knowledge gap. The review was done using online resources for example google scholar, published peer-reviewed journals, conference papers, published book chapters and relevant textbooks. Other resources used were technical data of vessels from relevant companies, online magazines (e.g. Offshore-mag, and Offshore Engineer Magazine), YouTube videos, etc.

1.4.2 Industrial Interview

A few selected companies were interviewed. Most of the interviews were conducted via skype due to the COVID-19 pandemic. The interview request messages were sent to companies as reported in appendix I. The primary goal for conducting the interviews was to gather firsthand information and feedback from OWTs expert, regarding operation procedures and vessel challenges during installation, maintenance and decommissioning.

1.4.3 Vessel Design

In 1991, a novel technique called system-based ship design was presented by Levander for the conceptual design of vessels while the application of the methodology was presented by Erikstad and Levander in 2012. They introduced this approach to provide technical and economic solutions to ship design through reductions in the number of iterations.

“In order to achieve this objective, the vessel is divided broadly into ship-systems and task/function-related systems (often called payload). Information from previous, similar designs is derived to build databases estimating the gross area and volume of the new vessel. The area and volume are used to derive a geometric definition, weight balance and main dimensions. Based on these main dimensions a modular concept sketch is developed.”

(van Bruinessen, Hopman and Smulders, 2013, p.6).

A bottom-up framework was utilized by this method to estimate the required volume or area before vessel drawing. This framework has been in used for designing offshore support vessels, merchant and cruise ships respectively (Vestbøstad, 2011).

The conceptual design of OWTs decommissioning was suggested in tandem with the operational requirements and market demand. The wind turbine recycling and storage concept onboard the offshore vessels were suggested for the decommissioning operations. The different components of the OWT were mechanically compressed using a heavy hydraulically operated, mechanical press to form scrap sheets/plates for easy storage.

Finally, OWT decommissioning cost estimation was modelled for each component of the (e.g. turbine components, substation, and cables decommissioning cost estimation). The design and modeling were the basis for analyzing the efficiency and sustainability of the OWTs operations.

1.5 Background

The decommissioning of OWTs is a new subject of discussion among the wind renewable energy experts and marine specialists. About 30% of the European OWTs would be approaching their estimated 20 years end-of-life in 2020 (Ziegler et al., 2018). The need to start preparing for wind parks dismantling or disposal is crucial to ensure adequate project planning, resources management, and effective time utilization. The wind park operator's decision to either repower or extend the life cycle of turbines or decommissioning is dependent on the regulatory, technical, environmental, and economic factors (Luengo & Kolios, 2015).

However, the probability of decommissioning OWTs is constant, 1 i.e. OWTs will certainly be dismantled after repowering or life extension of the structures reach their end-of-life (Topham

& McMillan, 2017). The summary of the main challenges facing offshore wind energy decommissioning is shown in Figure 1

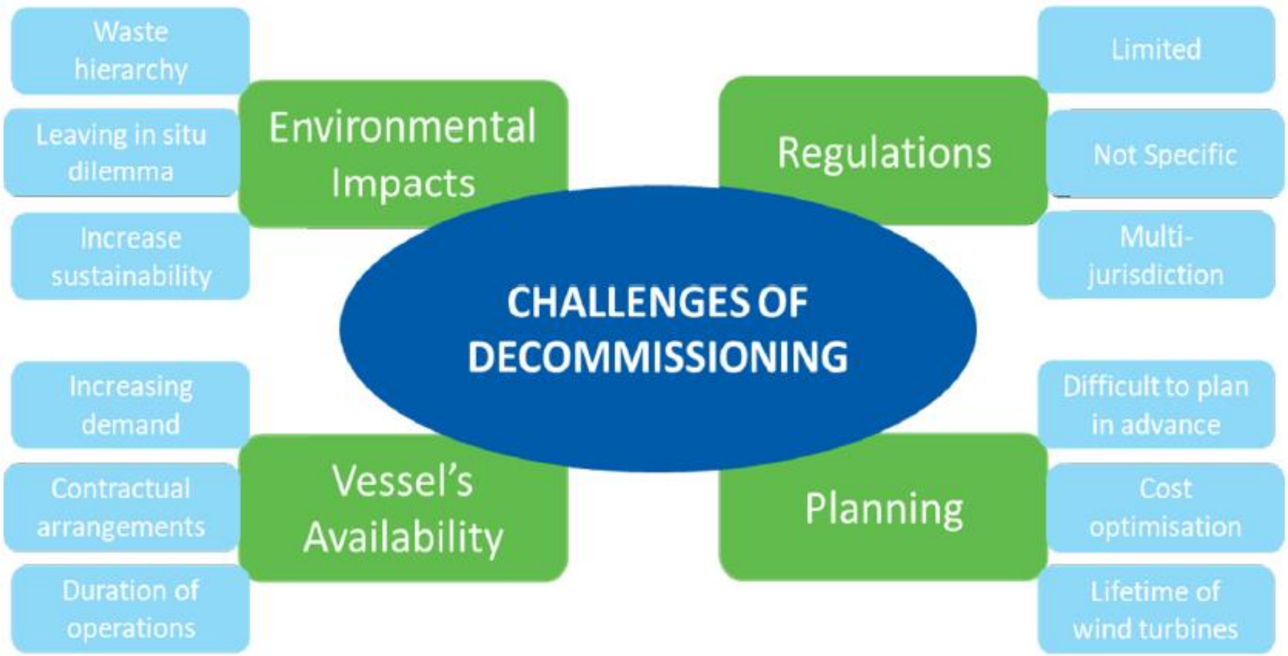

Figure 1. The major challenges experienced during the decommissioning of an offshore wind farm (Topham et al., 2019, p.4)

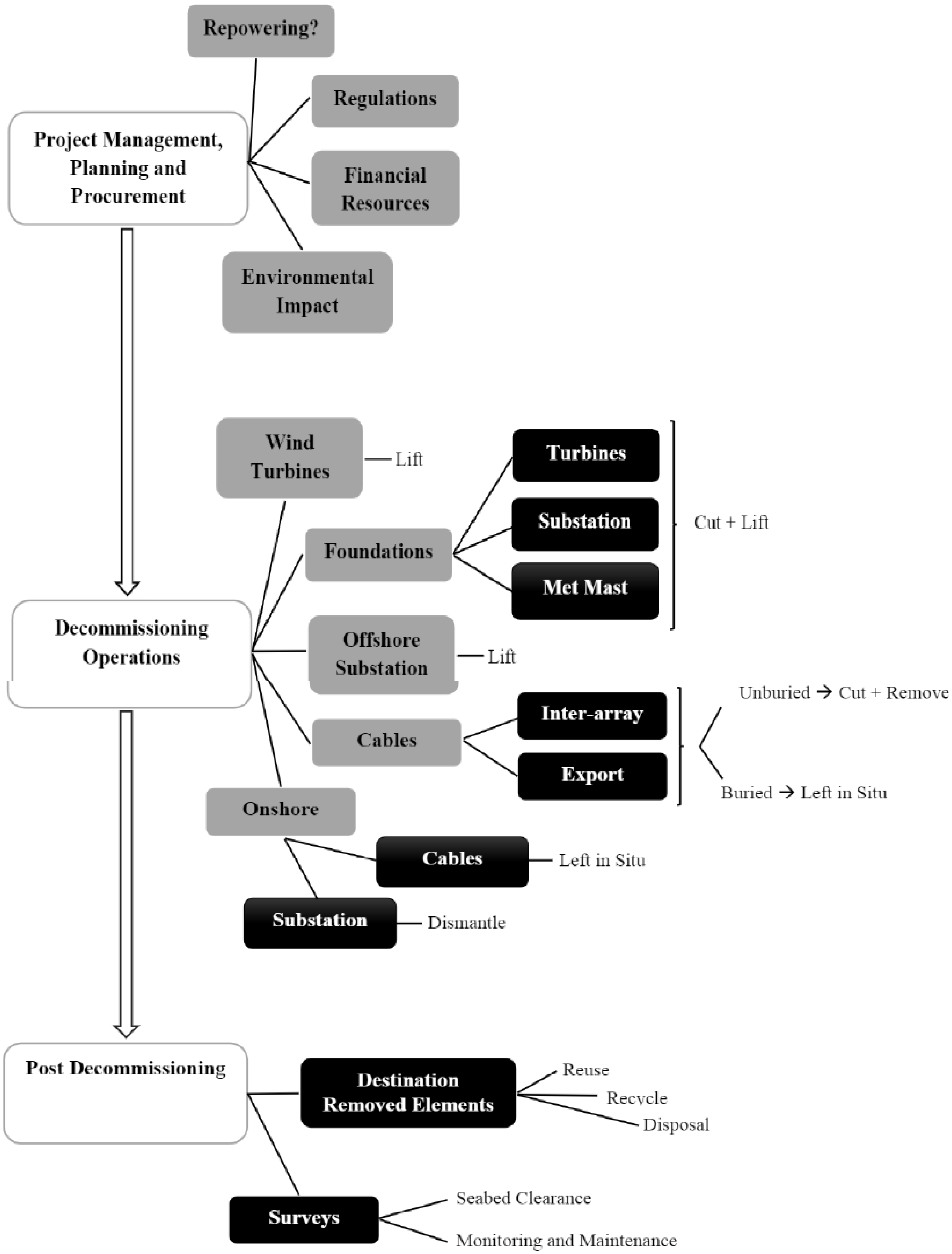

Figure 2 Breakdown of decommissioning process (Topham & McMillan, 2017).

Despite the forecasted opportunities in decommissioning of offshore structures in few years to come, the sector is yet to be fully explored, due to the challenges and shortage of experienced personnel (Ortegon, Nies & Sutherland, 2013).

The disconnect between the OWTs Installation, maintenance and decommissioning also contribute to the challenges of offshore wind energy industry. A strategy to establish an alliance or synergy between these three phases would assist to bridge the knowledge gap.

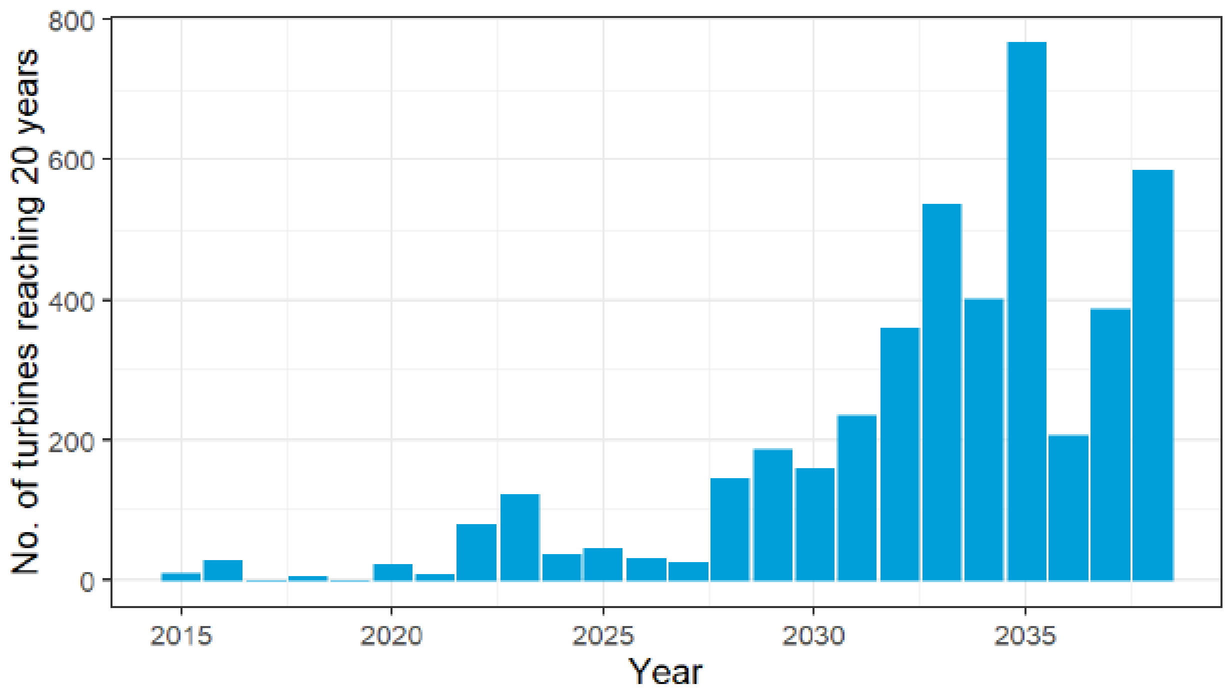

Figure 3. Annual forecast of No. of OWTs approaching 20-25 years of operation in Europe (Topham et al., 2019)

Furthermore, there are limited scientific information on the decommissioning procedure to ensure best practice in the offshore wind sector. This problem can be overcome through effective data gathering and proper documentation of the decommissioned wind parks across Europe and those data (information) should be made available and accessible (Topham et al., 2019).

This research addresses how the problem of vessel availability as highlighted in Figure 1 can be eradicated by designing vessels that can effectively decommission OWTs safely at a reduce cost. The OWTs tasks due require the use of specialized vessels with unique stability features and heavy lifting capacity for efficient offshore decommissioning tasks. Specialized vessels are also needed to meet both the location and operations requirements. The depth of water, seabed characteristics, type of vessels, type of foundation and number of turbines are essential factors to be examined prior to the commencement of the project (Topham et al., 2019).

However, there is a strong competition between the oil and gas, and the offshore wind sectors for the few available vessels (McMillan & Dinwoodie, 2013). Submitting an early contractual request is a major way-out to tackle this bottleneck. The development of vessels that can handle large structures that are free from crane or stability risks are in the advanced stage (Choudhary & Howes-Roberts, 2018). Though, the vessels availability cost account for the large percent of the overall cost OWTs decommissioning. The higher the operation flexibility, vessel speed, and deck capacity, the higher the chartering cost. The daily rates of most robust vessels are high and the uncertainties in market condition, weather and equipment is also a major concern. A viable means of reducing project cost is to minimize decommissioning tasks duration (Topham et al., 2019)

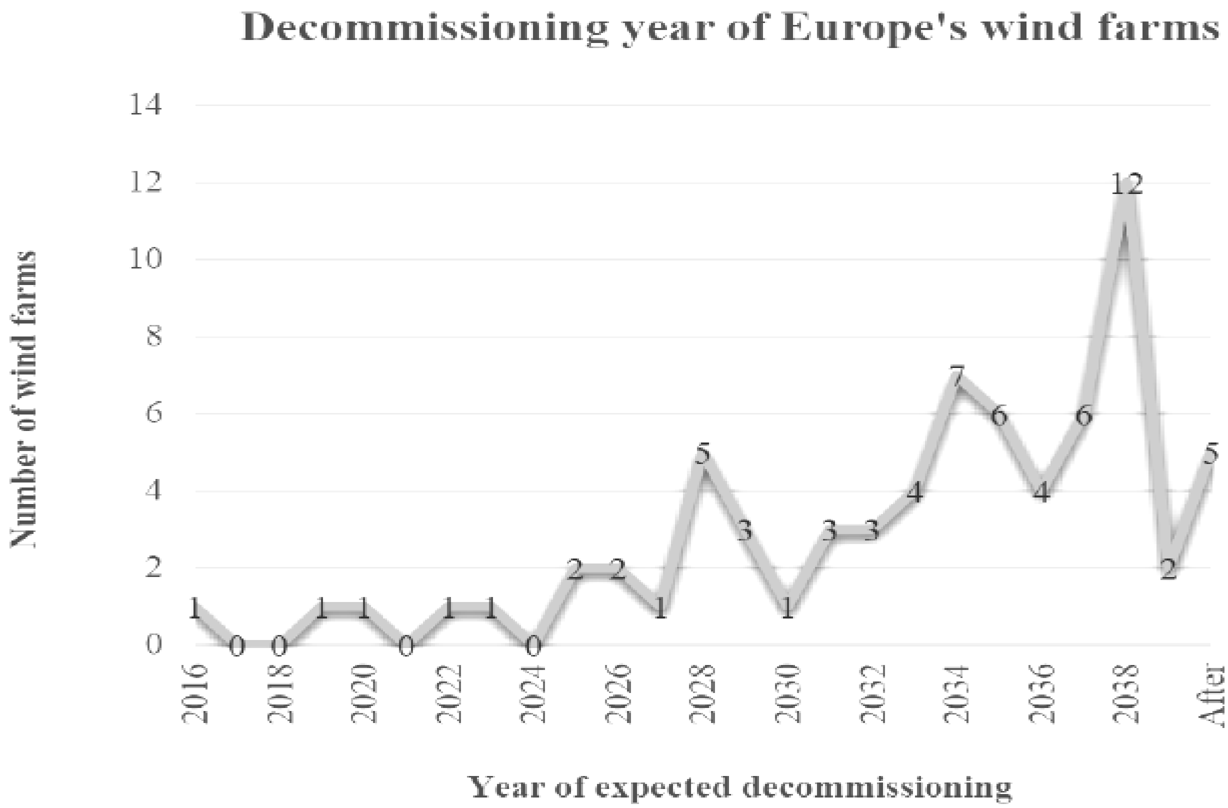

Figure 4 Projected year of European OWTs decommissioning (Topham & McMillan, 2017).

Topham, Gonzalez, McMillan, and João, (2019, p.6) stated that for an efficient and sustainable OWTs decommissioning;

"Therefore, a best practice would involve a strategy with the least amount of offshore lifting and operating time, leading to reduced costs and risks. This practice is supported by Beinke, Alla and Freitag (2018), where the total duration and consequently costs, can be reduced by a 6% only by adapting the number of vessels".

The decision to build a new ship or upgrade an existing one is dependent on several factors. An important factor to consider is the mission requirements. A comprehensive understanding of the tasks characteristics, the environment and safety is crucial in taking the right decision.

1.5.1 Vessel Design and Decision-Making

A good perception, understanding, and projection of situations can enhance the effectiveness of decision-making process. Effective decisions are taken based on the level of experience, technical competence, acquaintance with situation and the degree of proactiveness in responding to the situation. Decision-making is a process and there are several models and body of knowledge available depending on the circumstances and the nature of the challenges e.g. rational and normative, analytical, intuitive, naturalistic (dynamic), rule-based, team, and creative models.

Meanwhile, a model that is suitable for maritime activities is the naturistic model. This is the most preferred model due to the dynamic nature of the marine environment and its operations are strongly dependent on human-technology interaction. Human being are unpredictable and dynamic and most maritime related accidents or incidents are due to human errors. A dynamic decision-making model involves a continuous loop of appraising, monitoring and assessing the condition of events by re-evaluating the outcome and taking necessary actions (Flin 2008). Furthermore, in a dynamic system, decision-making is classified as a continuous cycle of problems identification, solutions generation, and selecting a 'suitable solution', monitoring of situations, taking the right action and re-evaluation of the outcome.

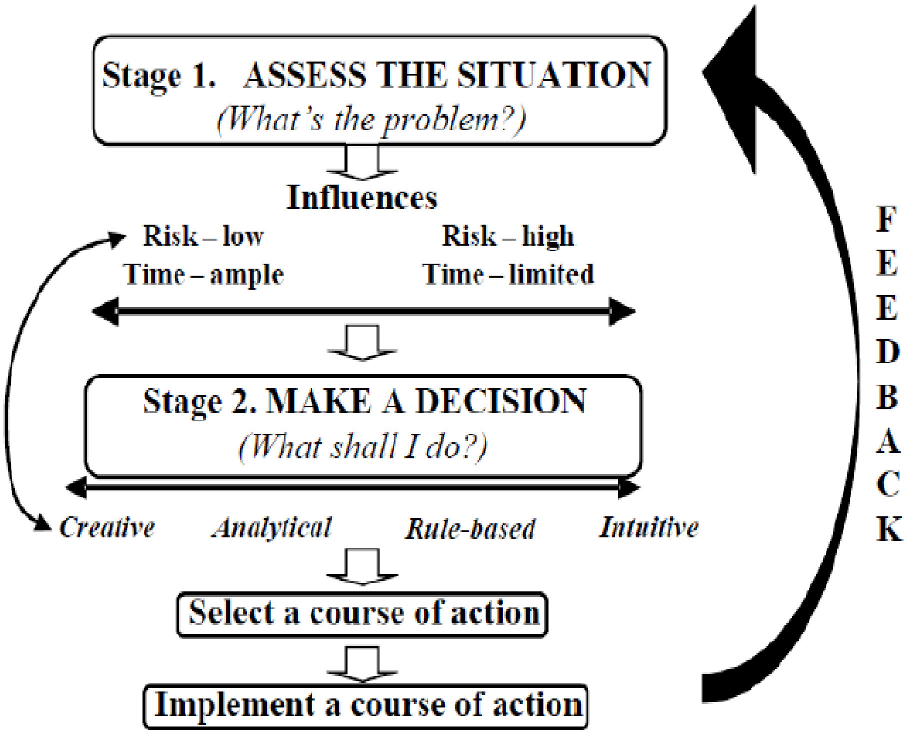

Figure 5 Simplified model of decision-making (Flin et al. 2008)

Figure 5 above is a simplified model suggested by Flin et al., (2008) for decision making. This decision-making model first starts with problem identification. The process of identification of situation (i.e. situation awareness) is carried out through experience and continuous monitoring of the environment, or system. More so, it is natural to think of different ways of solving situation awareness, cognizance or identification of problems. The ability to differentiate between an *assumed* and *realistic situation awareness* is crucial in taking an appropriate decision.

1.5.2 Vessel Design and Human Interaction

The concept of user-friendly design is urgently needed in shipbuilding and manufacturing sectors. Most transportation-related accidents are directly linked to either complex technology or poor interaction between human and technology.

The human-technology interaction factor involves knowledge acquired through experience, thought and senses; understanding and interactions between systems and machines (Illankoon, 2019). The degree of the participation of the intelligent systems has a substantial consequence on the extent of human engagement which assists to improve out-of-the-loop performance challenges (Endsley, 2015). Also, the Out-of-the-loop obstacles usually comes with surprises, that make humans display abnormal behaviors, according to Illankoon, (2019): "the recent advancements in the development of intelligent systems have led to an increased interest in understanding how humans learn about and respond to abnormal situations". (Illankoon, Tretten, and Kumar, 2019, p.1). The interaction between human and marine designs can be enhanced by harnessing technological innovations.

1.5.3 Ship Design Principle

Design scientists conclude that the first design is paramount in the creation of quality products at a reduced cost. (Dewhurst and Boothroyd, 1988; Gatenby and Foo, 1990; Dixon and Duffey, 1990; Suh, 1990; Hundal, 1993; Whitney, 1990). The statement "designers make million-dollar decisions every minute without knowing it", summarizes this. (Whitney, 1990).
Offshore vessel design is most approached using the "basis-ship" method. From a "mother" or "basis" -ship, a new design is formed (Birmingham and Smith, 1997). Short-cut design techniques extensively employ accumulated data from past designs (Tan and Bligh, 1998; Miller, 1965; Hekkenberg, 2010). Longer design time reduces competition of designers in bidding for the contract. The above process is therefore an effective way to reduce design time. (Tan and Bligh, 1998; Keane, Tibbitt and Maguire, 1996).

The design procedure is described by Evans (1959) spiral as a repetitive process from beginning to end of ship designing in 1959. With technological advancement and the introduction of computers, a lot has since changed. Ship design devoid of the use of computers is now unthinkable (Gallin, 1973). The Evans design spiral is deficient in areas of concurrent engineering, it sources information from previous projects, and reuse this information. Despite these, it is a much-used model to depict the sequential attributes of a design task. Furthermore, the essential first choice of basis ship is not covered. Mistree et al (1990) present a more current version that treats issues of concurrent engineering, thereby building on the Evans model. Depicting "Frustum of a cone", Mistree et al (1990) explain that the design task can be carried out in several directions at a time. The Evans model though with limited validity in explaining the true design process, it is still well used to depict the "ideal design process".

Levander's (2009) System Based Ship Design (SBSD) is dependent on data requiring the designer to organize attributes of new designs in a structured manner. In a search for the right basis vessels, it is beneficial to possess a database of well-structured data of previous designs by competitors and self. Information about recent and past projects can be used in several ways throughout the preliminary design phase. The designer makes accurate estimations and fair judgment promptly from key numbers in past projects.

Human expertise which can be expensive and scarce forms the foundation of designing (Moynihan, 1993). It becomes paramount to use human capital in the most effective way. Technology can only assist the designer to carry out his task, but computers still cannot replace the creativity and implicit knowledge to produce the best designs.
Dzbor and Zdrahal (2001) explain a model of how inexplicit and explicit interact throughout the design process. To develop a system for collecting knowledge, the interplay of the designer between knowledge about the approaching project and interpreting and collecting general information is essential.

The recent methodology used for vessel design is the system-based ship design. This approach is based on the arrangement of sub-dividing vessel into different divisions. Each division are referred to as system and are structured base on their functions. The vessel functional requirement is achieved through the combination of the systems (Levander, 2012).
The system-based design makes use of the bottom-up principle for vessel design unlike the conventional approach that uses top-down approach. The bottom-up method simply

commences the conceptual idea of vessel design from the mission or function requirement of the vessel to the construction stage. This usually start from investors specification of mission follow by tasks definitions, capacities and vessel's projected performance.

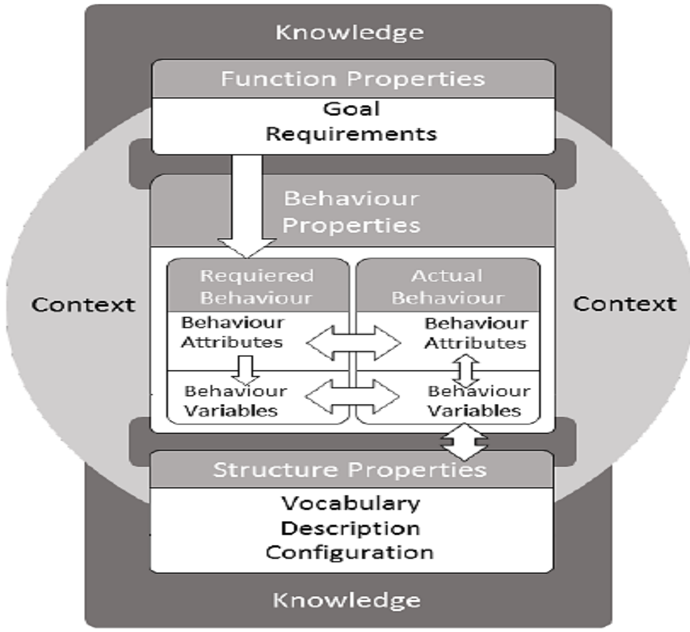

Figure 6 Schematic diagram of System-Based design Prototype (Gero & Rosenman, 1990)

The division of the vessel is carried out using functional hierarchy as shown in the Figure 7 below. The payload and the ship systems are the primary division into which the vessel is sectioned. The payload system (i.e. function requirements) refers to the systems or requirement that serves as additional source of revenue to the vessel while the ship systems are required for efficient and safe operation of the vessel. For some specialized vessels, the payload includes heavy lifting cranes, and winches.

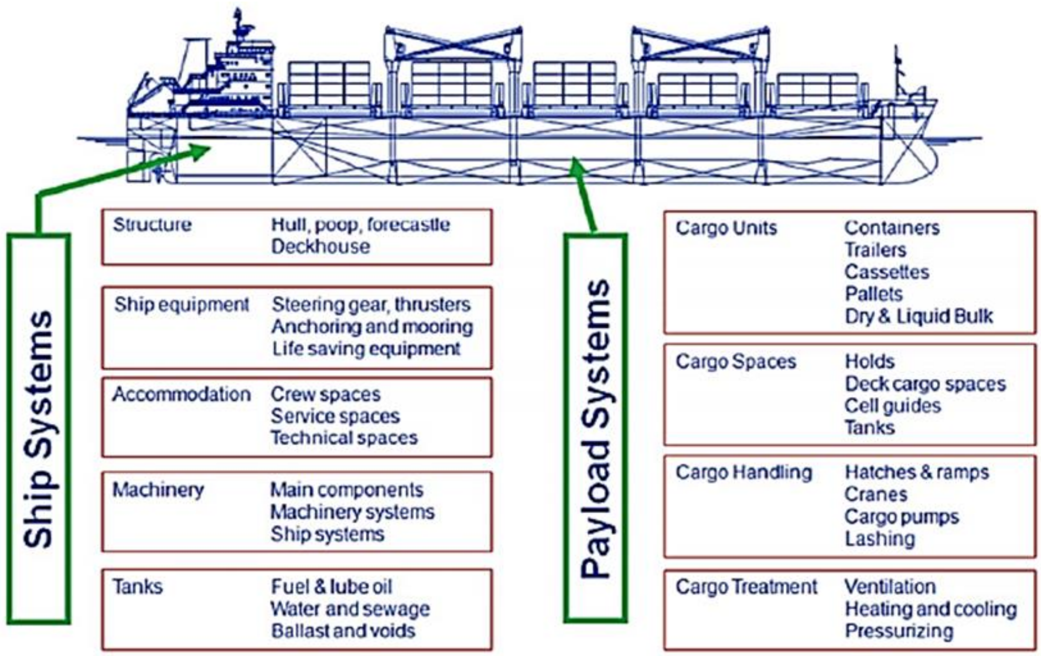

Figure 7 A cargo vessel payload and ship systems (Levander, 2012)

In conclusion, a novel conceptual vessels design using system-based approach and MPI resolution vessel as reference was proposed for the decommissioning of The Thanet windfarm. The Thanet OWTs decommissioning was used as a case study. The proposed models were expected to reduce vessel mobilization cost by 25 to 50 percent when fully developed and implemented. The vessel design process must effectively capture and address the challenges of environmental cognition (i.e. situation awareness), decision-making, human centered and technology and functional requirements

1.6 Thesis Layout

Chapter 1.0 – Introduction

This section provides the research guidelines and scope of work for the vessel design. A detailed summary of the research methodology, background study and thesis layout were explained.

Chapter 2.0 – Literature Review

This chapter gives a brief overview and critical evaluation of literatures from previous research studies. A glance into offshore oil and gas and wind turbine installations and decommissioning were discussed. A special review of vessel requirements, equipment, offshore wind turbine components in relation to decommissioning tasks were also highlighted.

Chapter 3.0 – Interviews and Discussions with Companies

This chapter describes the summary of the interview conducted with companies on vessel design for oil and gas, offshore wind turbine installation and decommissioning. Also, a glimpse into the present and future market condition, sustainability and efficiency assessment of offshore vessels for wind turbine decommissioning operations were discussed.

Chapter 4.0 – Vessels Design and Development

Chapter 4 describes the conceptual vessel design for offshore wind turbine decommissioning. The vessel specifications, design variables, and cost modeling for efficiency and sustainability were discussed.

Chapter 5.0 – Results and Discussion

In this chapter, explanations and results of the proposed vessel design as it affects each component of OWTs during decommissioning were discussed. The outcome of the findings and the economic implications of its applications were also compared.

Chapter 6.0 – Conclusions and Proposed future work

This chapter covers the concluding aspect of the studies and the proposed future line of research.

2.0 Literature Review

2.1 Offshore Oil and Gas Structures Installation

The structures for subsea oil and gas installation are usually design and constructed onshore before transporting it to the field offshore for installation. There are three subsea operations for installing structures at offshore location i.e. the structure loads out at the port or base, transportation of the structure and installation tasks. Most often, the operation can occur in four stages i.e. lifting, lowering, landing and locking respectively e.g. subsea Xmas tree, jumpers and manifolds (Bay & Bai, 2012).

2.1.1 Vessel Requirements for Offshore Oil and Gas Installation Tasks

The conventional subsea layout often involves umbilical's and pipelines for connecting subsea well to the top-side host structure e.g. floating, production, storage and offloading (FPSO) vessel, semi-submersible vessel etc. The following installation operations might be required for this type of subsea architecture:

- Hardware lifting and installation of Xmas trees, PLEMs/PLETs, SDU, UTA, etc.
- Laying of pipelines and umbilical's
- Tie-in connections

Meanwhile, the choice of vessel selection for the above operations or installation tasks depend on the following criteria:

- The scope of the installation tasks. This usually involve the type and features of the hardware to be installed.
- The sea state or the environment: The information about the depth of water and the weather window.
- Vessel requirements
- Estimated project cost or budget

From the above criteria, vessel requirement is the most crucial. The vessel characteristics can be classified as either basic or functional requirements (Bay & Bai, 2012).

The Basic Vessels requirements

The performance and strength of vessels are the basic prerequisite for selecting vessels for offshore operations or tasks.

The performance of the vessels during offshore installation and decommissioning operations are as follows;

- *Stability*: Stability is a phenomenon whereby a vessel can return to its original position upon removal of the applied moments or forces. There are two main classification of stability; (i.) Large inclination angle stability, and (ii.) Small inclination angle stability at an angle less than or equal 10^0 i.e. initial stability. This type of stability shows a linear trend for uprighting moment and angle of inclination.

- *Buoyancy:* The vessel should be buoyant under specific loading or unloading conditions. In practice, there are four conditions for vessels during loading or unloading situations i.e. trim, upright, heel and combined positions.

- *Insubmersibility*: This is a condition whereby vessel maintain its stability and buoyancy when flooded. Majority of surface vessels do have adequate stability and additional buoyancy during maritime operations.

- *Maneuverability*: It is the ease at which the pilot can control the direction, speed, power and navigation of a vessel. It also refers to the navigational capacity of the ship in relation to keeping a constant direction as determined by the navigator.

- *Seakeeping*: This is the ability of a vessel to maintain its position and ensure safe operation at sea. Sea keeping makes the effect of sea moments and forces created by waves, wind and ocean current to be minimal o the vessel.

Vessel Strength

The strength of a vessel is a measure of its resistance to failure. According to Bay and Bai, (2012), there are 3 types of failures that surface vessels can experience; (i) stability (ii) strength and (iii) fatigue failure respectively.

(i) Stability Failure: This usually occur whenever there is a large displacement and when the critical stress is less than the compressive stress.

(ii) Strength Failure: This type of failure occur when the minimum yield strength of the vessel is less than the stress on its structure.

(iii) Fatigue Failure: This is the failure of vessel's material structure as a result of the circulation of continuous stress. For the vessel strength must remain intact during loadout, operations (i.e. lifting, etc.) and transportation.

Functional Requirements

Vessels are also classified base on the functional requirements. A surface vessel is referred to as a platform that support certain operation equipment which are deployed for specific ocean operations. Before the commencement of an installation operations, equipment is usually mobilized onboard and subsequently demobilized to the logistic or loadout base after the completion of the tasks. The mobilization of equipment and demobilization tasks is capital intensive and require appreciable planning time. Therefore, specialized vessels purposely built for specific operations are often used in order to minimize project cost and time e.g. Wind turbine installation vessels (WTIV), diving support vessels (DSV), pipe or cable laying vessels etc.
The major functional difference between an umbilical /pipe laying vessel and subsea installation vessel is the tasks and equipment specific requirements. Each operations or tasks usually require detailed procedure, tools & equipment, and this functional requirement will determine the choice of vessel selection for the tasks (Bay & Bai, 2012).

Vessel Requirement for Subsea Installation

Technically, subsea structures are usually installed using surface vessels that has sufficient crane capacity, winch rope and heave compensator. Such vessels can be offshore support vessel, umbilical/cable laying vessel, pip-laying vessel or drilling vessel (Bay & Bai, 2012). Meanwhile, the important vessel requirements for such offshore and subsea installation are as follow:

- Deck space i.e. required for equipment positioning
- Deck capacity i.e. load bearing capacity
- Vessel response amplitude operators (RAOs) i.e. the sea behavior of vessel
- Crane coverage and capacity
- Accommodation
- Availability of ROV facilities. This usually involve one survey/observation and one work-class ROVs for umbilical/pipeline laying monitoring during laying, and two work-class ROVs required for subsea installations.
- Dynamic positioning requirements. Offshore installations and lifting operations are expected to be performed with a high level of safety and in a timely manner by considering all the field limitations like operating weather window, visibility and seabed conditions, other field limitations (other nearby subsea hardware, mooring lines etc.)
- Vessel transit speed. Deep water operations usually require a high transit speed due to the remoteness or long distance in getting to the field.

The lifting equipment and the deck handling system should be properly designed to prevent and control the pendulum movements of the lifted hardware while in air, at the point of passing through the splash area and during landing on the seabed. Also, the winches, cranes and other installation equipment must be designed, constructed and operated to meet their functional requirements. The hardware installation constraint and criteria must be ensured as recommended by the manufacturer/designer and the rules of the certifying authority or national codes e.g. API, DNV, ABS, etc.

Vessel for Umbilical and pipe Laying

For subsea installations of umbilical and pipes the choice of a pipe/cable laying vessel must have the following supplementary requirements for some specific devices/equipment:

- *The tensioner capacity*: This requirement is determined by the unit weight of the pipeline, buoyancy and depth of the water.
- *Winch abandonment and recovery*: This is often required during emergency conditions and when the umbilical or pipe laying is at the final stage.
- *The capacity of Davits*: This is most often needed during offshore connection of umbilical and pipelines and other situations when davit tasks is necessary.
- *The storage capacity of equipment/ product*: This is usually needed when the umbilical reels or pipe joints is difficult to move from the storage barge to the vessel as a result of bad weather (Bay & Bai, 2012).

2.1.2 Review of Vessels for Offshore Oil and Gas Installation Tasks

The installation of an offshore and subsea hardware can be performed using the following types of vessels:

- Offshore support vessels (OSV) for example field support vessels, diving support vessels, ROV support vessels etc.
- Heavy lift vessels
- Drilling vessels e.g. drill ships, semi-submersibles, jack-up rigs etc.
- Cable/Umbilical and Pipe laying vessels
- Barges and tugboat for transportation

Barges and Tugboats

The subsea assets are often conveyed to the offshore site from the onshore base using a barge. On arriving the installation site, the asset or hardware would be transferred to the construction vessel or platform prior to the commencement of installation tasks.

Figure 8 Transportation Barge (Pappas, Maxwell & Guillory, 2005).

The Figure above illustrate a Subsea Xmas tree which was conveyed to an offshore field by a transportation barge and set for deployment to the seabed using a rig winch (Bay & Bai, 2012). The following features determines the choice of selection of a transportation barge and the arrangement of subsea hardware on the deck:

- Transit distance and navigation route
- Center of gravity, weight and dimension of the hardware
- Project schedule and constraint
- Cost
- Avoidance of bad weather i.e. operating weather window

Figure 9 Tugboat (Dredge Brokers as cited in Bay & Bai, 2012)

The tugboats are often used for towing the transportation barges from the loadout or onshore location to the operation site. The Figure above is an illustration of a tug-boat.

Drilling Vessels

Drilling vessels usually includes drill ships, semi-submersibles and jack-up rigs. They are primarily designed to carry out drilling tasks but can also be used for installation of subsea production system because their lifting capacity, operation at deep water depth and positioning capacity (Bay & Bai, 2012).

Jack-Up Rigs

This is a self-elevating rig which was first designed and built in the year 1954. The mobile offshore drilling units was basically used for drilling tasks in shallow waters of approximately 110m depth. Jack-up rigs are easily movable, and it provide sufficient stability both in transit and during operation due to it contact with the seabed by its elevating legs. An illustration of a typical jack-up rig is shown in the Figure below (Bay & Bai, 2012).

Figure 10 Jack-Up Rig (Energy Endeavour, 2008 as cited in Bay & Bai, 2012)

Semi-Submersibles

Semi-submersible received a wide acceptance for offshore drilling due to it capability to drill at a greater water depth while in floating position and are stationed by means of anchoring or dynamic positioning system. The semi-submersibles rigs are classed as vessels because they float on water surface like ships when in transit to operation site and its pontoon are subsequently flooded in order to partially submerge the platform. The vessel is not usually affected by wave action due to the submersion of it structure beneath the water surface unlike drilling ships. Semi-submersibles have the following advantages when deployed as either a vessel or a platform: They have sufficient stability, greater depth of operation, reduced susceptibility to wave effect, a very small waterline plane, and can sustain itself for a very long duration. Also, they are normally used for subsea installations in water depth of 120 to 1200m or deeper depth (Bay & Bai, 2012).

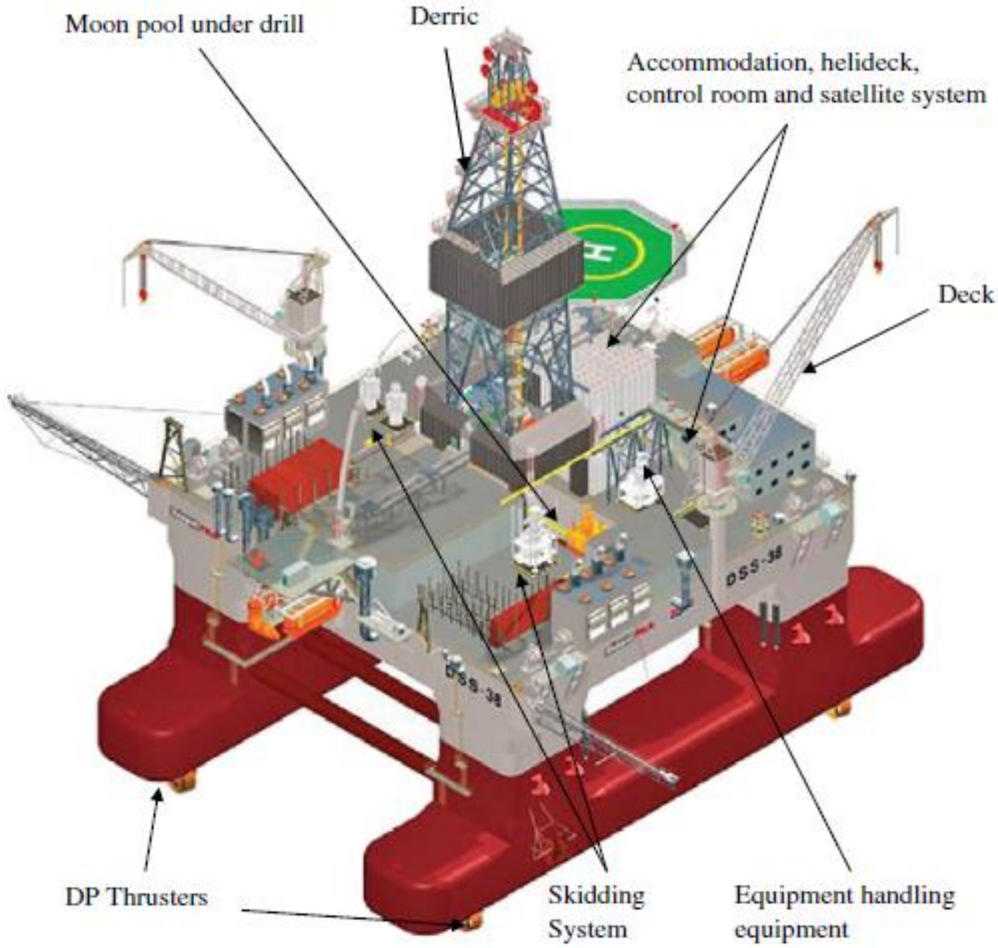

Figure 11 Semi-Submersible (Maersk Drilling, (2020) as cited in Bay & Bai, 2012)

Drill Ships

Drill ships are classified as both station-keeping equipment and drilling rig for deep water hydrocarbon drilling tasks. The payload capacity of a drill ship is larger than that of a semi-submersible drilling platform, but its motion characteristics is it primary concern.

Figure 12 Drill Ship (Saipem S.P.A, 2020)

Pipe-Laying Vessels

These types of vessels are classified based on methods of pipe-laying as determined by the characteristics of the site such as weather and water depth. There are three basic types of pipe-laying vessels: The J-lay, S-lay and reel-lay vessels (Bay & Bai, 2012).

S-Lay Vessels

The S-lay type of vessel or method of pipe-lay have been in use for several years and they are normally use for laying offshore pipeline. The vessel usually have a wide deck area for operation activities. The procedure for pipe laying is either at the side of the main deck or in the middle of the vessel with a pipe /cable conveyor system, coating unit, NDT inspection and welding facilities. The vessel has a sloppy slideway and a stinger astern that are used for modifying and controlling the pipeline configuration (i.e. pipe stress/strain distributions) into an “S” shape toward the seabed. The Figure below illustrate an S-lay vessel (Bay & Bai, 2012).

Figure 13 S-Lay Barge (Allseas Group Solitaire, 2020)

J-Lay Vessels

On the other J-lay vessel use a ramp/J-lay tower for laying of pipeline as oppose to the S-lay that make use of stingers. The primary difference between the J-lay and S-lay procedure is that pipeline is deployed to the sea from the laying vessel at an angle (e.g. 60^0 – 87^0) closer to a right angle (i.e. 90^0). Also, a stringer is not required for ensuring an overbend and this method is often use foe deepwater pipe-laying tasks (Bay & Bai, 2012).

Figure 14 J-Lay Vessel with a J-lay Ramp (Heerema Group, DCVBalder, (2020)

Reel-Lay Vessels

A reel-lay vessel provides a cost-effective means of laying small diameter pipelines (i.e. less than 0.4 meters diameter) through a very long distance. The pipelines are usually made onshore and reeled on a large diameter (~ width × diameter = 6m × 20m) drum at the center of the deck and the spool base of a purposely built vessel. In offshore installation, the pipeline is plastically deformed on the drum during reeling stage on the spool base and straightened by a specially designed straight ramp during unreeling process (Bay & Bai, 2012).

The unreeling of 3000m to 15000m of pipeline is normally done at a vessel speed of 1200m per day (Bai & Bai, 2005). The laying of the pipeline at the seabed in a configuration like that of a "S" lay vessel is carried using a steeper ramp. The laying speed is appreciably good, and the vessel can be operated easily using basic laying equipment (Bay & Bai, 2012).

Figure 15 Reel-Lay Vessel (Subsea 7, Seven Navica, 2020)

Umbilical-Laying Vessels

The umbilical vessel laying is basically used for umbilical installations either by a carousel or a reel laying method. The load-out can done easily with Reel -lay vessel and it can install between 3000m and 15000m umbilical length. Meanwhile a carousel laying vessel can install umbilicals for a longer distance (i.e. 100000m). However, the carousel most often require more time for load out and a specially designed vessel (Bay & Bai, 2012).

Figure 16 Carousel-lay Vessel (Solstad Offshore ASA, 2020)

Heavy Lift Vessels (HLV)

A specialized heavy lifting vessel with high crane capacity is referred to has a Heavy lift vessel (HLV). These types of vessels are used for lifting several thousands of tons weight. Most of the subsea hardware (e.g. subsea template etc.) and heavy structures are lifted using HLV. The HLVs have lifting capabilities range of 500 to 1000 tons which much bigger than the crane capacity for construction vessels with less than 250 ton. Also, seakeeping and stability characteristic are the crucial requirement of an HLVs (Bay & Bai, 2012).

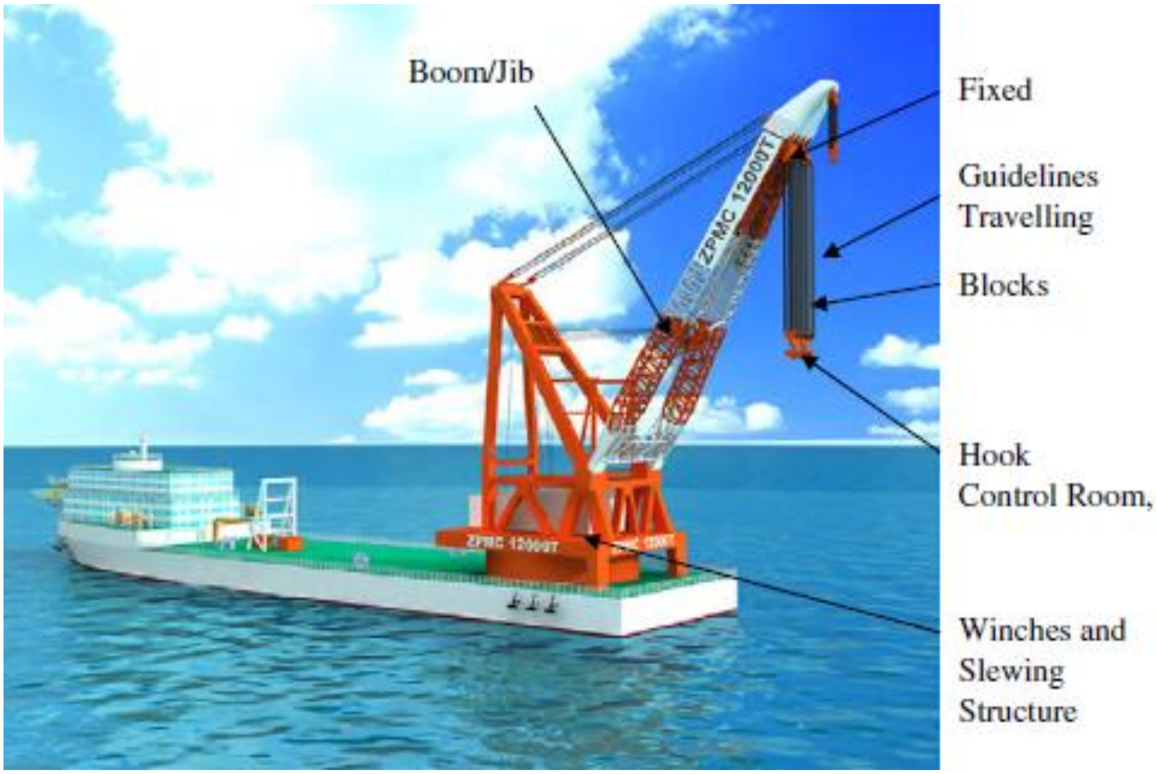

Figure 17 Conceptual Picture of a Heavy Lift Vessel (ALLSHIP, 2020)

Offshore Support Vessels (OSVs)

These are specialized vessels used for carrying out specific offshore support services or tasks for construction, installation, drilling, decommissioning and abandonment operations. The OSVs often render standby support, survey, installation and inspection assistance. The following are types of support vessels used for specific offshore tasks:

- Survey vessels
- Field support vessel (FSV) or Offshore supply vessel
- Diving support vessel (DSV)
- ROV support vessel

The ROV support vessel is a special vessel used specifically for ROV operations. It is usually equipped with functional ROV tools, equipment, and deck space for storage deployment and supporting ROVs during intervention and work-over subsea operations (Bay & Bai, 2012). The

Diving support vessels are specialized vessels that equipped with specific diving tools and equipment. They usually have certified and professional divers onboard in addition to the following equipment when preparing for intervention and work-over subsea operations: On-site diving hyperbaric chamber, compression chamber, submersible, diver to surface communication system etc.

An FSV is a multipurpose support vessel that are used offshore for providing transportation, rescue, supplies and diving assistance.
A survey vessel is specialized ship equipped with laboratories and instruments used for ocean research i.e. for studying ocean chemistry, physics, topography, geology, hydrology and aerography (Bay & Bai, 2012).

2.2 Offshore Oil and Gas Structures Decommissioning

2.2.1 Vessel Requirements for Oil and Gas Decommissioning Tasks

Basically, the vessel requirements for most offshore operations (installations, maintenance, decommissioning for either oil and gas or wind turbine applications are similar. The essential functional requirements, equipment and sea condition adaptability of the vessels are the primary prerequisite expected of the vessels. The oil and gas industry utilize heavy lifting crane vessels and conventional surface vessels for majority of its offshore operations unlike the OWTs which employ heavy lifting crane vessels and jack-up vessels.

Vessel	Company	Capacity (mT)	Type
Pioneering Spirit	Allseas	Topside – 48,000; Jacket – 25,000	Twin Hull
TML	SeaMetric	20000	Twin vessels
Thialf	Heerema	14200 (2 * 7100 tons)	Semi
Saipem 7000	Saipem	14000 (2 * 7000 tons)	Semi
Bottom Feeder	Versabar	10000	Dual Barges
Svanen	Ballast Nedam	8800	Catamaran
Hermod	Heerema	8165 (1 * 4536, 1 * 3629)	Semi
7500 Barge	ZPMC	8500	Monohull
Balder	Heerema	6350 (1 * 3629, 1 * 2722)	Semi
Borealis	Nordic	5000	Monohull
Oleg Strashnov	Seaway	5000	Monohull
Bottom Feeder	Versabar	4000	Twin barges
DB 50	J. Ray	3992	Monohull
Rambiz	Scaldis	3300	Catamaran
Asian Hercules II	Smit	3200	Monohull
DB 101	J. Ray	3185	Semi
DB 30	J. Ray	2800	Monohull
Sapura 3000	Acergy	2800	Monohull
Stanislav Yudin	Seaway	2500	Monohull

Table 1: List of selected heavy lift crane vessels with over 2000mT lifting capacities (BSEE, 2015)

Examples of oil and gas structures that are decommissioned are pipelines, drill cutting, topside, jacket, footing, subsea assets etc. Each of these operations would have its specific vessels requirements.

Among the vessel requirements of offshore oil and gas decommissioning tasks are lifting capacity, crane characteristics and capacity, deck characteristics (i.e. strength, space, and stability), heave compensation, deadweight capacity, station keeping and maneuvering systems (i.e. dynamic positioning system, DP), transit speed, ROV for special tasks, accommodation and operational flexibility.

2.2.2 Review of Vessels for Oil and Gas Decommissioning Tasks

A systematic summary of vessels for offshore oil and gas decommissioning are tabulated in the Table 2 below.

Vessel	Representative Figure	Basic Description
Saipem 7000		Length overall - 197.95 m Upper platform- 175 m x 87 m x 8.5 m Lower pontoons- 165 m x 33 m x 11.25/15.25 m Depth to main deck- 43.5 m Free deck area- 9,000 sq.m Deck load - 15,000 tonnes Operating draft- 27.5 m Survival draft 18.5 m Transit draft 10.5 m Transit speed 9.5 knots
Thialf semi-submersible crane vessel		Length overall- 201.6 m Length of vessel -165.3 m Width 88.4 m Depth 49.5 m Draught 11.8-31.6 m Gross Tonnage 136,709 t Net gross Tonnage 41,012 t Deck load capacity 15 t/m² Total deck load capacity 12,000 t
Versabar VB 10,000		Floating barge crane Tonnage: 10116t Length: 85 m Beam: 96m Draught: 6m Propulsion: none

Allseas Pioneering Spirit		Tonnage: 403,342 GT Displacement: 365,000 tonnes Length: 382 m Beam: 124 m Draft: 10–27 m Depth: 30 m Speed: 14 knots Capacity: 48,000t Crew: Accommodation for 571
Seametric International Twin Marine Lifter		Length of each vessel: 140m Bread of each vessel: 40m Semi-submersible at 20m depths Deadweight capacity: 25000t It has 4 lifting, 2,500 t capacity lifting arms. Length of arms: 75 m DP 3 class Accommodation-: 41

Table 2: Selected Vessels for Oil and Gas Decommissioning

2.3 The Offshore Wind Park Industry

An offshore wind park is a renewable energy generating plants that comprises of several wind turbines that are connected by internal grid for energy transfer to substation and power transmission to local grid through an export cable. The offshore wind park is capital intensive and complex technical project especially at the initial stage of development.

2.3.1 Offshore Wind Turbine Components

The main components of an offshore wind turbine (OWT) are as follows: foundation, transition piece, tower, nacelle, turbine blades, substation and cable (i.e. power collection and transmission systems). The nacelle is connected to the tower and tower connected to the transition piece. The term 'rotor' is used for the hub and blades arrangement. The blades are attached to the hub and the complete structure suspended on a foundation. The wind turbine plant can be installed using different approach (Kaiser & Snyder, 2010).

Figure 18 An Assembled Rotor Being Lifted onto a Nacelle at Nysted (DONG Energy 2010a as cited in (Kaiser & Snyder, 2010)

The OWTs usually generate 2MW, 5MW or more power and the table below show the typical weight of selected wind turbine components. There are variations in wind turbine rotor dimension, electrical capacity, hub, blade and nacelle materials.

Turbine	Capacity (MW)	Blade length (m)	Tower (t)	Rotor (t)	Nacelle (t)
Siemens 3.6 - 107	3.6	52	180-200	95	125
Vestas V90 – 3 MW	3	44	100-150	42	70
Repower 5M	5	61.5	210-225	120	300

Table 4: Weights of Commonly Used Offshore Turbines in tons (Kaiser & Snyder, 2010)

2.3.2 Turbine Blades

Turbine blades are reinforced plastics materials or composite airfoils that are connected to the hub while onshore or at offshore site depending on the installation method. Turbine blades are usually very sensitive to wind movement especially during lifting operations because of their long length, reduced weight and material composition.

2.3.3 Transition Piece and Scour Protection

Transition Piece

Immediately after the installation of the foundation, the transition piece is positioned on the foundation structure to level and correct horizontal anomaly. The transition piece is partially submerged through the water column and upper part of the foundation (i.e. above the seabed). Meanwhile, access deck, ladders, boat fenders and handrails are then connected to it outer surface and power generation accessories and equipment e.g. cables, switchgear, transformer and control systems are then installed. In monopile type foundation, a cement slurry/grout is normally used to fill the gap between the transition piece and the pile. The gravity and jacket type foundations, and transition piece are installed onshore and does not require electrical conduit connection, boat landing, or offshore lifting (Kaiser and Snyder, 2010).

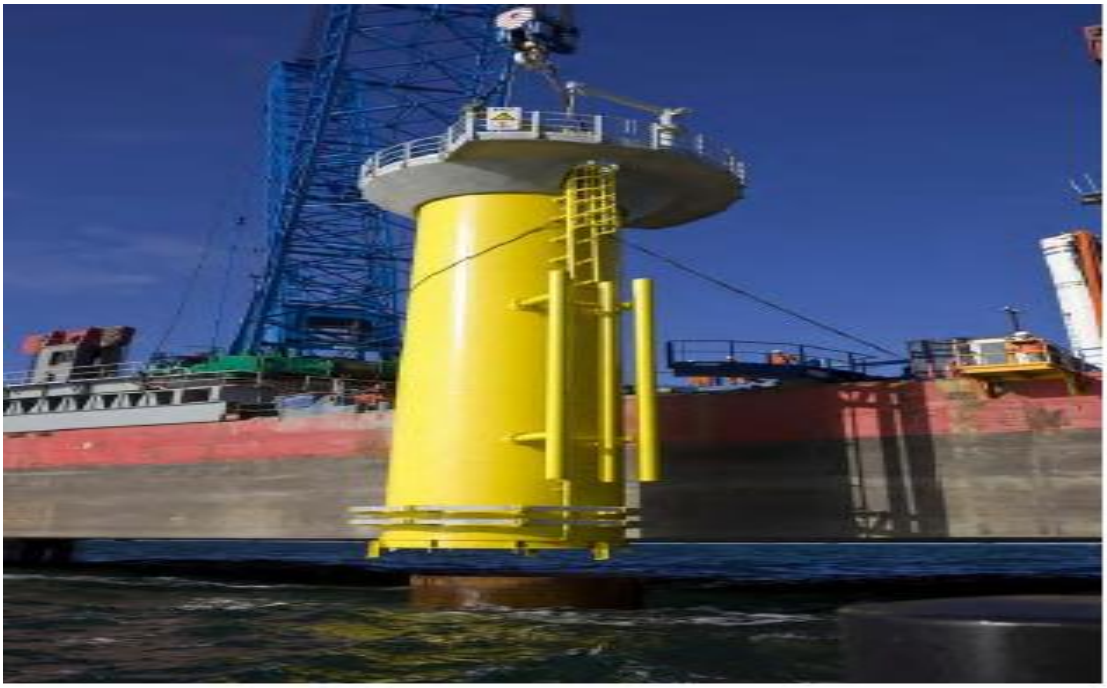

Figure 19 Transition Piece at Horns Rev II (DONG Energy 2010b as cited in Kaiser & Snyder, 2010)

Scour Protection

The scour protection simply means the complete removal of sediments formed on the base of the foundation. The formation of scour is normally observed when the foundation is exposed to ocean current that make the seabed eroded and make the foundation structurally unstable. The scour protection depends on the wave and current at the OWT site, the type or design of the foundation and the substrate. The problem can be eliminated using a less expensive and a simple technique. The typical measures or procedure for scour protection is by putting a concrete mattress and adding rocks of different grades close to the foundation (Kaiser and Snyder, 2010).

In monopile structure, the driving of the piles beneath the seabed is followed by layer of small rocks. A larger size of rocks/stones can then be set at the foundation after installing the cables (Gerwick, 2002).

The gravity foundation, tripods and monopile often require substantial scour protection and little or no scour protection is required in piled jackets foundation (Den Boon et al., 2004; Seidel, 2007; Larsen et al., 2005). Meanwhile, a rock wall can be used to encapsulate the whole wind park so as so to minimize scour formation and ocean current effect.

2.3.4 Tower, Nacelle, and Hub

Tower

The wind turbine towers are referred to as tubular structures which consist of steel metal plate that are plastically deformed, mechanically rolled, and joined together to form a large cylindrical section. During installation, the tower segments are fastened together at the port. The height of a tower is estimated by the clearance measured over the water level and the size of rotor diameter. A typical height of a tower is around 80 m while a total the height with hub is approximately 90 m in addition to the foundation measured above the water level. The anticipated wind load and the nacelle's weight often determines the strength and diameter of the tower. The tower supports an elevating system or as a ladder required to gain access to the turbine nacelle. The tower serves as support to the wind turbine configuration and to ensure the turbine components are in a stable condition (i.e. the power and communication cables, yaw motor which is positioned at the top of tower, and a transformer usually placed at the base of the tower) (Kaiser and Snyder, 2010).

Nacelle

The gearbox, generator, control, communication, environment maintenance and monitoring equipment are all housed in the nacelle.

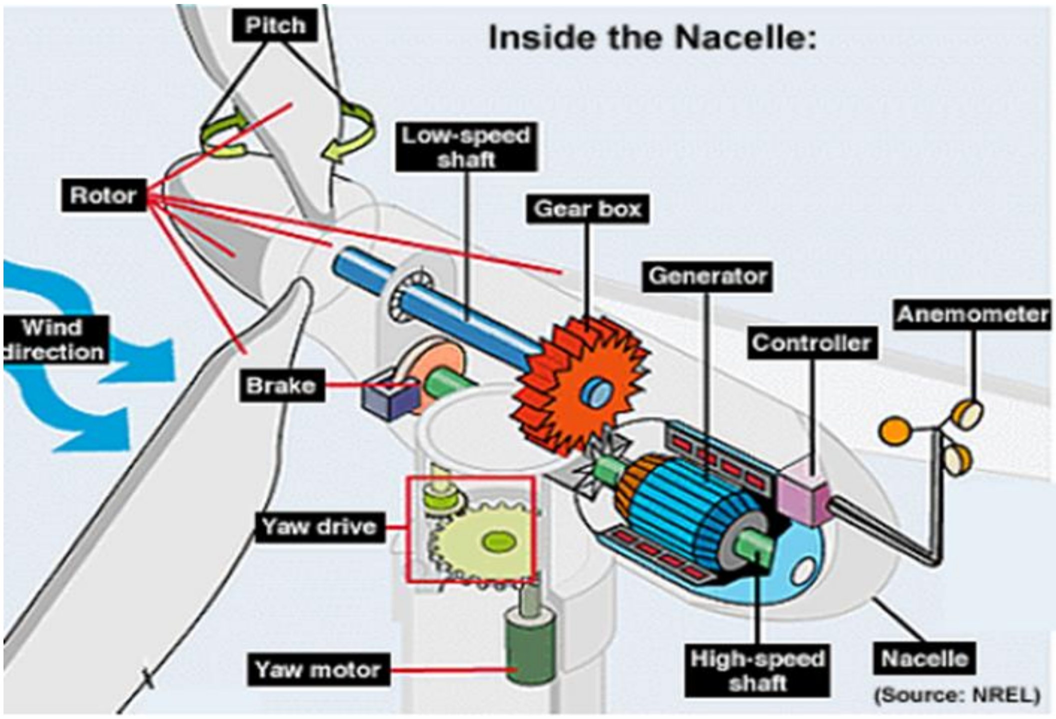

Figure 20 Diagram of a Nacelle (DOE, 2010)

The nacelle are heavy, highest lift and large unit which comprises of the cover and the main frame. The generator, brake and gearbox are attached to the main frame and the loads (i.e. reaction and rotor loads) are transmitted from the brake and generator to the turbine tower (Maxwell, McGowan & Rogers, 2002).

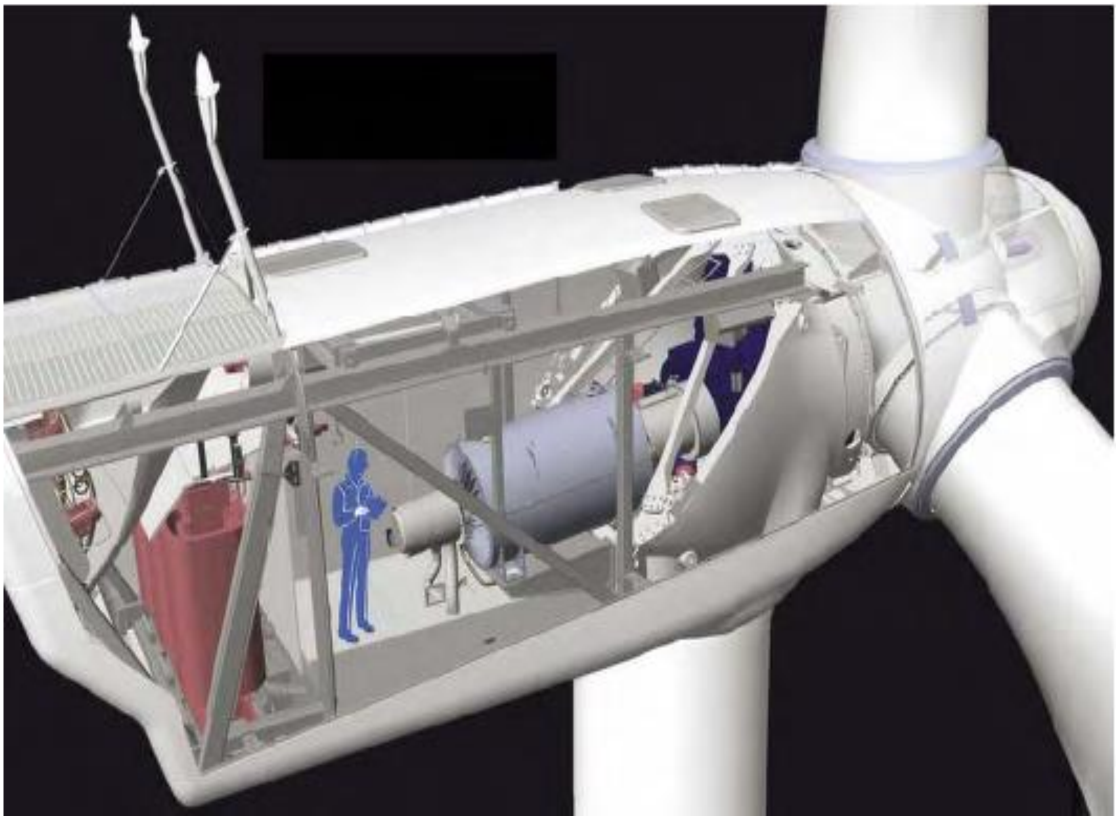

Figure 21 Inside of a Nacelle and Relative Size (Vattenfall, 2010)

Hub

The wind turbine hub is made from a cast steel and comprises of an electric motor for regulating the pitch of turbine blade pitch. The wind turbine hub conveys horizontal wind load to the nacelle from the blades and transmits rotational power through a low speed shaft to the gearbox and it is part of the most stressed component of a wind turbine (Hau, 2006).

2.3.5 Subsea Foundation

The subsea foundations are usually designed and constructed onshore as a single piece, then transported offshore using a towed or barge. The foundation is later lowered to the seabed by the derrick barge or crane. The foundation is produced based on the condition of the site and the foundation design and type is affected by the depth of water, wind speed, wave heights and ocean currents.

The crucial design variables considered in foundation construction are extreme loading frequency and loading conditions. In offshore wind park, there four types of foundations that are often used: monopiles, gravity foundation, tripods and jackets.

Figure 22 Alpha Ventus foundation installation (Alpha Ventus,2010 as cited in Kaiser & Snyder, 2012)

Monopiles

The Monopile foundation is a thick walled and large diameter tubular steel that is hammered (driven) or drilled through the seabed. The outer diameters of most monopile foundation is normally between the range of 4 to 6 m and approximately half of its length permeate through the seabed. The monopile piling depth and thickness is specified according to design standard and code and are determined by environmental condition, design load, depth of water, and the condition of the soil. However, driving /hammering of pile is less expensive and more efficient than pile drilling.

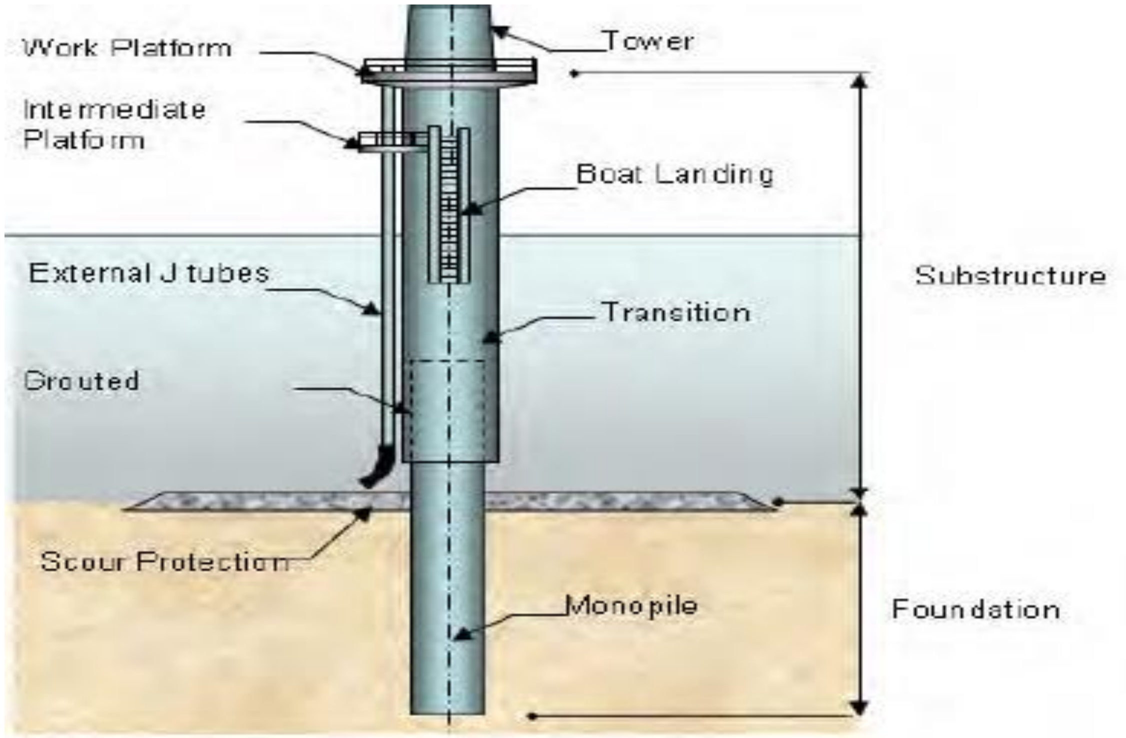

Figure 23 Components of a Monopile Foundation (EWEA, 2009)

Tripods

The tripods are heavy, strong and more expensive type of foundation than the monopile. They are suitable for deepwater application. The piles are hammered through the seabed by the cylindrical tubes which is connected to the central shaft.

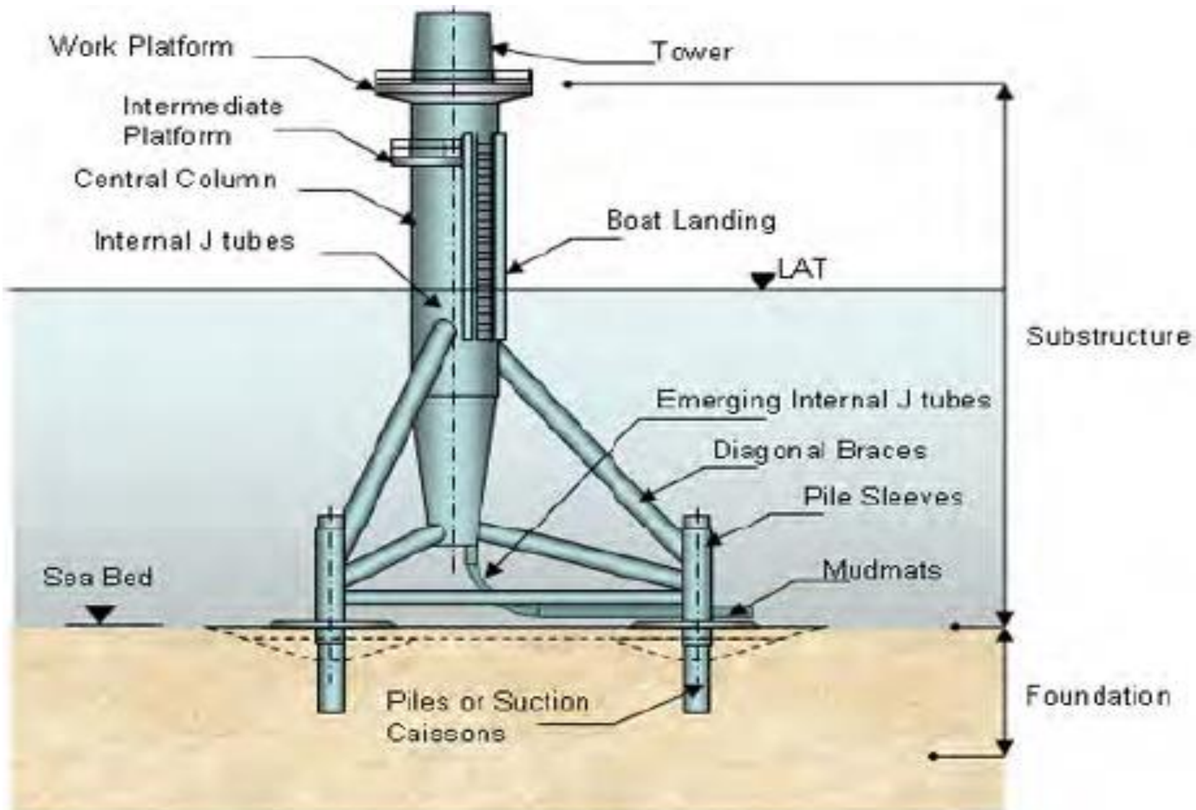

Figure 24 Components of a Tripod Foundation (EWEA, 2009)

Jackets

These are truss template made from lattice steel and consist of tubular frame components that extend above the water surface from the mudline. The Piling is drilled or hammered into the seabed through the jacket legs in order to protect the structure from lateral forces. The jackets foundations do require heavy equipment for lifting and transportation to the site due to its robust weight. The jacket is often used for shallow water to act as a support for substations. In principle, this type of foundation is applicable for deep water installations, but cost is a key factor to consider especially when considering water depth that is below 100m.

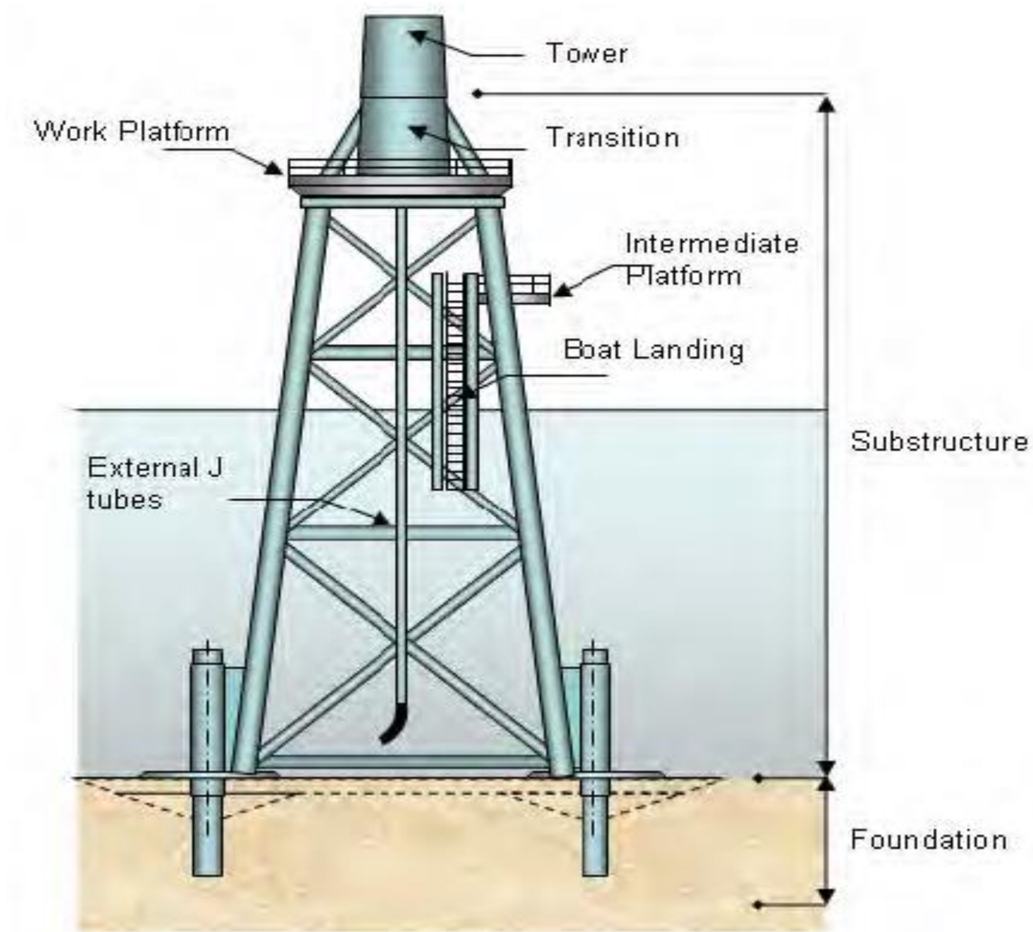

Figure 25 Components of a Jacket Foundation (EWEA, 2009)

Gravity Foundations

The gravity foundation is usually constructed from concrete structures and it uses it resultant weight to resist the impact of wave and wind loads. It also requires a special fabrication equipment that can withstand the suspended weight of concrete through reinforced quays, specialized barges or drydocks. A few examples of offshore wind park in which gravity foundations were used were the Lillgrund, Nysted, Thornton Bank, and Middelgrunden fields.

Figure 26 Lillgrund Windpark layout (Kaiser & Snyder, 2012)

Figure 27 Middelgrunden Windpark layout (Kaiser & Snyder, 2012)

Furthermore, this type of foundation is often used in situations where drydock equipment are available for concrete installation and when the conventional piles are difficult to install (Volund, 2005). Although, gravity foundations are more economical to construct than monopiles, but the cost of installation is higher because of the need for subsurface preparation, dredging operations and dedicated heavy lift vessels. These types of structures have been used in the North Sea for offshore oil and gas installations and also adopted in the Europe for wind park installations in a shallow and moderately deep water where driven pile method is a concern.

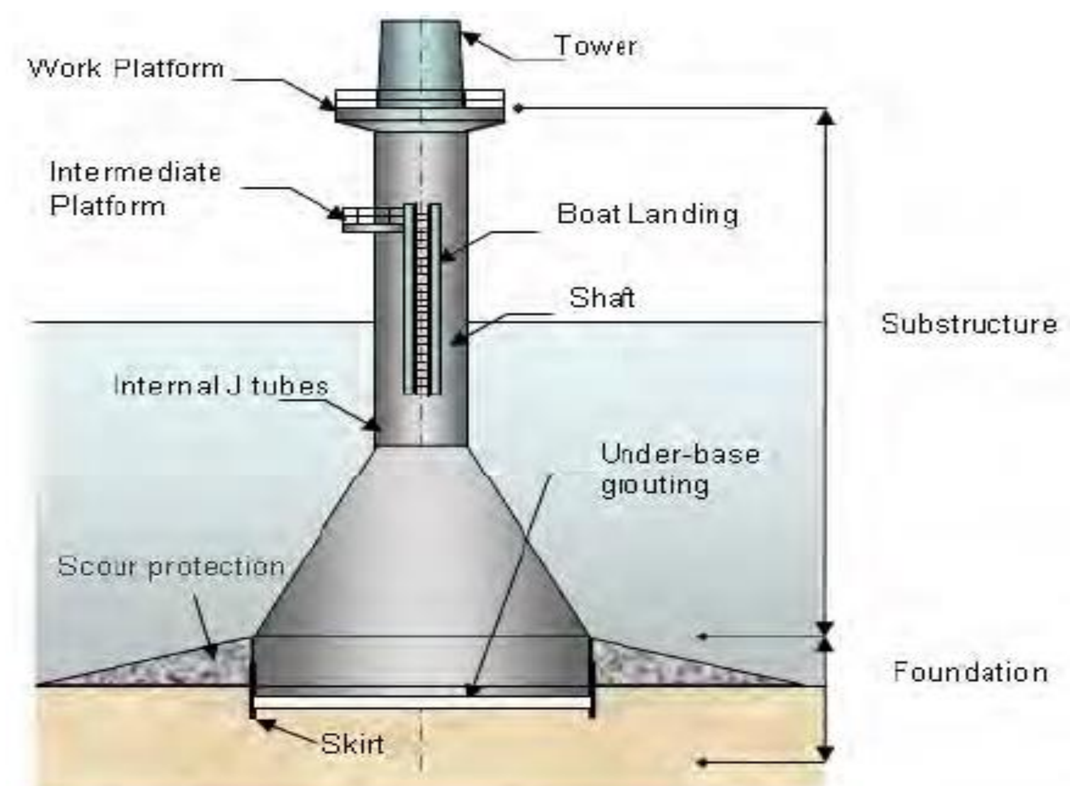

Figure 28 Components of a Gravity Foundation (EWEA, 2009)

Floating Structures

The floating structures comprise an anchoring system and a floating platform. The floating turbine have different foundation designs which are similar to the tension leg and spar used in the oil and gas sector. The offshore hydrocarbon sector has a limit of 450m depth for fixed structures while the limit is below 100m in offshore wind energy sector. In 2009, Equinor (formerly known as Statoil) developed the Hywind (i.e. a floating wind turbine concept) in Norway. The diameter of the is about 8.3m and approximately 100m of the cylinder is submerged beneath the seabed with the support of three or more mooring cables. The floating turbine was assembled onshore and then towed to offshore for installation and anchoring.

2.3.6 Cables and Substation

The OWT installation and decommissioning is determined by the available vessel equipment, inner array cable and the high voltage export array cable. The vessel operations for cable installation can either be a remotely operated vehicle (ROV) or plow concurrent cable lay and burying technique. Although the type of operation depends on the availability of vessel and cost, but it is very effective (Kaiser & Snyder, 2012).

The Inner–Array Cable

The OWT has a generator which produces a low voltage (i.e. approximately 1kV) that are not economical for direct connection to the near turbines. These inner array cables are usually used to connect close by OWT together and to the substations.

The 500V to 600V voltage generated by the turbine is stepped up to a voltage range of 10V to 36kV for inner array cable connections. The inner array cables are connected to the turbine's generator and exit the turbine at the foundation close to the mudline. The cables are buried few meters beneath the mudline prior to connection of its second terminal to the next close by turbine in the layout. The number of turbines, separation between turbines and the farm design layout are factors that determines the quantity of cabling required for the wind farm connection. The higher the number of connected turbines, the higher the voltage and power to be conveyed by the cable. The inner array cables are often lighter than the export cable and are transported in smaller units (less than 1 km) to the installation site. A self-propelled vessel with are usually used for inner array cable installation with less consideration to turntable capacity (Kaiser and Snyder, 2012).

Export Cable

The wind park is connected to the transmission system (i.e. located onshore) through the export cables. For export cables, turntable is essential for installation with self-propelled vessels or barges. This type of cable is usually protected with scour protection after they are buried. The nature of the coastline, type of soil, water depth in relation to cable route and other physical parameters are factors that determines the cost, time and cable route for export cables. The export cable ensures that the power or energy being generated by the OWT is efficiently delivered to the onshore grid.

The export cables are made up of three protected conductors which are galvanically coated (i.e. using galvanized wire). For a wind park without offshore substation in place, a medium voltage export cables are usually used with peak voltage supply of 36kV. On the other hand, high voltage cables are used for a maximum of 150kV voltage supply with offshore substation installed. The high voltage is usually wider in radius, longer, heavier and can deliver more power or voltage than the medium cables. They normally require a high capacity vessel which can feed cables of several thousand tons. The weight of the medium cable is approximately between 200 and 400g/cm while high voltage cables is between 500g/cm and 1000g/cm respectively (Kaiser & Snyder, 2012).

Figure 29 Cable laying barge with spread (Global Marine Systems, as cited in Kaiser & Snyder, 2012)

Substation

The offshore substations are used for stepping up the generated electricity (or voltage) by the OWT prior to transmission onshore to a much higher voltage. The substations also help to reduce the energy losses during transmission ashore. The capacity of substations is often rated in terms of its power bearing capability i.e. Mega Volt Amp (MVA). There is an increase in the efficiency of the substations and energy loss reduction whenever the generated power or voltage flows through the lines (i.e. export cables) at high voltage. Most offshore wind parks have their substations installed offshore while in some cases the substations are installed onshore. The location of the substation either offshore or onshore is dependent on the nature of the project, the quantity of the generated power, the distance between the OWT and the base, and the balance between the energy losses during transmission and the capital expenditure (CAPEX) (Wright et al.,2002).

Examples of substations components include switchgear, high voltage cables, j-tubes, accommodation, tank and diesel generator for backup, and transformers. The position of the substation is usually optimized by installing it within the wind park in order to reduce the separation between the inner array and export cables. The substations foundations are comparable to that of the turbine and the typical weight of a substation is approximately 907kg or more (Kaiser & Snyder, 2012). Furthermore, the substations also comprise of the control and monitoring system (SCADA), equipment for monitoring the quality of the power (i.e. harmonics irregularities and voltage stabilization)

Figure 30 Substation Being Lifted onto Monopile at Gunfleet Sands (Offshore Wind Power Marine Services, 2010)

2.4 Components of Offshore Wind Park Vessels

2.4.1 Dynamic Positioning

The dynamic positioning (DP) can be defined as a computer control system which is automatically used for controlling the horizontal movement and position of vessels through its propellers, engines, rudders and bow thrusters. The data input into the computer system are received from vertical reference units, gyrocompass, and wind sensors. The DP systems makes anchor handling tugs usage to be less essential and redundant during ship operations **(**Kopits and Losz, 2013).

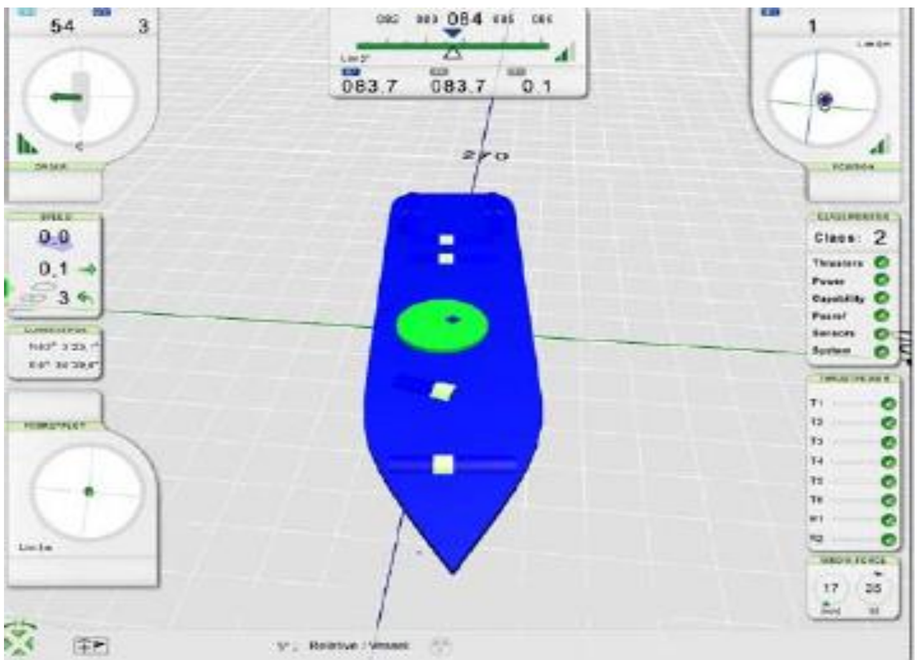

Figure 31 Diagram Showing the DP System of the Olympic Octopus (Kopits and Losz, 2013).

The DP system can easily be retrofitted or reconfigured to improve vessel performance efficiency. They are also used for offshore installations operations involving oil and gas, and wind energy e.g. survey tasks, cable and pipe lay vessels. By this, the vessel need not be dry docked and extra thrusters can be installed with a separate power supply source. These new thrusters are less expensive and fast to installed and are used for maintaining vessels positions whenever the need arise **(**Kopits and Losz, 2013).

A vessel to vessel coordination and navigation can be achieved through DP system when set to specific coordinates. DPs are rated or categorize into four classes i.e. DP0, DP1, DP2 and DP3 respectively. The redundancy of a classed DP is a function of the redundancy (i.e. the degree of using in independent power and thrusters as back-up). DP1 systems are used in crew and supply vessels while most support, supply and construction vessels make use of DP2 systems. The drilling rig or vessels make use of DP3 system **(**Kopits and Losz, 2013).

Figure 32 Portable Dynamic Positioning System (Kopits and Losz, 2013).

2.4.2 Heave Compensation

The active heave compensation mechanism is designed for adjusting the vertical movement of vessels. The operation of heave compensation usually involves the use of an electronic system for monitoring the vessel's vertical motion and automatically control the crane winch in order to compensate for the vertical motion. The cable connected to the crane is uninterruptedly whirled to make the load hang directly above the seabed (Kopits and Losz, 2013).

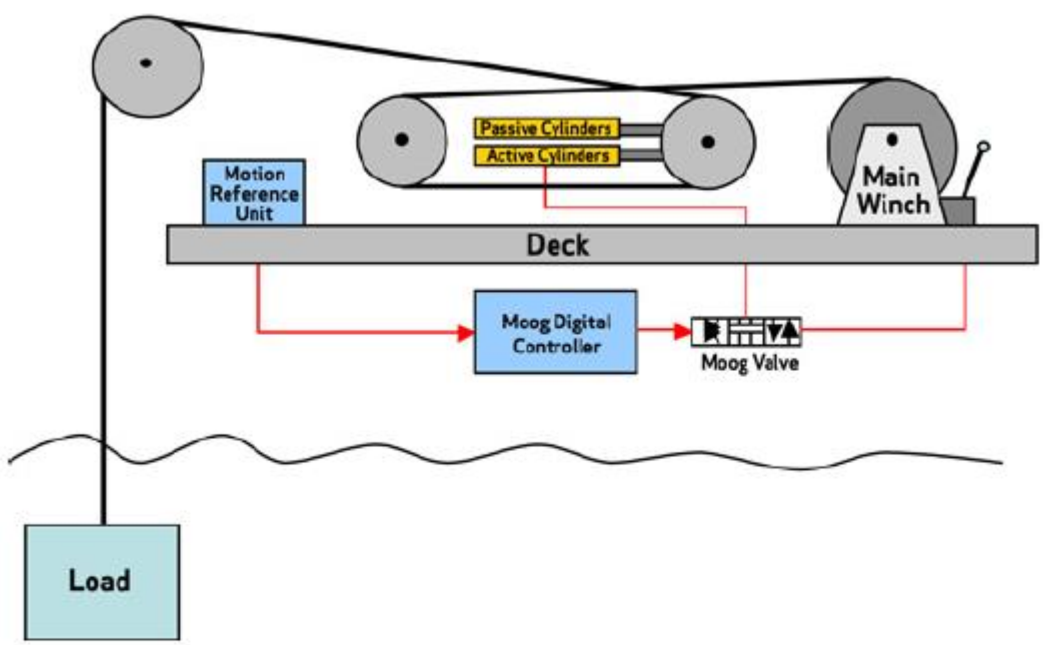

Figure 33 Functional Schematic of a Heave Compensation System (Kopits and Losz, 2013).

For most offshore construction vessels, the function of the heave compensation is similar to the phenomenon of jacking up of vessels. During offshore operations, jack-up vessels are not usually affected by the movement of sea water. But, in situations whereby it is difficult to jack up a vessel either due to the condition of the sea or lack of jack-up capacity then heave compensation is crucial to ensuring an efficient operational performance (Kopits and Losz, 2013).

Figure 34 Heave Compensated Barge Installing a Transition Piece (Kopits and Losz, 2013).

2.4.3 Navigation tool

The electronic chart display and information systems (ECDIS) is the main navigational systems that most advanced vessels used for voyage and route planning. Prior to the commencement of voyage from the port, the vessel uses the navigation system to plan and monitor the sailing route and create an emergency alert whenever a possible hazard is detected along the forecasted route or when the vessel's stability is endangered. The position, distance, speed details and route of all the vessels within the radar coverage are automatically plotted and alert the reference vessels should there be possibility for collision. This is one of the means vessels used to avoid collision especially when in transit along a busy route (Kopits and Losz, 2013).

Figure 35 Navigation System Interface Installed on the Bridge of the Ship (Kopits and Losz, 2013).

The international maritime organization (IMO) in 2000 approved a new rule which mandated all vessels to have an automatic identification system (AIS). The AIS ensures information is available to the coastal authorities as well as other vessels at the specific location. It is informally referred to as ‘ship black box’ which provide real time and post voyage record/information of the vessel’s activities. Furthermore, the AIS ensure information share information with navigation system to prevent collision accident and other related mishap (Kopits and Losz, 2013).

Figure 36 AIS Systems Sharing Information (Kopits & Losz, 2013).

2.4.4 Deck Capacity and Space

The load bearing capacity of a vessel and volume planning are important in ship systems design. For a harsh environment like the North Sea, the deck should be able to resist the pressure or load from the ocean current and waves. Also, the load bearing of the ship is related to its stability and ease of maneuvering. That is why it is essential to allocate area and volume in line with Norwegian standard for offshore structures (i.e. NORSOK N-001 to N-006) and international regulations for all the equipment and accessories during the design phase of the vessel.

2.4.5 Cranes Capacity

The reach of crane and the height are the most important component of an offshore wind vessel. The geometry of today's OWTs components increases as technology and development advances. Kopits and Losz, (2013) also explained that

"Taller towers and larger nacelles require cranes to have a higher reach and be able to carry larger tonnage. Over the last few years many dedicated offshore wind vessels like the MPI Resolution have fitted larger cranes on deck to accommodate the growing size of wind turbines. Whether the crane is loaded onto a vessel or it is permanently mounted, the crane should have an upward reach of 125 meters with a load capacity of 600 to 1000 tons".

(Kopits and Losz, 2013, p.80)

Figure 37 Rambiz Installing a Wind Turbine at the Beatrice Wind Farm (Kopits & Losz, 2013).

The conventional derrick cranes incorporated with lattice boom are the mostly found on construction vessels for offshore wind operations. However, the telescope cranes were introduced in 2010 for OWT installations. The deck space requirement and center of gravity for the telescope cranes are lesser than for the derrick cranes due the availability of retractable boom. Cranes are either temporarily installed on the vessel or presently welded for lifting tasks and power by the vessel diesel engine (Kopits & Losz, 2013).

Figure 38 MV Wind Installing a Nacelle Using a Lattice Boom at a Dutch Wind Farm (Kopits and Losz, 2013).

2.4.6 Jack-up Legs

The legs of jackup barges and vessels are often exposed to severe ocean pressure due to the condition of the offshore environment specifically during the upward and downward jacking of the vessel. The stability of the vessel would be greatly affected if the leg is broken or stucked to the seafloor. Therefore, proper planning of the vessel design and construction is crucial. There are several distinguishing factors for jack-up vessels which are types of jacking legs, seafloor stabilization method, number of jacking legs, types and nature of elevating equipment etc. (Kopits & Losz, 2013).

Number of Legs

Most typical jack-up vessels do have 4 or 6 legs depending on its weight or size. Meanwhile, majority of turbine installations vessels (TIVs) have 6 legs while 4 legs are found in the conventional jack-up vessels. The stability of the vessels increases with the number of legs and vessel cost. However, more legged vessels are suitable for harsh weather and for operations with reduced weather window. The sustainability of the offshore wind energy depends on the availability vessels with robust capability to maneuver during harsh weather condition (Kopits & Losz, 2013).

Types of Legs

Open Truss legs

The jackup vessel with open truss legs are similar to telecommunication tower and are constructed from a crisscrossed tubular steel. They provide more stability in severe weather conditions and deep water but are more expensive.

Figure 39 Open Truss Jackup Legs (Kopits & Losz, 2013).

Columnar Legs

Jack-up vessels with columnar legs are constructed from steel tubes and they offer less stability compare to the open truss legs. Although, they are cheaper and easier to fabricate but their operational capability in harsh weather conditions and deep waters are limited.

Figure 40 Columnar Jackup Legs (Kopits and Losz, 2013).

Seafloor Stabilization

The total weight of a jackup platform/vessel is exerted on the legs when jacked up. It is important to make sure the legs are firmly attached on the seafloor. The stability of the vessel is affected when the legs are not evenly erected or when the loads are not uniformly distributed. A jacked-up vessel might be difficult to lower back to water surface or formation of kink on the legs when tilted. Spud cans and mat are usually fitted on the legs in order to reduce the risks associated with loss of stability or broken legs (Kopits & Losz, 2013).

Mats

Mats are usually required by jack-up vessels whenever the seafloor is soft for the legs. The mats (i.e. placed on the floor) are connected to the vessel legs during jacking up process to enhance it stability and ease of operations.

Spud cans

The spud cans are cylindrical steel with cleats and spike which penetrate the ocean floor to ensure vessel legs are stable. They are similar to 'shoes' and are connected to each leg of the platform/vessel.

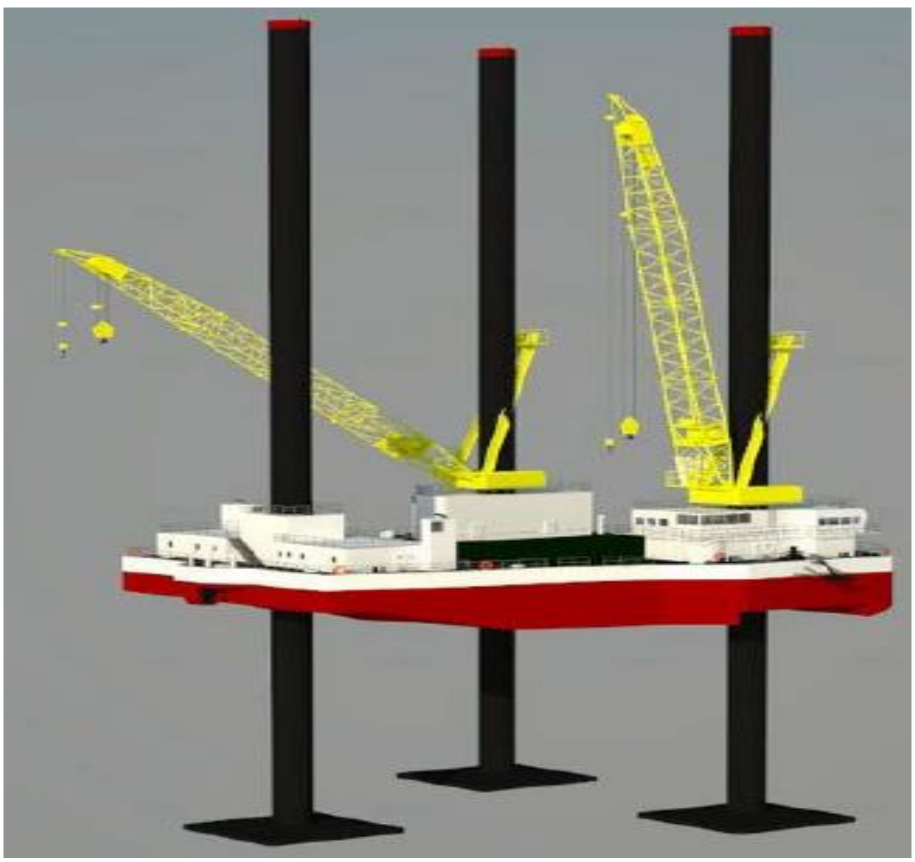

Figure 41 Jackup Design with Columnar Legs and Spud Cans (Kopits & Losz, 2013).

Elevating Devices

The elevating devices are technology adopted by vessels to move its legs upward and downward. On most conventional jack-up vessels/platforms, two of this type of technology are usually available.

(i) *The Hydraulic cylinders*

The hydraulic cylinder with moveable and stationary pins for unfolding and retraction of legs during upward and downward movement.

(ii) *Rack with 2 Pins Gears*

The rack with 2 pins gear is activated to unfold and retract the jack-up legs. This technology is can be found mostly in modern jack-ups (Kopits & Losz, 2013).

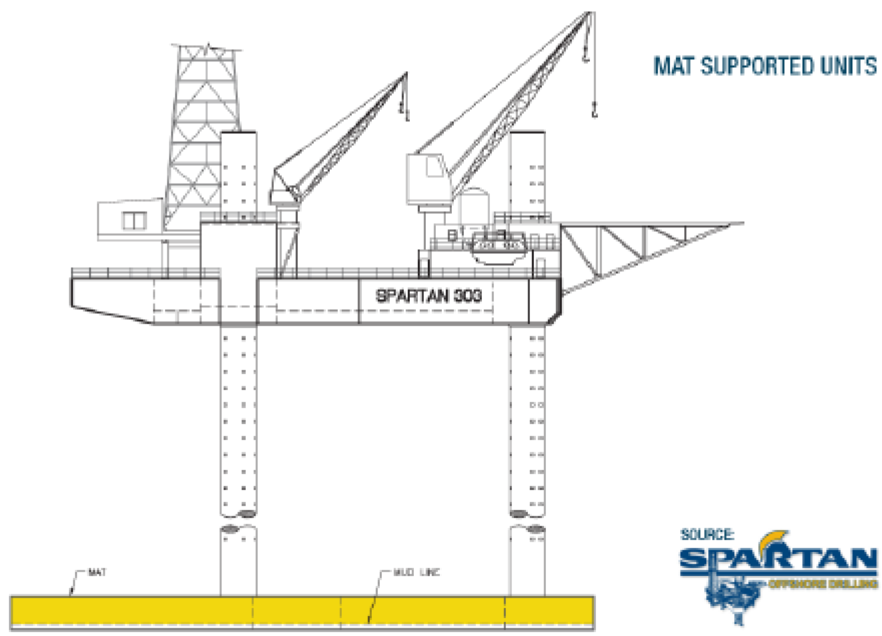

Figure 42 MAT Supported Jackup Legs (Kopits & Losz, 2013).

2.4.7 Other Vessel Equipment

Power

Vessels are powered by engines which can either be main or auxiliary energy source. The propulsion of ship derives its power from the main engine while all other activities and components on the ship uses auxiliary power source. The main and auxiliary engines, fuel and feed pumps, air compressors, gearboxes and generators are all housed in the engine room. The main engines can work with heavy fuel oil or diesel and are usually 2-stroke engines. The main engines are also referred to as the propulsion engines because they power only the propellers and not the thrusters (Kopits & Losz, 2013).

The thrusters are powered through electric motors and controlled from ship's bridge. They are specifically used to navigate vessels through a narrow path. The reversible motion of thrusters and propellers are influenced through the rotation of blades at 180^0. The Auxiliary engines are of different sizes depending on the load and are faster and smaller type of 4 stroke engines when compared with the main engine.

Kopits and Losz, (2013) also stated that;

"Larger auxiliary engines are used to drive electrical generators that support the vessels electrical systems. Most vessels have three or more generators that have more power than is needed, but this ensures smooth operations during planned or emergency engine repairs. Auxiliary engines require constant care and have their own cooling systems, fuel systems and lubrication system, among others. Diesel engines can be classified on the basis of speed (slow, medium, and highspeed), working principle (two vs. four stroke) and arrangement of cylinders (vertical vs. radial)". (Kopits and Losz, 2013, p.81)

Figure 43 Engine Room in an Offshore Supply Vessel (Kopits & Losz, 2013).

2.5 Vessels for Offshore Wind Park Operations

Vessels play a crucial role at different stages of offshore wind turbine installations, operations, maintenance and decommissioning. The success of an offshore wind park project is dependent on the efficiency and suitability of the deployed vessels. Majority of the offshore wind park vessels are classified either as support vessels or construction vessels.

Support Vessels

The important types of support vessels are as follows:

- Personnel transfer vessels (PTVs)
- Survey vessels
- Heavy maintenance vessels
- Transport barges
- Tugs

Construction Vessels

The following are main types of construction vessels:

- Heavy lift vessels / Derrick barges
- Purposely built turbine installation vessels (TIVs)
- Jack-up vessels / barges
- Cable-lay vessels

2.5.1 Turbine Installation Vessels (TIVs)

The turbine installation vessels (TIVs) are purposely built offshore vessels for wind park installation, operations and maintenance tasks. The vessels usually have an approximate length of 90 m or more in some cases and a beam of 40m or more. They have jack-up capacity and are self-propelled. The modern TIVs have the capacity to transport up to 10 wind turbines.
"TIVs are equipped with at least one crane, are DP rated, and designed to carry foundations and turbines on board. These vessels have 4 to 8 jack-up legs. Newer TIVs are larger, and they have higher crane capacity, reach, and deadweight tonnage" (Kopits and Losz, 2013, p. 57).

Figure 44 TIV at Sheringham Shoal (World Maritime News as cited in Kopits and Losz, 2013)

2.5.2 Heavy Lift Vessels

Heavy lift vessels are specialized vessels that are specifically designed for lifting and transporting heavy, large or an irregular structured cargo in which a conventional vessel cannot handle. These vessels are globally used for both offshore wind, and offshore oil and gas projects. In offshore wind farm installation and decommissioning, the heavy lift vessels are often used to install and remove substations, turbines and foundations.

There are two classifications of heavy lift vessels: The construction semi-submersibles which are basically used transporting heavy cargoes and the heavy lift crane barges or vessels which used for lifting heavy cargoes either offshore or portside (Kopits & Losz, 2013).

Figure 45 Semi-Submersible Heavy Lift Vessel Transporting an Offshore Platform (Kopits & Losz, 2013)

Figure 46 Heavy Lift Vessel with a Load of Turbine Blades (Kopits & Losz, 2013)

The heavy lift vessels can be categorized into two groups which are (i) the non-propelled heavy crane barges i.e. derrick barges and (ii) self-propelled heavy crane vessels/barges respectively. The heavy lift vessels do have large cranes with high load capacity and reach on board.

Figure 47 Heavy Lift Vessel Rambiz (London Array as cited in Kopits & Losz, 2013)

2.5.3 Jack-up Vessel

The jack-up vessels are the most popular type of vessels used for wind turbine installation. They can either be towed or self-propelled barges with either four, six or more legs depending on it weight and size. The jack-up vessels are primarily used for construction activities at the portside or offshore. The installation and decommissioning of offshore wind turbine transition pieces and foundations are part of the routine operations that can be performed using jack-up vessels or barges.

Figure 48 Rendered Image of a Jackup Barge in Operation (offshorewindbiz, as cited in Kopits and Losz, 2013)

2.5.4 Cable-Lay Vessels

The Cable-lay vessels are typically used for laying underwater cables required for power telecommunications, transmission, or other related purposes. cable lay vessels are often equipped with Dynamic Tracking (DT) and Dynamic Positioning (DP) systems. These types of vessels are usually large in size and difficult to be mobilized for operations in shallow waters. These vessels can lay single or multiple cables at a time and can join and repair cables to specific requirement.

Big cable-lay vessels are not practical in shallow waters beside the shore, instead, cable-lay barges are used. Underwater cables are best buried in shallow waters, especially where fishing is predominant, to avoid spoilage from fishing apparatus and anchors. An underwater cable can be entirely torn apart by trawling and other deep-sea fishing techniques. Cables are buried via either the rock dumping technique- a simple technique in which a bed of rocks covers the cable, or the ‘trenching and burial’ technique- in which an underwater plow dragged by a cable-lay vessel buries the cable into the trench (Kopits & Losz, 2013).

Figure 49 Cable Lay Vessel Normand Cutter (ISB offshore as cited in Kopits & Losz, 2013)

Figure 50 Cable Lay Vessel North Ocean 105 (MB 50 as cited in Kopits and Losz, 2013)

2.5.5 Survey Vessel

The Survey vessels are widely used for different types of activities, which include oil and gas seismic investigation, as well as naval and scientific research scientific and naval research. Prior to the construction stage of an offshore wind park, three types of survey are usually carried out i.e. Environmental, geophysical and geotechnical surveys.

Autonomous underwater vehicles (AUVs) or vessels fitted with sensors can be used to carry out environmental surveys. Seismic surveys of the seabed are termed geophysical surveys. These surveys are essential in planning the cable routes, jack-up operations, and installation procedures, among other functions; and are carried out before construction. Geophysical work includes various aspects as stratigraphy (geological layering), seabed features mapping, analysis of hazardous areas and seabed bathymetry (depth data). Owing to shallow water requirements for majority of recent offshore wind projects, comparatively low-cost and small vessels may be utilized for this work. Bigger and more stable vessels having highly skilled operators is required for geotechnical work. Normally, geotechnical investigations include the drilling of cable routes and sample boreholes at suggested foundation sites, plough trials for cable-lay operations, jack-up operations, and penetration tests for foundation installation. Using dedicated geotechnical survey vessels, geotechnical surveys requiring core samples can be completed. These surveys can also be accomplished by making use of any fixed platform having a drilling equipment attached to the deck (Kopits & Losz, 2013).

Figure 51 Fugro Searcher Offshore Survey Vessel Designed for Geophysical Research (Kopits & Losz, 2013)

2.5.6 Platform Supply Vessel

The platform supply vessels are also known as the offshore supply vessels (OSVs) and they are basically used for transportation of crew, supplies and cargo to either a wind farm field or an offshore platform. Most of the supply vessels are usually loaded below and above the deck to maintain vessel stability. They also have cranes on the deck to facilitate loading and offloading of supplies and cargo. The platform supply vessels are usually designed in order to sustain high speeds during severe weather conditions.

Supply vessels can be modified for a defined activity. A large number can help to clean-up oil spill while having fire-fighting abilities. Vessels require navigation near offshore structure, as such, dynamic positioning (DP) is becoming essential. Large number of modern-day supply vessels have a DP system. **(**Kopits & Losz, 2013). Supply vessels give essential service to oil platforms, based on need, they can achieve increased dayrates. When a supply vessel is employed in the offshore wind sector, an OSV can transport at a time several nacelles and two monopiles. Owing to their well-distributed accessibility coupled with the North Sea oil and gas industry, OSVs are routinely utilized in the offshore wind sector of Europe but in the united states offshore wind activities, they are used less, particularly in the primal stages of development (Kopits & Losz, 2013).

Figure 52 Offshore Supply Vessel Offloading Supplies at Platform (Kopits & Losz, 2013)

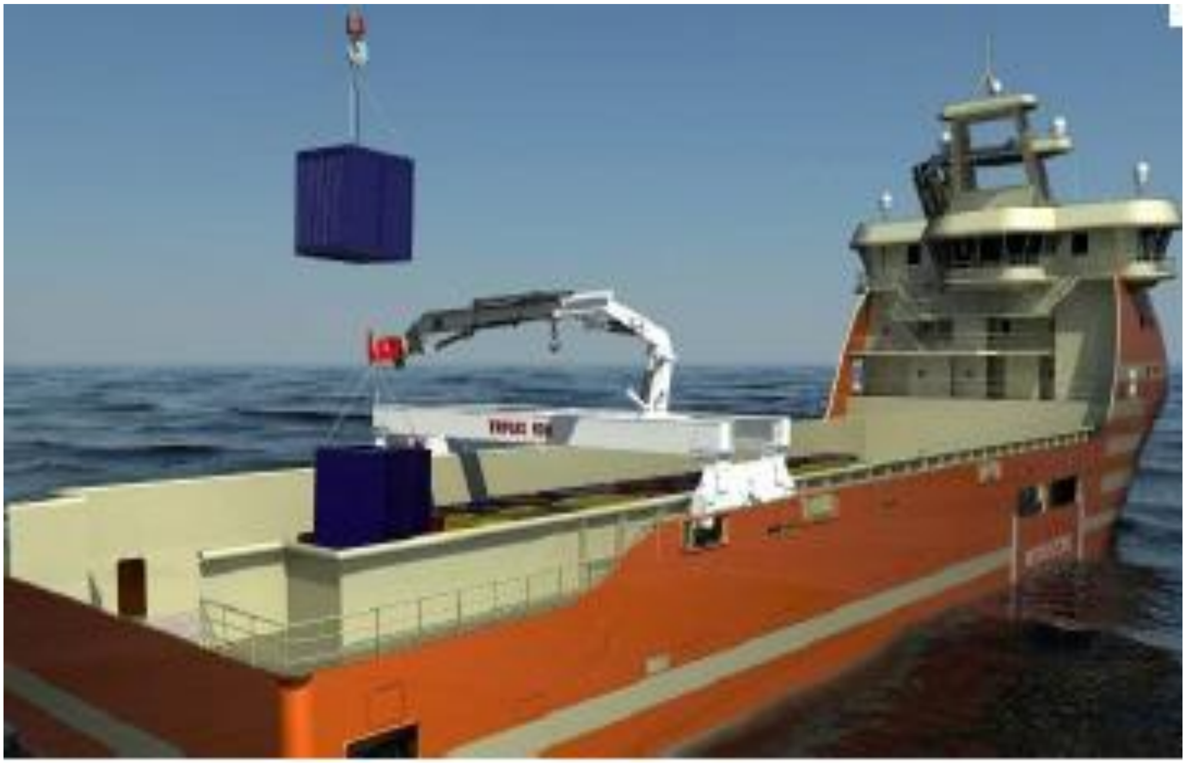

Figure 53 OSV Offloading Supplies at Platform, Assisted by Deck Crane (Kopits & Losz, 2013)

2.5.7 Personnel Transfer Vessel (PTVs)

The Personnel transfer vessels (PTVs) are needed during offshore wind turbine installation, operation and maintenance stages of the projects. PTVs are used for supplying resources and crew change to the wind turbine installation vessels during installation stage. It also provides support to the heavy maintenance vessels for transporting and transfer of crew and resources. The current design of PTVs are primarily based on a 15 to 20 m hull length and has capacity to transport 10 to 15 personnel, between 81 to 113 km. The future PTVs are expected to have 25 to 30 m hull lengths and personnel capacity of 25 to 30 crew (Kopits & Losz, 2013).
Speedy growth is estimated to occur in the PTVs industry. To aid the fast-growing installation rate in Europe and to help the maintenance activities at an increasing fleet of wind turbines globally, it is estimated that PTVs must triple in number within the next 5 years.

A few small to medium sized organizations offer personnel access services and specialized tools to the offshore wind industry in Western Europe. Offshore Wind Power Marine services, Windcat Workboats, Northern Offshore Services, North Sea Logistics, MPI workboats and Turbine Transfers are currently active companies in the sector. Should the Northern European offshore wind installation continue to grow as projected, companies not presently active in the offshore wind industry may join easily. (Kopits & Losz, 2013).

Figure 54 Motion Stabilized Personnel Transfer Vessel (Kopits & Losz, 2013)

Figure 55 Marine co Shaman Personnel Transfer Vessel (Kopits & Losz, 2013)

2.5.8 Wind Park Maintenance Vessels

Heavy Maintenance Vessels

The offshore wind turbines or wind parks do require specific repair and maintenance some periods after installations. These repair and maintenance activities can be simple or rigorous upgrade of wind turbine component like gear box accessories, blade replacement etc. A personnel transport vessel or a helicopter (i.e. helipad is required) can be used to convey the crew to the site. Meanwhile, a major repair or maintenance work in remote locations might require vessels similar to that used for wind turbine installations. As wind turbines approach the end of it life cycle, the need for either life cycle extension or decommissioning operations will arise and for wind parks with at least 100 turbines, an economy of scale would play a major role in ensuring life extension maintenance or decommissioning is carried out at competitive cost. These operations can be executed using a heavy maintenance vessel specifically designed for wind parks operations or the conventional turbine installation vessels (TIVs) and Jack-up vessels (Kopits & Losz, 2013).

Figure 56 Maintenance Crew Arriving at and Offshore Wind Farm (Kopits & Losz, 2013)

2.5.9 Barges

A barge is usually a boat or vessel that are not self-propelled that are used in offshore construction operations and for transporting heavy cargoes. They are also known as river or ocean-going boats with a flat bottom. The two functional classification of barges are construction and transport purposes.

Construction Barges (CBs)

The construction barges are specialized barges that are used for offshore wind installation and other related offshore construction projects. There are either temporary or permanent cranes on the deck of CB for specific offshore operation. A jack-up barges can be classified as construction barges while a specialized barge with derrick cranes are refer to as derricks barges. A jack-up barges can be classified has construction barges (Kopits & Losz, 2013).

Transport Barges

Barges that are specifically built for the transportation of cargo and heavy equipment are called transportation barges. The ease of loading and offloading of heavy cargoes, large and irregular shaped structures was due to their design. They are cheap means of transporting wind turbine accessories during installation or decommissioning from port to offshore location and vice versa.

Transport barges are more sensitive to bad weather and slower than turbine installation vessels (TIVs) and supply vessels. They can be stabilized with jack-up legs or spuds, although, simpler barges do not need to be stabilized. Compared to turbine installation vessels and supply vessels, transport barges are cheaper to charter and build, and are more available for use. Barges are valuable in the construction of offshore wind farm construction, especially if the wind farm is not far from shore. To guarantee a stable provision of turbine components for specialized installation vessels (TIVs or jack-ups) functioning at the installation site one or more feeder barges can be hauled. Installation vessels can thereby function more effectively as hauling between the installation site and the staging port is carried out by inexpensive transport barges instead of advanced turbine installation vessels. (Kopits & Losz, 2013).

The development of offshore wind energy industry in Europe has made the design and construction of new set of fleet barges to be manufactured. These specialized barges are designed to suit the logistic and operation need of the offshore wind industry. Some of the logistics involving heavy lifting operations (i.e. Crane operations), loading, offloading and transportation of wind turbine components.

Figure 57 Wind Feeder – Artist Rendition (Kopits & Losz, 2013)

Tug

The tugs are most often needed at various stages of the offshore wind turbine operations (i.e. installation, maintenance and decommissioning) and supply chain. Meanwhile, the primary purpose of using this type of vessel is to ease vessels, cargoes or barges pushing and pulling i.e. (towing or tugging). A tug has an efficient engine with higher capacity for towing weights or loads that are five or ten times of its weight. The power ratings of most tugs are usually specified as its bollard pull or engine horsepower. Most tugs do have two-stroke engines because two-stroke engine produces a faster revolution than engines with four strokes. The power generated by a tug's engine is dependent on the size of propeller, size of engine, type of engine, size and shape of tug. A tug can attain a sailing speed of approximately 8 to 12 knots, of which half of these sailing speeds would be needed for pulling a barge in an open water. It is much easier for a tug to pull than push a vessel or barge through a long distance (Kopits & Losz, 2013).

Figure 58 Five Harbor Tugs Assist an Ocean Going Tug with Mooring a Platform (Kopits & Losz, 2013)

Integrated Tug Barge (ITB)

The integrated tug barges are specially designed unit of a barge and a tug that are coupled together to function as a single entity. The ITB can also be used as a small vessel and it is difficult to operate it independently from a barge when they are connected as a unit.

The type of vessels was initially produced so as to meet specific functional requirements for cargo vessels with reduced size. At present, they do not have wide usage because of the negligible advantage over small cargo vessel (Kopits & Losz, 2013).

Articulated Tug Barge (ATB)

The articulated tug barge (ATB) are variate of ITBs which are joined to a barge through a notch on the stern. The barge and tug are not fixed together as rigid component, but barge and tug are rather connected together using a hinged or an articulated connection. Thus, movement is allowed along one plane or axis and in crucial area of aft and fore. In ATB, a barge can be pushed using an ATB irrespective of the load (Kopits & Losz, 2013).

Anchor Handling Tug Supply Vessels (AHTVs)

The AHTVs is very powerful and versatile types of tug that are used for transporting offshore platforms to operation sites or to ensure vessels are anchored in specified position. Furthermore, the AHTVs are used as cargo supply vessels and for transferring offshore workers to wind park field or offshore platforms. The AHTCs are specialized vessels that are not specifically built for a barge or connected to a barge unlike the standard tugs. Compare to a tug and barge entity or cargo vessels, the AHTVs have the capacity to maintain higher speed and suitable for rough sea conditions.

Ocean tugs having high bollard pull only are considered in the offshore wind sector. Different types of tugs can be used in various ways within the offshore wind industry, ways ranging from construction to operation and maintenance of offshore wind farms. Standard tugs are utilized to haul jack-up barges from a turbine to another within the construction site, and to and from the wind farm. Tugs can also haul supply barges and monopiles (with no barge) to wind farm sites. With the monopiles, there are limitations. The distance from shore to wind farm should not go beyond fifty (50) nautical miles and the tug can only sail 4 knots to 8 knots. (Kopits & Losz, 2013).

Figure 59 Aerial View of an ATB (Kopits & Losz, 2013)

Figure 60 Aerial View of AHTS (Kopits & Losz, 2013)

2.6 A Review of Offshore Wind Park Installation Vessels: *Selected Case Studies*

The OWTs installation vessels are highly specialized vessels that are specifically constructed for the wind industry. The industry players are Hereema, Saipem, Fred. Olsen wind carriers etc. The ability of the jack-up vessels to lift wind turbine components and perform other operation in a challenging offshore environment differentiate them from normal surface vessels. The propulsion speed, payload, crane capacity, station keeping, versatility and depth of operation in water are some of their unique features. The recent development in the wind energy industry whereby larger and taller turbines are now being constructed makes the call for new vessel requirements to support the advancement crucial. The efficient methods to install, maintain and decommission these latest types of OWTs is a major concern to the sustainability of the wind energy market.

Meanwhile few of the 'Fred.Olsen windcarrier' vessels and their features are highlighted in the Table 5 below.

Vessel	Pictorial Descriptions	Descriptions
Brave Tern and Bold Tern		*Length-132m* *Hull Breadth Mid-39m* *Propulsion Transit Speed -12 Knots, DP2* *Water Depth Range-5.5 To 60m+* *Crane - 800 tonnes - 26m Outreach, 102m Over Deck* *Typical Payload - 9500 tonnes*
Blue Tern		*Length - 151m* *Hull Breadth Mid - 50m* *Propulsion - 8 to 10 knot DP 2* *Water Depth Range - 65m* *Crane - 1,200MT* *Typical Payload - 7,000 tonnes*

Jill Specs		*Length - 56m* *Hull Breadth Mid - 41m* *Propulsion - Transit speed of 6 knots, DP2* *Water Depth Range - 85m* *Crane - 250 tonnes at 17m outreach* *Typical Payload - 680 tonnes*

Table 5: Selected OWTs Installations and Maintenance Vessels (Fred.Olsen Windcarrier, 2020)

2.7 Vessel Regulations and Classifications,

2.7.1 Regulations

The term 'decommissioning' is general word which simply means to abandon or remove or dispose a structure after the end of their service life as recognize by national and international legislations. In the UK, decommissioning program is stated in the UK petroleum act of 1998. The recognition of decommissioning program by an act and legislation is a global practice. The international act and regulations are subjected to an overriding agreement that decommissioning must not constitute harm or threat to the environment and other sea users (IOGP Report 584, 2017).

In the Europe for example, the Norwegian regulations and acts support decommissioning of offshore structures and most government agencies are involved in issuing permit and regulating the decommissioning program. The removal and recycling of offshore assets in Norway are regulated by other appropriate legislative authorities such as

- The Norwegian Petroleum Act
- The Parliament white paper Report, (1999-2000) – (cables and pipelines)
- Radioactive waste and pollution regulation
- The Pollution Control Act (1981)

"The Petroleum Act (1996) governs the decommissioning of offshore installations and pipelines in the Norwegian sector of the North Sea. The Act is administered by the Norwegian Ministry of Petroleum and Energy (MPE) who make decisions on the acceptable disposal method based on each individual case. A Decommissioning Plan (Cessation Plan) must be submitted by the licensee two to five years prior to the shut-down of the facility. Decisions are made based on technical, safety, environmental and economic factors as well as regard for other users of the sea. Prior to the submission of the Decommissioning Plan, the licensee is required to clarify the scope of the Impact Assessment with the Ministry. Decommissioning Plans must consist of two parts, a Disposal Report and an Impact Assessment, as set out in Sections 43–45 of the Petroleum Regulations, (Norwegian Petroleum Act, 1996). The MPE makes final decisions on disposal with feedback from other governmental bodies such as the Norwegian Petroleum Directorate (NPD) and Petroleum Safety Authority (PSA)" (IOGP Report 584, 2017, p.58)

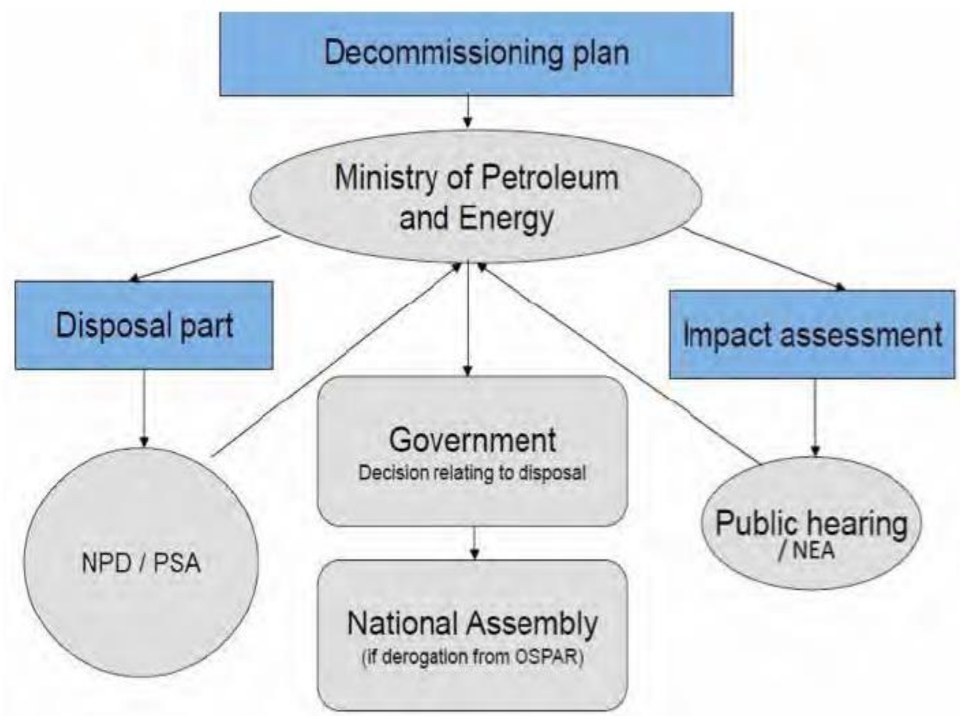

Figure 61 Decommissioning Plan Approval Process (Norway) (IOGP Report 584, 2017)

The environmental impact of the decommissioning program must be evaluated by the EIA and the Norwegian Environmental Agency (NEA) suggest means at which the pollution can be reduced. The assessment of the installations to be decommissioned should be done by considering the following (IOGP Report 584, 2017):

- Reuse for petroleum operations or tasks
- Other usage
- Total or incomplete removal
- Abandonment

Normally, cables and pipelines and cables can be abandoned in as much as they do not pose safety or environmental risk to fishing or other marine activities especially when it is not economical to bury or totally removed. Based on IOGP Report 584, (2017), the MPE are responsible for making decisions on decommissioning of oil and gas assets for example pipelines. The decommissioning strategy adopted can be any of the following:

- Clean and abandon;
- Trenching;
- Covering with rocks; or
- Complete removal.

However, the primary for cleaning and abandonment is to ascertain that the structure will not cause harm to either the environment or human health

Item	Nominal requirement	Legislation driving requirement
Platforms and other facilities	Removal but derogations possible.	OSPAR Decision 98/3.
	Removal but derogations possible.	
	Under Decision 98/3 the dumping and leaving wholly or partly in place of offshore installations is prohibited.	
	Decision 98/3 recognises it may be difficult to remove the 'footings' of large steel jackets weighing more than 10,000 tonnes and concrete installations. As a result, there are derogations for these categories of installations if the internationally agreed assessment and consultation process shows leaving them in place is justifiable.	
	Removal or abandonment dependent upon location and in accordance with 'good industry practice'	NOROG guidelines.
Pipelines	Removal or leave *in situ* if they do not constitute a hazard to navigation or commercial fishing or interfere with other uses of the OCS.	Parliament Whitepaper No. 47. NOROG guidelines.
Drill cuttings piles	Case by case.	OSPAR 2006/5 and OSPAR 2009. OSPAR currently developing sampling and monitoring guidelines in relation to cuttings piles.
Decommissioning Plan needed	Yes, a Cessation Plan incorporating a Disposal Plan and an EIA for public consultation. These must be submitted between two and five years before installation is taken out of use.	Norwegian Petroleum Act, 1996.

Table 6: Norway Summary Decommissioning Requirements (IOGP Report 584, 2017)

2.7.2 Classifications

Vessels can easily secure insurance coverage and make a call at international ports when the necessary classification has been acquired. The vessel classification can be obtained from any of the thirteen classification societies which form part of the International Association of

Classification Societies (IACS). The oldest and biggest of the classification societies are the American Bureau of Shipping, Det Norske Veritas of Norway, Lloyd's Register of UK, Germanischer Lloyd of Germany and Bureau Veritas of Belgium respectively. In December 2012, the Germanischer Lloyd and the Det Norske Veritas merged to form the world's third largest classification, certification and inspection society (Kopits & Losz, 2013).

The maiden classification society that develop a classification notation offshore vessel used for wind turbine installation was Det Norske Veritas. The developed classification was a replica of an oil and gas DNV classification for vessels used production and drilling. The requirements for construction and general vessel design of an offshore turbine installation were included in the rules (Kopits & Losz, 2013).

The primary goal of classifying ship is to examine the reliability of crucial components of the ship's structure (i.e. Hull), its structural strength, appendages, and the functional and integrity status of the steering and propulsion systems, auxiliary systems, power generation and other important features. All these are achieved by the classification societies through the developments of effective rules and verification compliance with both national and international statutory regulations which are representative of the flag administrators.

"The classification process begins in the design phase, focusing heavily on the implementation and manufacture of key components and technical specifications. During the construction of the vessel, classification society surveyors attend the vessel to verify that it is built in conformance with its approved design plans and the society's rules. A surveyor will also visit the relevant production facilities of key component suppliers to the vessel to verify that the components conform to the society's rules. The classification society surveyor(s) will also attend sea trials and other trials relating to the vessel and its equipment prior to delivery. If all requirements are met, then the society issues a certificate of classification. On delivery, the vessel will receive periodic surveys by the society to verify that it is being maintained to the required standard. These surveys generally follow a 5-year cycle of annual, intermediate and special surveys. A

class renewal (special) survey is typically held every 5 years and includes extensive in-water as well as out-of-water examinations".
(Kopits and Losz, 2013, p.88).

2.8 The Offshore Wind Decommissioning and DecomTools Project

The majority of offshore wind parks are planned for an active lifecycle of 20 - 25 years. At the end of their lifespan, they are either repower with latest components, recycled or decommissioned. The DecomTools project is an alliance of different stakeholders from Denmark, Germany, the Netherlands, Belgium, Norway and UK with the motives of developing an innovative and eco-friendly concepts of decommissioning wind turbines.

The DecomTools is a 4-year projects which is part of the *'Interreg North Sea Region Programme'*. Part of the roadmap agenda of DecomTools project is to perform novel research and demonstrate pilots modeling of vessels design, infrastructures, recycling and logistics as it related to OWTs decommissioning.

"*As part of the project, a market analysis of offshore wind and decommissioning has been published. According to the market analysis, the number of turbines coming into question for decommissioning will steadily increase from 2020 onwards. It is estimated that 22 turbines in 2020, 80 turbines in 2022 and 123 turbines in 2023 will become obsolete which raises the question of how decommissioning must be organized. According to the market analysis, Europe will have a unique potential within the field of decommissioning".* (WindTech International, accessed online January 2020).

2.8.1 Decommissioning Methods

The OWTs decommissioning begins with electrical component isolation and synthetic fluids (i.e. fuel oil, lubricants etc.). This is then followed by the turbine components removal (i.e. blades, nacelle, hub, tower, transition piece, scour protection, foundation, cables and substation. The order of removal can either be a reversal of the installation procedure or a new technique.

The process of removing OWTs from the site normally occur whenever the facilities reaches the end of its life cycle. Sometimes the need to extend the life cycle of the turbines through repowering (refurbish) of the wind farm might arise. The decision could be further examined through an objective risk assessment, safety and cost implications. Meanwhile, the functional requirement for OWTs installation is the same for decommissioning as the weight of the turbine is constant for specific case.

There are several methods of installing and disposing wind turbines, but the vessels cost, and location topography are important factors that determines the choice of approach to adopt. The crane and the lifting tasks also account for the larger percent of the vessel chartering cost. The higher the number lifting the more expensive the project.

Decommissioning Steps

Kaiser and Snyder, (2012) proposed the following procedures for the decommissioning of OWTs

1. Vessels mobilization to the offshore wind farm site
2. Preparation of turbines for cutting and lifting operations
3. Removal of turbine components in 1 to 6 lifts
4. Transportation of the decommissioned components from site to onshore for recycling, disposal or reuse.

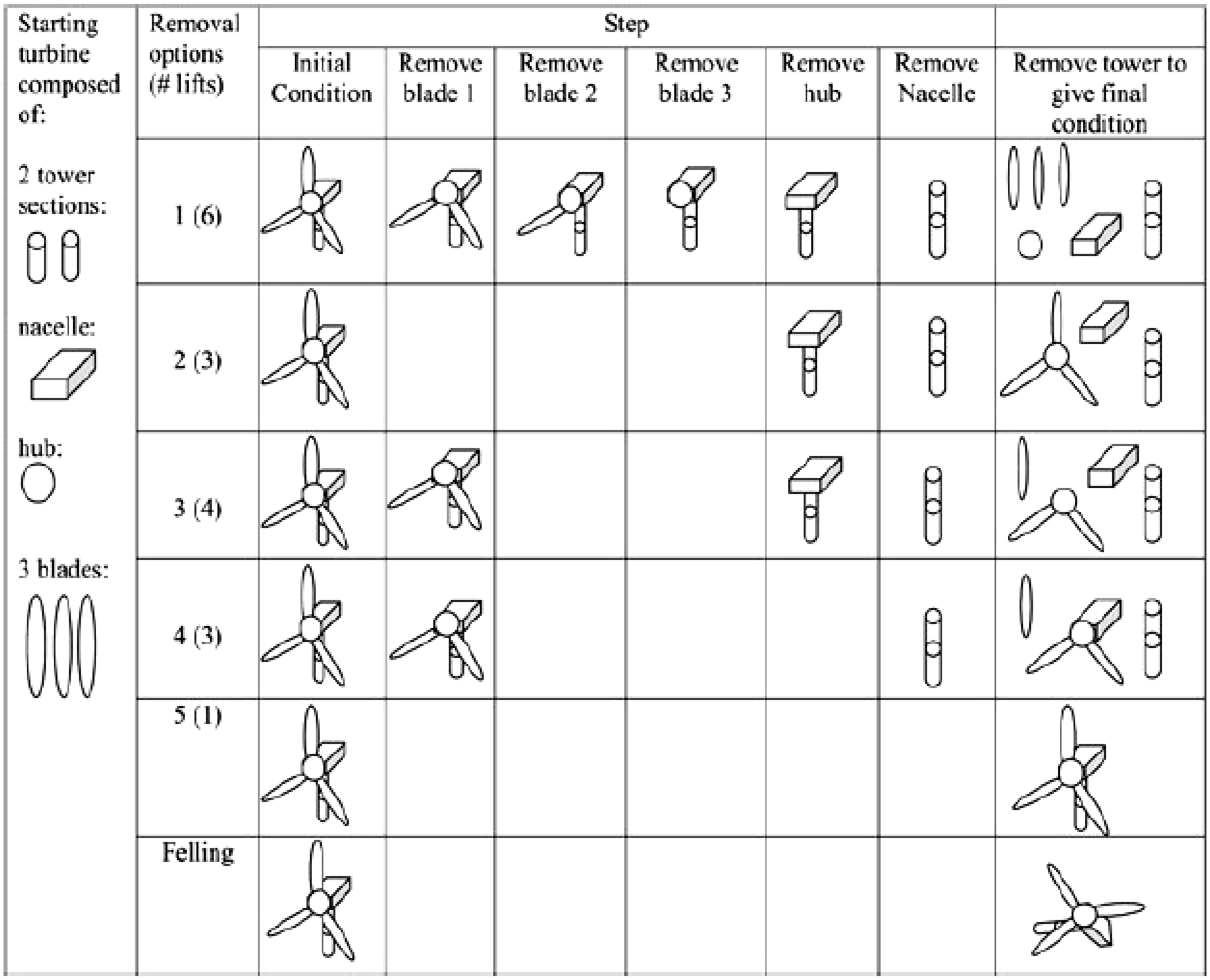

Figure 62 Traditional offshore turbine decommissioning options and an alternative (Kaiser and Snyder, 2012).

2.8.2 Vessel Requirements for OWTs Decommissioning

The vessel requirements for OWTs installation is similar to that for decommissioning. The following requirement in addition to the general vessels criteria are essential for offshore wind turbine removal.

- Lifting capacity of 300-800 tons at 120-200 meters above sea and 4m to 10m away from the vessel.

- Sufficient deck space for OWTs storage. This deck space should have a capacity for large volume of processed turbines after decommissioning.
- Efficient lifting capability in an environment with severe weather and sea conditions. The lifting operations are carried out using jack-up crane vessel. The higher the number of jacking legs, the higher the stability and the more expensive the vessel.

2.0 Interviews and Discussions with Companies

The major players in the wind energy industries where contacted but just few were eager to give out useful information either due to their company's policy, or other reasons. This is one of the challenges facing the OWTs industry as there are no standard regulations, information on procedures or methodology, technical expertise among others. The knowledge gap is wide, but this thesis is likely to bridge the gap and reveal the latent opportunities therein.

The interviews were conducted remotely with few companies via skype and phone calls due to the COVID-19 pandemic. Majority of the companies reached out to could not honor/grant the request for the master thesis interview as operations have been suspended to curtail the spread of the disease. Some of the companies did not have capacity or time for interview while others ignore the request message. The summary of the information from companies are provided in the next sub-heading.

3.1 Summary of Information from Companies (Heerema and DeepOcean) and Important Vessel Requirements

The operations of different companies are in line with their areas of specializations. Some of them specifically focus on cables (inter-array and export cables) and general oil and gas operations while others specialize on installations and decommissioning of wind turbines. The area of specialties determines their response to the interview questions. The offshore and subsea companies' experience on vessels are restricted to offshore surface vessels. These vessels are designed to meet up with the functional or mission requirements of oil and gas structures like installations, maintenance and decommissioning of templates, pipeline, flexible flowlines etc. Such requirements can be ROVs, diving systems, deck capacity, DP system, crane capacity etc. For such companies the height and weight of wind turbines pose some challenges that makes OWTs installations and decommissioning projects difficult for them aside from the fact that such projects are not within the scope of their business. The most important features of OWTs are the legs of the vessel, deck capacity, payload, crane characteristics and DP systems.

They all agreed that the future of offshore vessels lies in hybrid vessels and remotely operated vessels. However, autonomous vessels are still far from reality as automotive companies like *'TESLA'* are still experiencing some difficulties and constraint in producing autonomous cars. Therefore, improving on drone technology for ROVs, Unmanned vessels are the future of the offshore and marine industry.

3.0 Vessels Design and Development

Designing a maritime vessel do requires a thorough knowledge of the functional requirements, construction method, repair and maintenance strategy, and decommissioning of the vessel. The life cycle information of the design from the conceptual idea to the decommissioning of the vessel is essential for efficiency and sustainability reasons. In this research, the vessel requirements for offshore wind turbine decommissioning was used as guidelines and MPI resolution installation vessel as reference. The proposed concept of compressing the turbine components and storage for space management which in turn will reduce the project duration and cost is similar to the oil and gas floating, production, storage and offloading (FPSO) vessels.

There is a high market potential for this type decommissioning vessel as the energy policy tend to favor the offshore renewable wind energy now and in the future.

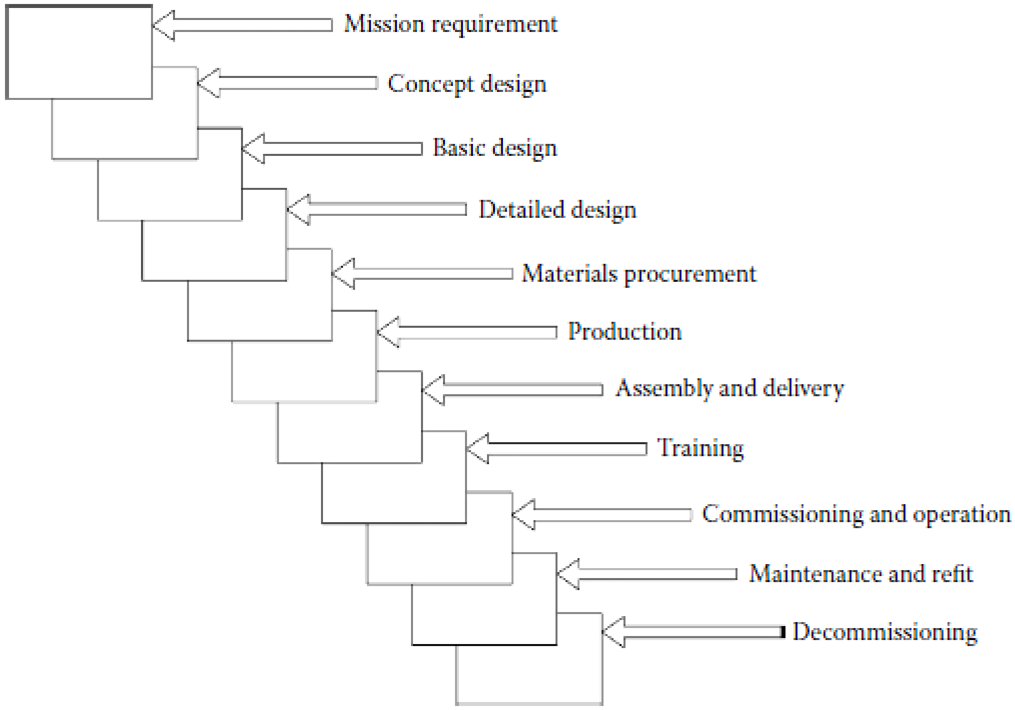

*Figure 63 Maritime product life cycle (*Misra, 2015*).*

Misra (2015), suggested a marketing strategy for marine product can be implemented through the steps:

- Identification of customers need through an effective market survey
- To design and develop product that can satisfy the need
- To identify interested industries for product manufacturing and relate to enterprise
- Increase product awareness to the identified market

4.1 Vessel Design Concept

The main objective of this master thesis is to develop a conceptual vessel design concepts OWTs decommissioning. The vessels are expected to meet up with the future requirements for efficient, and sustainable operations, in the North Sea. The system-based vessel design framework was used for the vessel development. The proposed conceptual vessels design for decommissioning tasks has a capacity to remove, lift, store and transport at least 20 wind turbines to the shore after the components have been processed to sheets or plates for vessels space management. The main advantage of this vessel is the reduction in project or operations time and cost. The two models of vessels suggested for the decommissioning operations were the floating, processing and storage vessels (FPSV) and jack-up, processing and storage vessels (JPSV) respectively.

It is envisaged that the two models met up with the vessel, functional and operations requirements in an efficient and sustainable manner.

4.2 Conceptual Description of Heavy Hydraulic Press

The heavy hydraulic metal press was adopted to mechanically compress the turbine and its components for compaction or compression to form metal sheets/plates. The pressing machines was used for metal pressing and recycling i.e. scraps compaction prior to further processing or charging into the furnace. Some of their processing unit do involve extrusion but, in this study, the pressurized compaction was the only functional requirement in the design. There are two processing procedures for the OWTs before storage in the compartments.

(i) Processing of OWTs scrap to sheets or plates
(ii) Processing of the OWTs scrap to balers (more compact cubes)

Figure 64 Metal Baler (TCM baler, 2020)

A schematic diagrams of case (i) and (ii) are shown in Figure 65 and Figure 66 respectively.

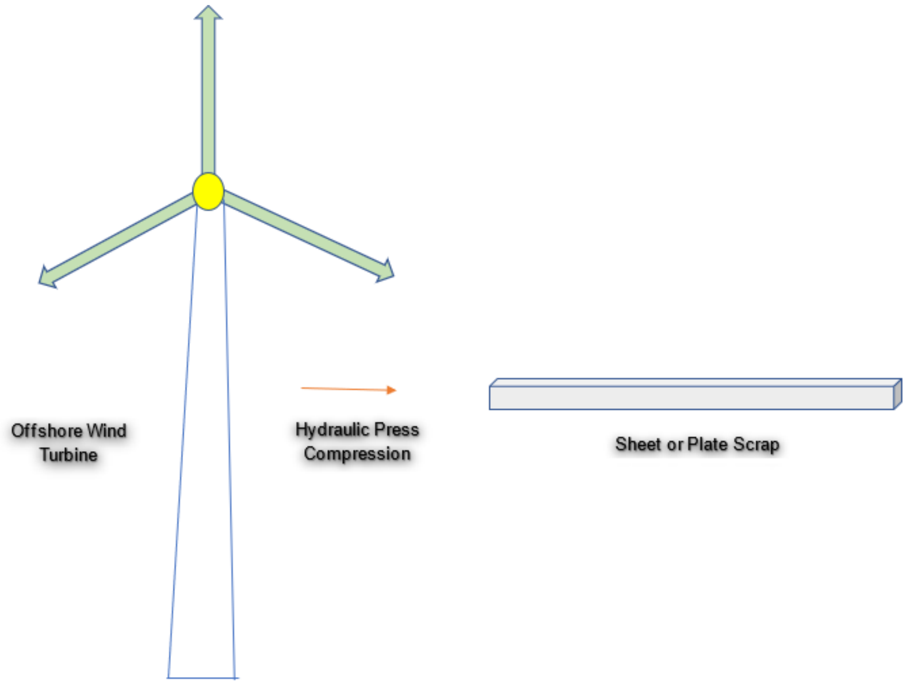

Figure 65 Processing of OWTs scrap to sheets or plates

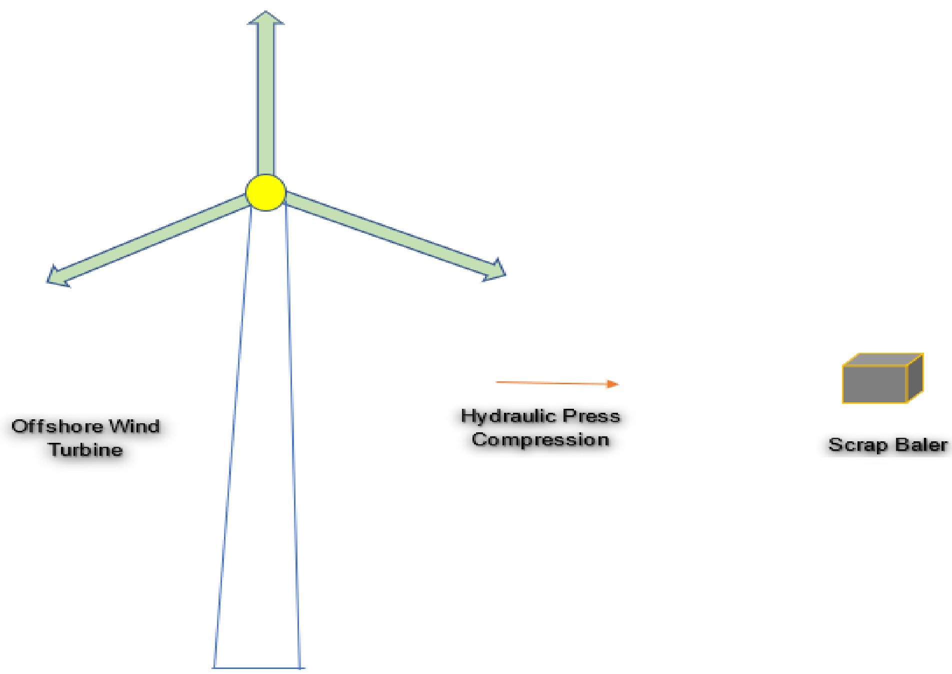

Figure 66 Processing of the OWTs scrap to balers (more compact cubes)

4.3 Principle of Operation of Hydraulic Compression Baler

The baling press has a lateral pre-extrusion frame a long carriage with the primary compactor, automation system, and vertical ejector door. The frame is the main component of the bailing machine press. It is usually made up of strong, and thick steel. Although the cost of constructing or purchasing the equipment is high and the design is slightly complex but its high production rate, security reliability and increase life cycle could offset the cost and make it market viability sustainable.

In this investigation, a 1500 tons hydraulic press was proposed for the OWTs compaction. The equipment would be installed on the vessel using welding process. The baler press machine has three technical features which are as follows (Li et al., 2016);

(i) A 3-D extrusion system

(ii) A container with block fixed on the sides

(iii) A vertical/horizontal ejector door

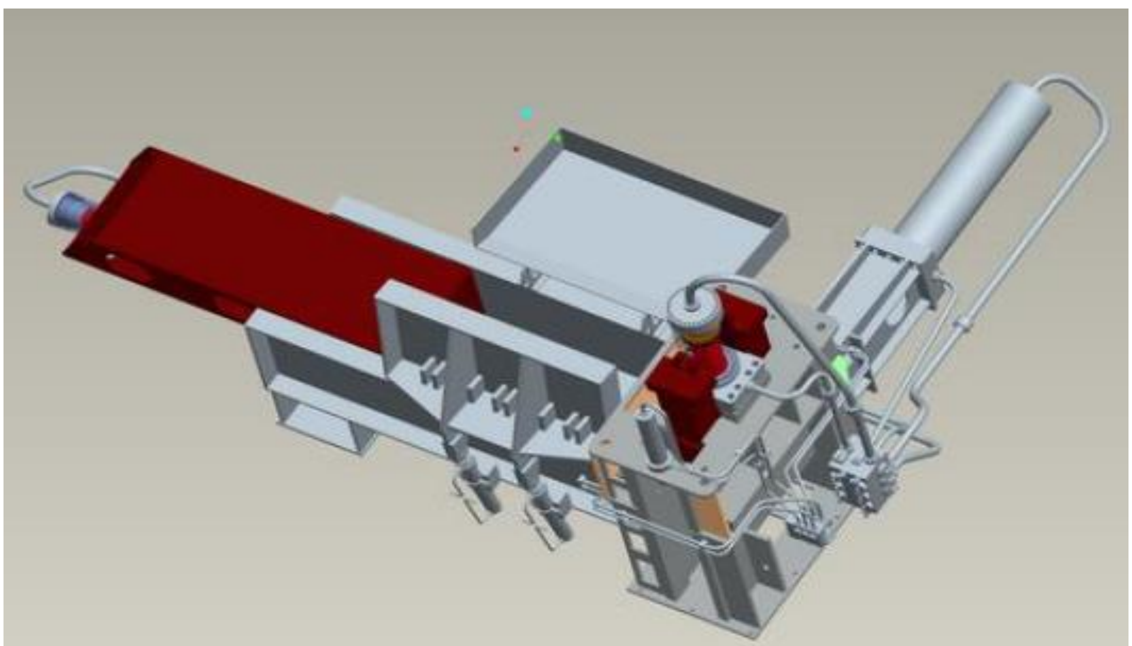

Figure 67 Schematic 3-D diagram of Bailing Press (Li et al., 2016)

4.3.1 Electric control system

This is an important system of the equipment. The electrical system comprises of the network diagnosing and remote monitoring systems. It also has monitoring interface for human to machine and a programmable controller (PLC) for executing logic control.

4.3.2 Hydraulic system

The hydraulic system adopted are the cartridge and integrated block valves. This choice of valves makes the structure to be more compact and ensures the high reliability of operations.

Parameters	**Descriptions**
Dimension (mm)	51400 x 33420 x 14480
Weight (t)	520
Power Rating of Main Motor (kW)	10 x 180
Bale production size (mm)	1600-3000 x 1200x 1200
Density of Bale (kg/m^3)	4400 - 6400
Number of bales (bales/h)	76 x 80
Feed box size (mm)*	11020 x 4000 x 3000
Length of feed box (mm)*	-
Nominal pressure (kN)	63
Main pressure(kN)	20000

Table 7: Design Parameters: Compression Press (Li et al., 2016)

Note*: The dimension of the OWTs is used to define the feed box geometry (i.e. Feed box size and length respectively).

4.4 The MPI Resolution Vessel

The MPI Resolution is a world class and purposely built OWTs installation vessel. The vessel has a proven record of having a strong versatility in a dynamic and harsh environment. The consideration of MPI model while designing a new vessel decommissioning vessel was based on the principle that an OWTs installation steps could be reverse for removal. Meanwhile, the vessel requirements for the new tasks is high due to an increase in components weight, propulsion system demand, vessel speed, deck capacity and recycling/processing equipment. The methodology adopted for the vessel design was system-based design concept. The approach is a bottom-up principle and emphasis is placed on the functional requirements.

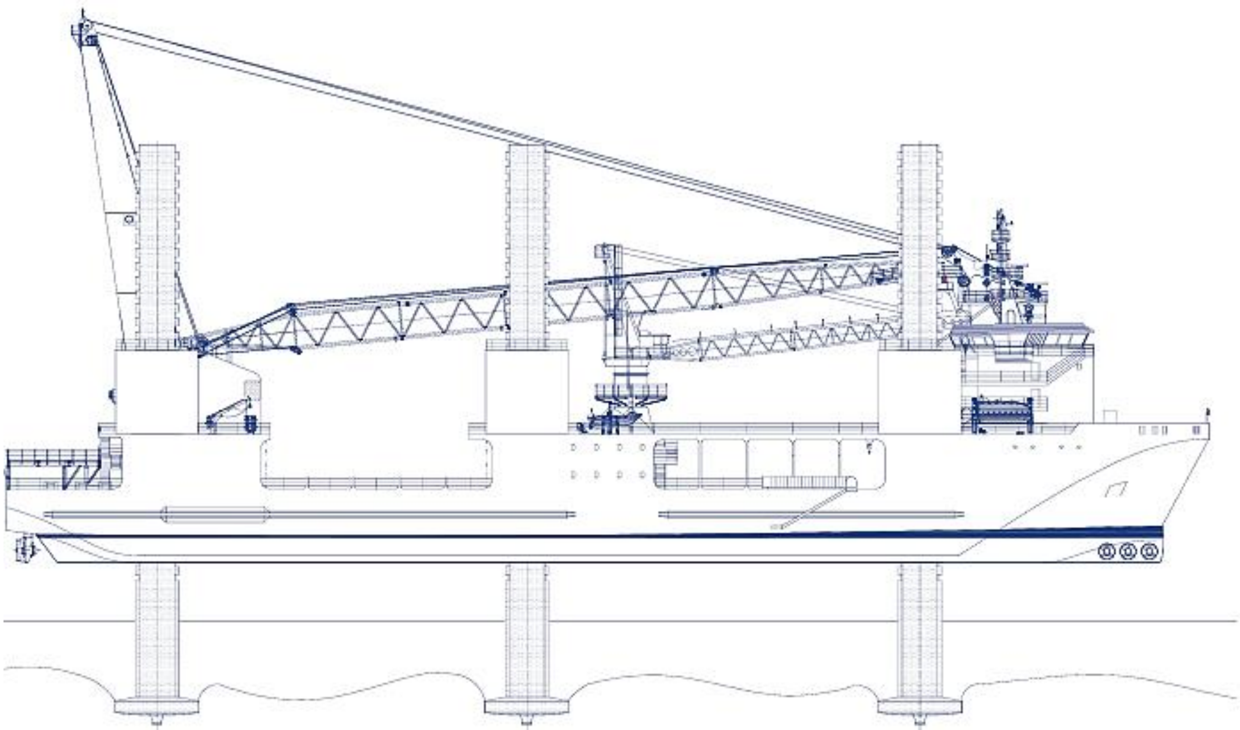

Figure 68 Elevation view of MPI Resolution (MPI Data Sheet, 2017).

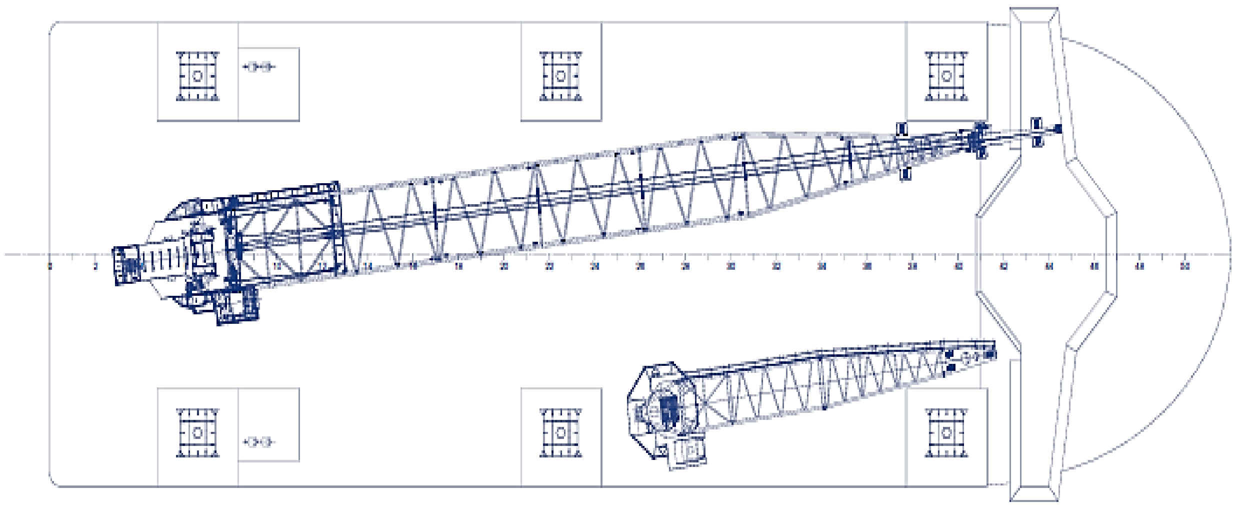

Figure 69 Plan View of MPI Resolution (MPI Data Sheet, 2017)

Specification	Description	Total weight of 20 units (tonnes)
Capacity (MW)	300	
Distance (km)	11.3	
Depth (m)	20-25	
Turbines (MW)	100 x 3 (V90-3)	
Weight (tonnes)	396	7920
Hub height (m)	105	
Blade length* (m)	55	
Rotor diameter*(m)	113	
Expected life (years)	20 x 2	
Meterological mast and Foundation type	Monopile	
Foundation type	Steel Monopile: Cu (2m)	
Offshore substation	1: Jacket, lifted + piles cut (2m)	
Weight Topside (tonnes)	1460	29200
Weight foundation (tonnes)	820	16400
Inter-array cables	Copper 33kV: Left (buried 1-2m)	
Total length (km)	65	
Total length sections (mm^2)	95/300/400	

Table 8: Description of Thanet OWTs (Topham, and McMillan, 2017).

*Note: The blade length and rotor diameter are assumed**

*Total weight of hydraulic press ~ **800t***

*Total cargo load for 20 turbines excluding substation and cable = 800t +7920t = **8720t***

*Total weight of 20 turbines including substation = 29200 +16400+8720 = **54,320t***

*Assuming the weight of inter-array cables in kg per m = **7740kg/m***

*Therefore, weight of inter-array cables in tons/km = **8532t/km***

*For a 11km inter-array cables, the total weight of cables = 11*8532 **= 93,852t***

4.5 Conceptual Description of Vessels

The Thanet wind farm decommissioning operations would be described with special consideration to the vessels. The description of the field was described in table 1 below. Meanwhile, the MPI resolution vessel was used for the installation of wind turbines. The primary Vessel requirements – Deck space, crane capacity, DP system, etc.

4.5.1 Vessel Specifications

The specification of the proposed vessels is highlighted in the Table 9 below.

Design Model	Model A	Model B
Parameters	**Jack-up Processing Storage Vessel (JPSV)**	**Floating Processing Storage Vessel (FPSV)**
Length (m)	200	340
Breadth (m)	40	60
Maximum water depth (m)	40	32
Maximum draft (m)	5.5	20
Cargo area (m^2)	4000	10,000
Main crane load (t@m)	1200@26m	1600@26m
Crane height (m)	120	150
Payload (t)	12,000	280,000
Speed (knot)	12.5	-
Jack up legs	6	-
Accommodation	120 persons	170
Dynamic positioning system	DP2	DP2
Helideck Class	HELDK SH	HELDK SH
Propulsion System	Diesel 2 stroke engine	-
ROV System	2 Work class and 2 observation inbuilt system	-

Table 9: Conceptual Vessel characteristics

In the table above, data for Model A was developed in line with vessel DP regulation which is referenced to an existing vessel (i.e. MPI resolution). The new mission requirements were also considered in the design process e.g. payload, crane and deck capacity respectively. The data acquisition procedure for Model B was similar to Model A except for the fact that Model B is a non-self-propelled vessel with DP 2 system for station keeping.

4.5.2 Operational Profile

The operational profile of an existing MPI resolution vessel was used guide to proposed vessel characteristics for the JPSV. The Thanet offshore wind farm has 100 OWTs installed and the decommissioning process could be effectively carried out using the proposed concept. The proposed vessels are expected to decommission 20 wind turbines (i.e. wind turbine components and inter-array cables). The design should be able to sustain and adapt to different operational requirements that are related to logistics and transit time.

Among the functional requirements are efficient crane capacity, deck space, and deck capacity. The processing of the decommissioned turbines to plates or bales for effective storage is a newly introduced concept. These procedures will reduce the travel time of the vessel from site to port has the vessel can remove more turbines on a trip.

4.5.3 Environment

The characteristics of the environment often affect wind turbine operations. The offshore weather condition is also very harsh for both the personnel on board, fastened equipment, and the ship. Meanwhile, the structural design of the ship, the shape geometry, and intact stability are essential factors to be considered for a successful offshore operation. The proposed vessels should withstand the North Sea environmental conditions.

Sea State Parameters	North Sea (Ekofisk)	North Sea (Troll)	Norwegian Sea
Hs (m)	14.0	15.0	16.5
Tp (s)	15.0 – 17.0	15.5 – 17.5	17.0 – 19.0
One hour Mean Wind Speed (m/s)	34.0	45.5	37
Surface Current (m/s)	0.55	1.5	0.9

Table 10: The Sea state conditions and a 100 years corresponding return period, mean wind speed for 1hour and 10 years return period for three different locations in the North Sea (Standard, D. O DNV-OS-E301, 2004).

4.5.4 Important Deck Equipment

Detailed engineering and design analysis of the facilities/equipment onboard the vessel are essential tools to ensure intact stability of the vessel. These facilities or equipment are part of the offshore requirements. The size of the ship and the number of personnel on board will determine how these facilities could be designed or planned. The following are a list of the standard facilities to be designed on an offshore vessel; (i) modularized accommodation, (ii) high redundancy machinery, and (iii) cargo capacities. Due to time constraints in writing this thesis, the engineering and design analysis of these facilities would not be performed.

Offshore vessels are characterized by six (6) important variables that define its cargo capacity, stability, etc. The variables are the length of the vessel (L), the breadth of the vessel (B), depth of the vessel (D), draught (T), block coefficient (Cb), and freeboard (F). The displacement of the vessel can be estimated if the volume and weight of the components are defined. The block coefficient is derived from the standard guideline of existing vessels. The depth, draught, and breadth are then calculated when the speed and displacement of the vessel are ascertained. The cost of vessel, capacity, and stability are then derived using the six (6) variables. (Schneekluth, and Bertram, 1998)

The length of a vessel with low construction costs can be estimated using Schneekluth and Bertram's model (1998).

$$L_{pp} = \Delta^{0.3} * V^{0.3} * 3.2 * \frac{C_B + 0.5}{(\frac{0.145}{F_n}) + 0.5} \qquad [1]$$

Where $\Delta \geq 1000[t]$ and $0.16 \leq F_n \leq 0.32$

F_n – Froude number = $\frac{V}{\sqrt{g*L}}$ [2]

L_{pp} – Length between perpendiculars [m]

V – Speed [kn]

Δ – Displacement [t]

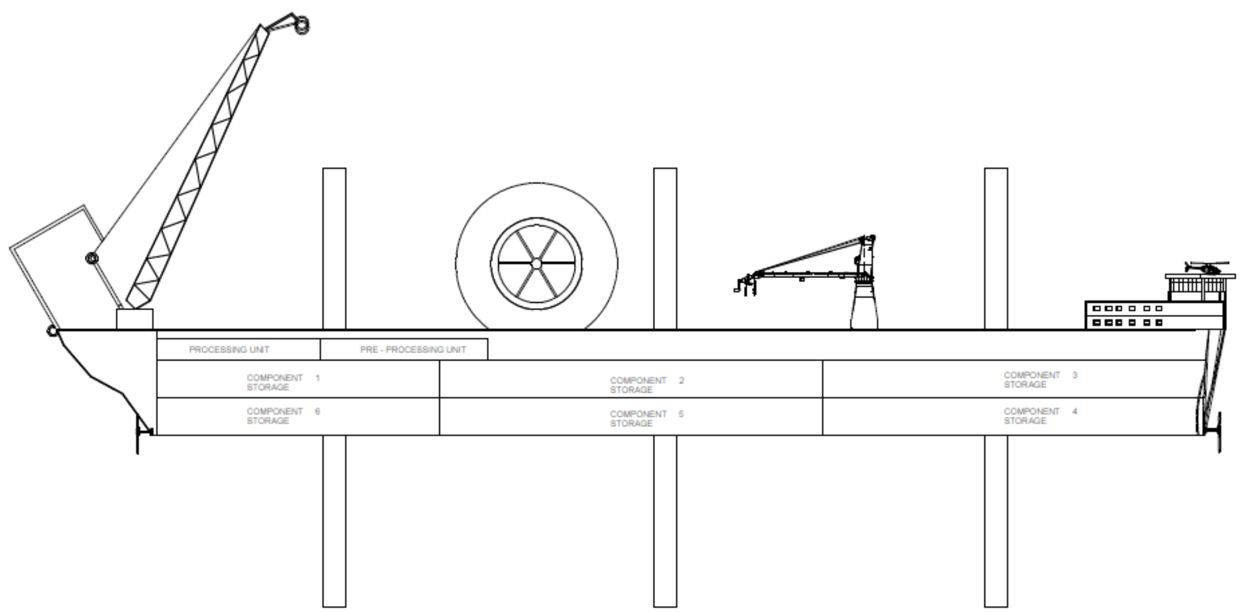

Figure 70 2D view of the proposed vessel with storage compactment of JPSV

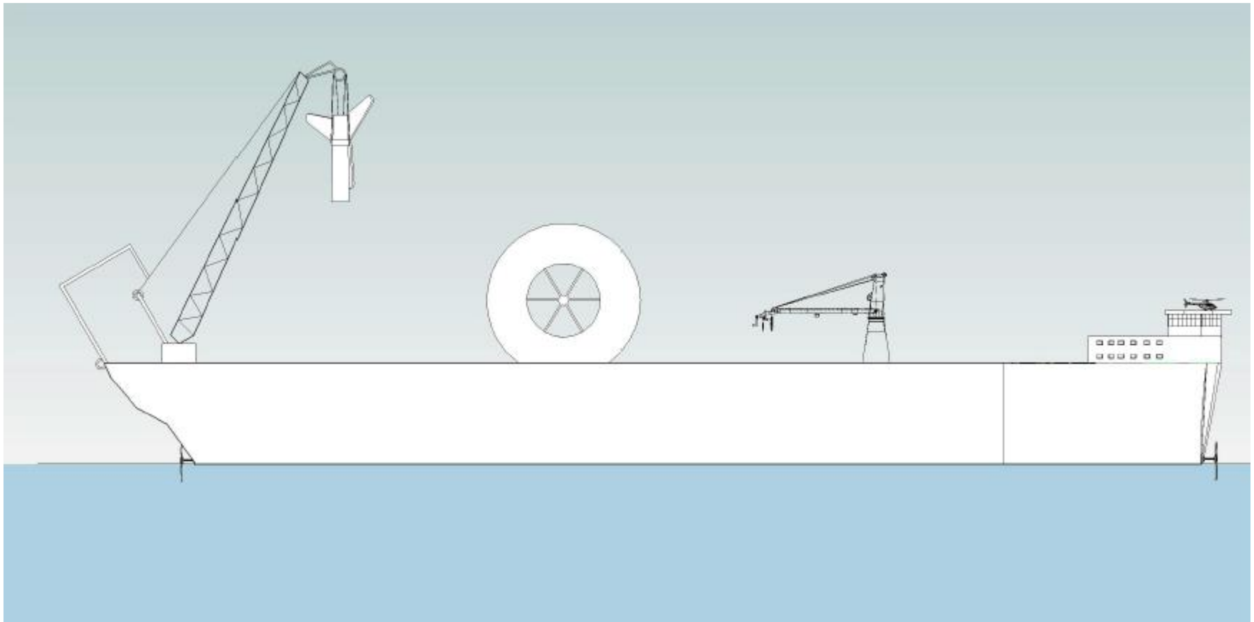

Figure 71 2D view of the proposed vessel of FPSV

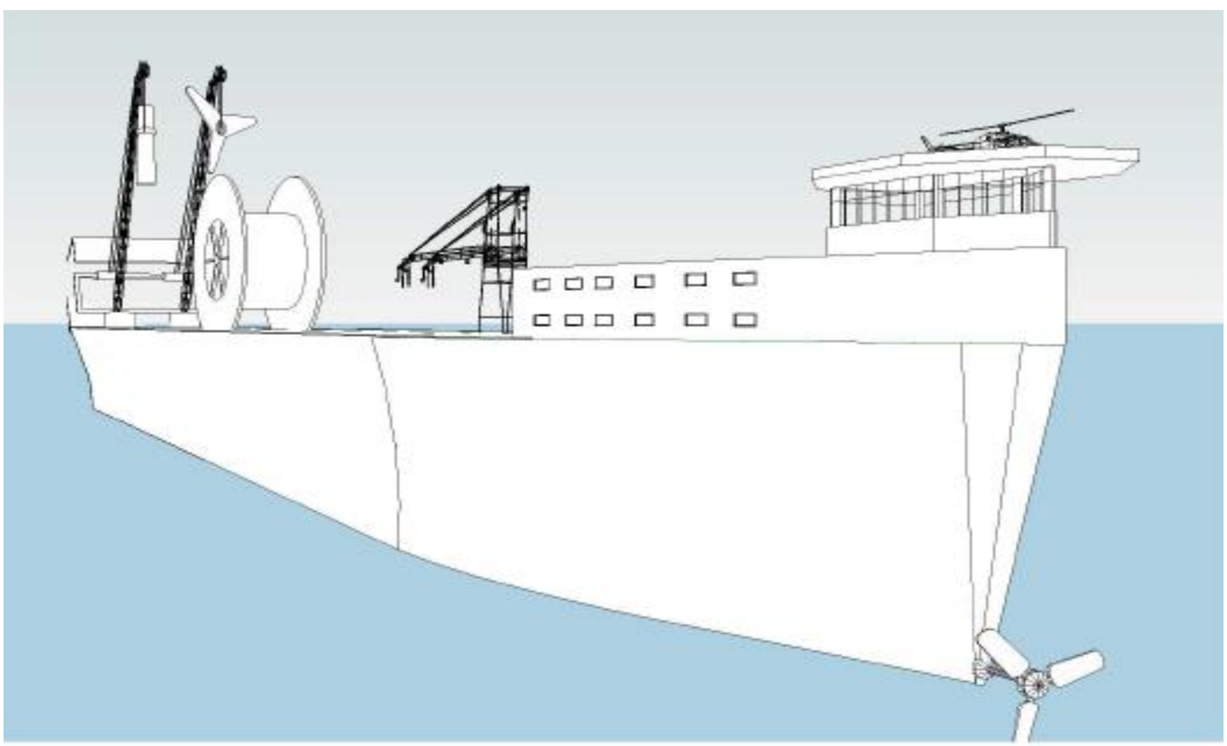

Figure 72 3D view of the proposed vessel FPSV

4.6 Vessel Operation Variables

The vessel operations variables are factors that can affect vessel activities if not properly managed. The wind park decommissioning period is also affected by the environmental factors for example sea state, wind speed, ice, snow, visibility, ambient temperature, lightning etc. Meanwhile, the operations must be executed at situations when the environmental influence is considered safe and secured as stated in the equipment's manufacturers guide. The following are list of the variables which can influence the offshore maritime operations:

- The seabed condition i.e. seabed penetration of 2 to 6m for jack-up vessels,
- The lifting capacity of the crane with respect to the tower height environmental conditions
- Sea state or weather window
- Wind speed
- Wave Current,
- Significant wave height,
- Air gap,
- Weather window
- Deck capacity,
- Cranes capacity for lifting operations,

The decommissioning method adopted, size of turbine, expertise of the personnel onboard and crane efficiency, weather window for safe operations etc. are variables which are peculiar to specific site locations and they greatly affect the completion time of the decommissioning tasks.

4.7 Decommissioning Cost Estimation Modeling

The Decommissioning process are carried in steps using different vessels. The cost of removing wind turbine components are estimated using a precise model with each component having it specific cost of removal, recycling or processing, scrap revenue and disposal. The decommissiong costs depend on the removal duration per unit, total number of units and vessel(s) dayrates for the operation. The recycling cost, disposal cost , and revenue from scrap are calculated per weight (ton) for each turbine component. The total cost for decommissioning all the wind turbines are the summation of the individual cost for removal, recycling, disposal and scrap (Kaiser & Snyder, 2012).

Kaiser and Snyder (2012) proposed cost estimation models for decommissioning tasks and vessels spread as shown in the equations below.

4.7.1 Cost estimation Model for Self-transport Vessels

The self -propelled vessels are assumed to remove, store and offload the turbine components at the port. The vessels are expected to reach their maximum capacity before leaving the site for the port. The removal rates are estimated per trip and the total time per trip is the addition of removal time, loading time, transit time, and intra-field movement time (Kaiser & Snyder, 2012).

TRAVEL, h - total travel time

D, nm - distance to port

S, kn - speed of vessel

$$\text{TRAVEL} = 2 = \left(\frac{D}{s}\right) \quad [3]$$

REMOVE, h - total per-trip removal time

LOAD, h - total off-loading time

MOVE, h - total per-trip intra-field movement time

VC - vessel capacity (number turbines)

R, h - removal

L, h - off-loading

M, h - intra-field movement times per turbine

$$\text{REMOVE} = VC \times R \quad [4]$$

$$\text{LOAD} = VC \times L \quad [5]$$

$$\text{MOVE} = VC \times M \quad [6]$$

ADJTRIP, h - weather-adjusted time per trip; where W = duration of time that vessels are unable to travel

W - 1 No weather delay and W = 0.5 when half of time that vessels are unable to operate

TRIP, h - total time per trip

$$\text{TRIP} = \text{TRAVEL} + \text{LOAD} + \text{REMOVE} + \text{MOVE} \qquad [7]$$

$$\text{ADJTRIP} = \text{TRIP} \times \left(\frac{1}{\text{W}}\right) \qquad [8]$$

NUMTRIP - number of trips

NUMTURB - number of turbines

REMTIME, h - removal time

$$\text{NUMTRIP} = \frac{\text{NUMTURB}}{\text{VC}} \qquad [9]$$

$$\text{REMTIME} = \text{ADJTRIP} \times \text{NUMTRIP} \qquad [10]$$

TDC, $/day - total daily cost

VDR, $/day - vessel dayrate

SDR, $/day - spread dayrate

$$\text{TDC} = \text{SDR} + \text{VDR} \qquad [11]$$

COST, $ = total project cost ($)

$$\text{COST} = \frac{\text{REMTIME}}{24} \times \text{TDC} \qquad [12]$$

4.7.2 Cost estimation Model for Non-Self-transporting Vessels (Barges)

Since the turbine decommissioning vessels do not convey the components from the site to the port, then a cargo barge is usually made available to receive the components then transport it to the port to avoid operation downtime(Kaiser & Snyder, 2012). The total removal time per unit can be estimated as follows;

TURB, h - total turbine removal time per turbine

R - time to remove a turbine

M - move to another field location

$$\mathrm{TURB} = \mathrm{R} + \mathrm{M} \quad [13]$$

ADJTURB - Weather adjusted time per turbine

$$\mathrm{ADJTURB} = \mathrm{UNIT} \times \left(\frac{1}{W}\right) \quad [14]$$

$$\mathrm{REMTIME} = \mathrm{ADJTURB} \times \mathrm{NUMTURB} \quad [15]$$

$$\mathrm{COST} = \frac{\mathrm{REMTIME}}{24} \times \mathrm{TDC} \quad [16]$$

4.7.3 Cost estimation Model for Jack-up Vessels to Dispose OWT Foundation

The total time for a jack-up vessel to remove a turbine can be estimated per unit foundation. The time to remove turbine foundation is the sum of jack-up stabilization time, mud pumping from foundation time, foundation's pile diameter cutting time, and time to jack down the vessel and move to the next foundation (Kaiser & Snyder, 2012).

JACK-UP, h - time to stabilize on site

PUMP, h – time to pump mud from the foundation

CUT, h/m – time to cut the foundation

D, m – pile diameter

LIFT, h – time to lift the foundation and place on a barge

MOVE, h – time to jack the vessel down and move to the next foundation

TPF, h – total time per foundation

NUMFOUND – number of foundations

TDC, $/day - total daily cost

VDR – vessel day rate

SDR – spread day rate

$$\mathrm{TPF} = \mathrm{JACKUP} + \mathrm{PUMP} + (\mathrm{CUT} * \mathrm{D}) + \mathrm{LIFT} + \mathrm{MOVE} \quad [17]$$

$$\mathrm{COST} = (\mathrm{VDR} + \mathrm{SDR}) * \frac{\mathrm{FC}}{\mathrm{TC}} * \mathrm{TPF} \quad [18]$$

4.7.4 Cost estimation Model for Offshore Support Vessels

The cost of the jack-up vessel (main turbine removing vessel) and the cost of OSV are summed. The jack-up daily cost is the addition of the vessel day rate and spread day rate. The vessel removal time per foundation is sum of the vessel stabilization time at site, foundation lifting onto a barge time, and time to jack down and move to the next foundation (Kaiser & Snyder, 2012).

TPFr, h – time per foundation for the removal vessel

TPFo, h – time required to cut the monopile

STABILIZE, h – time to stabilize at the foundation and move to the next foundation

ODR, $/day – OSV dayrate

$$\mathrm{TPFr} = \mathrm{JACKUP} + \mathrm{LIFT} + \mathrm{MOVE} \quad [19]$$

$$\mathrm{TPFo} = \mathrm{STABILIZE} + \mathrm{PUMP} + \mathrm{CUT} + \mathrm{MOVE} \quad [20]$$

$$\mathrm{COST} = [\mathrm{TPFr} * (\mathrm{VDR} + \mathrm{SDR})] + [\mathrm{TPFo} * \frac{\mathrm{FC}}{\mathrm{TC}} * \mathrm{ODR}] \quad [21]$$

4.8 Efficiency Assessment of Vessels for Decommissioning Tasks

The efficiency assessment of the vessel was measured through the propeller's configuration, hull design, crane characteristics, deck space, and vessel speed. The performance of each of the aforementioned equipment when examined using pre-defined criteria or key performance indicators (KPI) determines the efficiency of the vessels. During turbine removal operations, the JPSV vessel will display crane efficiency. Although the deck space is small compare to FPSV, its stability through jacking up and down of its legs to extreme turbine height would override the payload. With reference to the Thenat windfarm decommissioning, the JPSV can successfully decommission, process, and store 20 turbines (topsides) from the calculations in Table 8 and Table 9. The total cargo load for 20 turbines is estimated to be 8720t while the JPSV design payload is 12,000t.

The ease of mobilization and demobilization of the two vessels are equally very important in the assessment of their efficiency. The JPSV can be easily mobilized and demobilized due to its narrow size and adaptability, unlike the FPSV.

Both vessels could operate efficiently in extreme weather conditions. The DP 2 class systems and active heave compensation of the vessels are survival mechanisms during harsh weather conditions.

Finally, the design of the configuration of the propulsion systems of the vessels is to ensure decommissioning tasks are carried out effectively and efficiently without any downtown

4.9 Sustainability Assessment of Vessels for Decommissioning Tasks

In this report, sustainability was assessed based on the emission capacity of the vessels. The deadweight and transit speed. From the proposed models, the JPSV has smaller storage capacity compare to the FPSV. This implies that FPSV is likely to emit more dangerous gases due to heavy cargo load. However, the JPSV can equally releases pollutants when operated at a high transit speed to gain more time. However, slow steaming of the JPSV could help to reduce this emission but the trip will take longer duration. Also, a non-self-propelled FPSV that utilizes the conventional anchoring and mooring system would reduce or eliminate emissions. The following are other sustainability measures incorporated in the prototype;

- Hybrid propulsion system
- Low carbon emission (Green vessel design)
- Health, safety and security compliant
- Eco-friendly design i.e. having little or no impact on environment

The sustainability of maritime products is important when discussed in relation to business and market demand. The product must be viable without harming the environment and human. Meanwhile, offshore vessels are designed for the survival, safety of lives, environmental protection and continuity of the business.

The sustainability of vessels for decommissioning are equally considered in terms of operational and technological performance. These assessment measures the means of curbing the rate at which emissions of hazardous gases are released into the environment. These goals can be actualized by reduction in fossil fuel usage, adoption of renewable source of power, reduction in sea contamination and ensuring that vessels are constructed using recyclable materials

4.0 Results and Discussion

In this investigation, the JPSV would be used to execute the disposal tasks. The vessels were designed to have 6 legs to support the load and ensure stability. The processing of the wind turbines on the jack-up vessel before loading onto the FPSV would make the task effective and reduce the transportation logistics from the site to the port. Although, the JPSV is bound to consume more fuel but from the cost estimation model above, the fuel consumption cost can be offset by reduction in transit time. Also, the JPSV is designed to dispose and store only the wind turbine topside components and foundation (i.e. Blades, Nacelle, Tower, and hub) while the FPSV is designed to multi-tasks between the turbines, substations, and cables.

Offshore decommissioning vessels are guided by specific operational conditions for example crane lifting performance, deck capacity, transit speed, payload etc. Meanwhile, the ability of OWTs decommissioning vessels to adapt to their mission and design requirements were discussed. The introduction of processing and storage concept into vessel design would greatly reduce the operations time of the projects. This principle has been efficiently used in the oil and gas industry in which a floating vessel (i.e. FPSO) is employed for production, storage and offloading of the crude oil. However, for wind energy, heavy weight scrap is processed, store and offload at the port after decommissioning. The reason for converting the turbine component into sheets, plates or scrap bales would ensure effective vessel space management.

The two models proposed for the decommissioning were the JPSV and the FPSV respectively. The JPSV was used for turbine removal while both vessels have storage sections for scraps. The storage capability of FPSV is bigger and can also serve as cables retrieval vessels. The combination of the two vessels for wind park decommissioning would not only reduce the operation duration and cost but also reduce the number of vessels spread for the project.

5.0 Conclusions and Proposed future work

5.1 Conclusions

The North Sea and offshore environments are highly challenging especially for operations that involve lifting of heavy structures. The conditions such as sea conditions, currents, waves, wind speed, water depth due have direct influence on the duration at which an operation will be completed. These factors primary affect the vessel performance, therefore the need for vessel that has sufficient flexibility and capacity to scale through the weather challenges of these environments.

A model for decommissioning cost estimation was suggested. The vessel cost of removing, transporting, recycling and offloading each component of the OWTs can be calculated before the commencement of the tasks. A comprehensive knowledge of the procedure, operations options will assist in the initial project planning. In this report, discussions on conceptual vessel design for offshore wind turbine decommissioning as it relates to maritime operations has been presented with little or no consideration on technology and engineering aspect of vessel design.

In conclusion, several factors are affecting the OWTs industry aside from the challenge of weather in the offshore environment. The problem of vessel availability, lack of expertise, and non-effective procedures for decommissioning and poor rules and regulations to support the operations. This thesis specifically addresses the method of eradicating the challenges through vessel design. The ability to design vessels that can operate efficiently in the offshore environment at minimized time is very important for the sustainability of the renewable energy industry. A vessel with high versatility and large deck and crane capacity would improve the operation logistics and efficiency. The concept of offshore recycling and storage of the wind turbine has been introduced as part of the ambition to ensure affordability of wind renewable energy.

5.2 Recommendations and Proposed Future Work

In furtherance to the development of new specialized vessels, the OWTs decommissioning program can be planned and synergized with the initial wind turbine design, installation, operations and maintenance. The bubble synergy or chain will ensure effective and efficient management of the entire system. This approach will make the disposal of the wind turbine less challenging.

With the advancement of technology and the development of smart, 'functionally graded' and 'self-healing' materials, a turbine with 30-50 years life cycle could be designed, modelled and constructed. These set of materials are characterized with unique and dynamic mechanical and electrochemical properties which can resist the severe pressure from ocean current.

Biofuel for running offshore wind vessels is important in order to close the sustainability and renewable cycle. Offshore wind energy vessels running on diesel or other fuel sources make our call for a green world ironical. The release of dangerous pollutant into the environment pre-exposes the living and nonliving to severe health and extinction hazards. The geometric effect of NOx, SOx and CO2 on biological systems and climate is alarming. The earlier we incorporate renewable energy fuel into the renewable energy operations, the better the future of the yet unborn generations.

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APPENDIX I

Dear Sir,

I am a Master of Maritime Operations student, Offshore and Subsea Specialization at the Western Norway University of Applied Sciences, Haugesund, Norway & University of Applied Sciences, Emden/Leer, Germany.
I am currently researching on Conceptual Design of Vessels for Offshore Installations and Decommissioning as part of the Interreg DecomTools EU Project. Part of the scope of the study is to interview people from recognized establishments who have had experiences in Offshore Vessels Designed for Installations and Decommissioning tasks. A discussion with a member of your organization would enrich my knowledge of vessel operations and give my research a unique dimension.
Finally, I have come to respect the professionalism characterizing your organization and its employees and I am confident that the company's team, values, and objectives would highly complement my enthusiasm and pursuits. Below is the contact detail of my project supervisor.

Thank you for your cooperation and I look forward to receiving your positive response.

Project Supervisor
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INTERVIEW QUESTIONS

DECOM Tools Project

1.0 OFFSHORE OIL & GAS INSTALLATION AND DECOMMISSIONING

-Has your company been involved in installation & decommissioning of offshore Oil and Gas structures?

- What has been your Scope of Work in these projects?

-What are the Offshore installation requirements?

- What methods have been used for installing the structures (subsea and topside)?

- What vessel equipment and tools have been used for installing the structures (subsea and topside)?

- What is your experience using these methods/tools?

- What are the vessel requirements for the installation & decommissioning tasks?

- How are the parts/components lifted onboard the vessel(s) and transported to the offshore site?

- Which types of vessels have you been using?

-What alternative vessels can be used for installation & decommissioning tasks?

- Has towing of structure elements been used?

-What is your/company's experience using different vessels for different offshore oil and gas tasks?

-What is your submission about the future of vessels for these types of operations?

-How does your organization measure vessel efficiency during offshore installation & decommissioning operation?

-What is the significance of vessels toward ensuring your company remain relevant in the offshore energy industry?

2.0 WIND PARK INSTALLATION

-Has your company been involved in installation of offshore wind park? Which wind parks? How many wind turbines? What is duration of the installation? Which period of the year?

- What has been your Scope of Work in these projects?

-What are the Offshore wind farm installation requirements?

- What methods have been used for installing the structures (subsea and topside)?

- What vessel equipment and tools have been used for installing the structures (subsea and topside)?

- What is your experience using these methods/tools?

- What are the vessel requirements for the installation tasks?

- How are the parts/components lifted onboard the vessel(s) and transported to the offshore site?

- Which types of vessels have you been using?

-What alternative vessels can be used for installation tasks?

- Has towing of structure elements been used?

-What is your/company's experience using different vessels for different wind turbine Installation tasks?

-What is your submission about the future of vessels for wind park turbine Installation?

-How does your organization measure vessel efficiency during offshore installation operation?

-What is the significance of vessels toward ensuring your company remain relevant in the wind energy industry?

3.0 WIND PARK DECOMMISSIONING

Have you been involved in decommissioning of offshore wind park? Which wind parks? How many wind turbines? What is duration of the project? Which period of the year?

- What has been your Scope of Work in these projects?

-What are the Offshore wind farm decommissioning requirements?

- What methods have been used for decommissioning the structures (subsea and topside)?

- What vessel equipment and tools have been used for decommissioning of structures (subsea and topside)?

- What is your experience using these methods/tools?

- What are the vessel requirements for the decommissioning tasks?

- How are the parts/components lifted onboard the vessel(s) and transported to the offshore site?

- Which types of vessels have you been using?

-What alternative vessels can be used for decommissioning tasks?

- Has towing of structure elements been used?

-What is your/company's experience using different vessels for different wind turbine decommissioning tasks?

-What is your submission about the future of vessels for wind park turbine decommissioning?

-How does your organization measure vessel efficiency during offshore decommissioning operation?

-What is the significance of vessels toward ensuring your company remain relevant in the wind energy industry?

- Can the installation process and vessels be easily reversed for decommissioning of the wind parks?

- Will decommissioning projects related to wind energy be a growing part of your

business for the next 20 years?

- Are you planning to expand your international operations related to decommissioning

projects?

-What are your recommendations on the sustainability and reliability of vessels for wind park decommissioning?