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The challenges in installation of offshore wind farms

A case of Lillgrund and Anholt wind farms

Master's thesis in Design and Construction Project Management

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ABSTRACT

Wind energy is one of the rapidly growing sources of energy due low emissions resulting from its use. The energy can be harnessed both onshore and offshore. There is however, a growing interest in developing offshore wind resources owing in part to the large energy resources available offshore and availability of development space. Offshore wind energy is however more expensive than other energy sources due to the large capital expended during wind farm development.

The construction of offshore wind farm can either be successful or unsuccessful since it encounters many challenges throughout its construction processes. Installation of offshore wind turbines is one process among others in wind farm construction and it is conducted under several phases.

The aim of this thesis was to identify the constraints and challenges encountered during the installation phase of offshore wind turbines with specific focus on the Baltic Sea region. Offshore wind farm installation was considered as operation. Consequently the theories on operations management, operations strategy, supply chain as well concepts on offshore windfarm development were used for this study.

A qualitative approach was applied for the research and data was collected from six interviews conducted with professionals that were involved in installation of Anholt and Lillgrund offshore wind farms. The analysis of collected data showed that installation challenges exist and can either be due to nature such as sea bed and weather conditions or technical issues related to equipment, planning, technology and working methodology.

In attempts to increase power generation wind turbine components are becoming bigger and heavier and the wind farms increasingly being located further from shore. As the components size and distance from shore increase the installation challenges also increase. Therefore, developers and contractors have to continuously develop processes and equipment to overcome the expected challenges.

Key words: offshore wind turbine, challenges in offshore projects, offshore vessels, supply chain, operations management, wind farm.

Contents

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1 Introduction

The global energy consumption is growing and is projected to grow by 56 % between 2010 and 2040 (U.S. Energy Information Administration, 2016). A larger percentage of the global energy used is mainly from non-renewable sources such as fossil fuel. Non-renewable energy has been associated with different negative environmental impacts such as greenhouse gas emission and their consequent effects (Rodrigues et al., 2015).

The above mentioned challenges require strategic solution by either decreasing energy consumption or finding other alternative sustainable and clean energy sources. In 2007 the European Union committed to reduce emissions by 80–95% by 2050 through gradually changing from using fossil energy sources to renewable energy sources rather than decrease energy consumption, as it is quite difficult to reduce energy consumption in short time. To achieve this, 20 % of energy consumption will be generated from renewable energy by 2020 and a predicted 34 % of electricity to be generated from renewable sources (Rodrigues et al., 2015).

Also to meet these challenging targets, Intergovernmental Panel on Climate Change plans to have 80% of the world's energy supply from renewable sources by 2050 and have wind energy as a major source of electricity generation by the same year (Sun, Huang and Wu, 2012). As countries in the European Union seek to meet their targets for renewable energy use, wind energy is increasingly being adopted for electricity generation. The installed wind energy capacity is estimated to grow up to 150 GW by 2030 (EWEA, 2011).

Wind energy can be harnessed by facilities based both onshore and offshore. Onshore wind farms have been in use for a much longer time than their offshore counterparts. Both offshore and onshore developments have advantages and disadvantages. Onshore wind farms are cheaper and easy to install compared to offshore wind farms, but are restricted by availability of land, noise and poor visual impact.

On other hand, offshore wind farm development is constrained by large capital investments resulting from among others costly marine foundations, expensive installation procedures and limited access for operation and maintenance (Bilgili et al., 2011). The development process is further complicated by the involvement of different stakeholders, a complex set of contracts (Koch, 2014) as well as increasing interest in locating larger offshore wind farms farther offshore and in deeper water (EWEA, 2011). As result, offshore wind energy remains much more expensive and less competitive than other energy sources.

Regardless of the disadvantages, offshore wind power continues to grow due to the availability of consistent and stronger wind speed which enables higher production per installed unit. Additionally large areas for project development and fewer complaints from the public make offshore development attractive.

Against the background of increasing interest in offshore wind farm development coupled with complexities in the offshore development processes, there is need to continuously reduce the constraints by continuously improving the operating methodology involved in offshore wind farm planning, design and installation processes. This can be achieved by among others learning from challenges encountered and processes employed on completed projects.

1.1 Aim and Objectives

Due to the success of the initial projects and the commitment of different countries to develop sustainable, clean and renewable energy sources, several countries especially northern European countries continue to invest in the offshore industry. However, offshore wind turbine makes new technological demands not only in its design but also in the fabrication, transport, installation, operation and maintenance. Although there is a large growth potential, offshore wind turbine is still more expensive than onshore wind turbine. Various challenges occur from their feasibility study to the final completion. These constraints and challenges affect the project both technically and financially.

The aim of the research was to identify the challenges faced in the installation of offshore wind farms (i.e., from installation of foundations to commissioning) with specific focus on offshore activities within the Baltic Sea region.

To achieve the aim of this research, the objective was to find answers to the following questions:

- What are the major decisions to be considered for an installation of offshore wind farm?
- What are the challenges faced in the installation of the different components of wind turbines and how do the identified challenges arise?
- What are the persisting challenges? Why and how can they be mitigated?

The identified main constraints and challenges were further described according to the above research questions.

1.2 Scope

The research work was limited to the challenges faced within the installation phase from foundation to commissioning of wind farm. Particularly the research concerns the offshore wind farms constructed in Baltic Sea region. The study addresses the main constraints and challenges that hinder all involved stakeholders during installation of wind turbines.

1.3 Methodology

Study design
The research was conducted with the aim of identifying the challenges in the installation phase of offshore wind turbines and focused on learning from some

completed projects as case studies. A qualitative study design, using personal interviews with offshore wind power professionals, was employed. By using interviews for data collection, the encountered challenges could be known.

The research was conducted considering offshore installation as an operation, to this end the theory about operations management, operations strategy, supply chain as well as concepts on offshore windfarm development were adopted and used for analysing and discussing the collected data.

Source of data

To collect scientific information, a literature search was conducted; Chalmers library and Google Scholar were used as the main sources for acquiring literature. Specific keywords such as wind turbine, offshore wind power, offshore oil and gas industry and challenges in offshore projects were used to attain reliable and relevant academic articles and journals. Initially, the abstract and conclusion sections of the papers were read to check for relevance to the aim of the thesis .Based on the year of publication the articles published from 2010 were prioritized. A total of 52 articles were screened out of which 39 were considered and carefully read for this research. The 39 consisted academic journal articles, books and reports.

The obtained literature and other information concerning previous experiences from offshore wind farms were studied to compile the theory and get an insight of challenges faced in installation of offshore wind power projects. Supplementary information was obtained through conducting interviews and email correspondence with professionals in the industry. Additionally, information on the wind farms chosen for the study was obtained from websites dedicated to offshore wind reporting. During the research process, information and data was continuously updated. Fortnightly supervision meetings were organised to discuss results, progress and to seek guidance from supervisors.

Selection of case studies

In 1998, Baltic Sea countries and the European Commission initiated the intergovernmental Baltic Sea Region Energy Co-operation (BASREC). In 2009, the parties agreed to continue strengthening energy co-operation with strategic actions to accelerate the development of offshore wind power in the Baltic Sea Region in the coming years. The ambition was to optimise the contribution of wind power to accomplish European vision targets (20% less CO_2 emissions, 20% more energy efficiency and 20% of energy from renewable sources in 2020). In regard to the above commitment, the cases studied were selected from the Baltic Sea.

In order to select case studies for this research, wind farms constructed within the Baltic Sea region over the past 10 years (2005 – 2015) were considered as shown in Table 1. With the exception of EnBW Baltic 2, the rest of the wind farms could be categorised within the 20-20 segment (i.e. constructed less than 20 km from shore and in water depth of less than 20 m) with the dominant foundation structure as gravity base and monopile.

Table 1: Existing wind farms constructed between 2005 and 2015 in the Baltic Sea (Source: 4C offshore, Wikipedia)- Edited by Authors

EXISTING

Wind farm	Capacity (MW)	Turbine capacity (MW)	Construction year	Depth Range (m)	Km to shore	Foundation	Developer	Owner	Country
Anholt	400	3,6	2013	15	20	Monopile	DONG Energy	DONG Energy	Denmark
EnBW Baltic 2	288	3,6	2015	23-44	35.4	Monopile & Jacket	EnBW Baltic 2	EnBW Energie	Germany
EnBW Baltic 1	48,3	2,3	2011	16-19	16	Monopile	EnBW Baltic 1	EnBW Energie	Germany
Rødsand II	207	2,3	2010	6-12	9	Gravity	E.ON	E.ON	Denmark
Lillgrund	110	2,3	2008	4-13	9	Gravity	Vattenfall	Vattenfall	Sweden
Karehamn	48	3	2013	6-20	7	Gravity	E.ON	E.ON	Sweden
Sprogø	21	3	2009	6-16	10	Gravity	Sund&Baelt	Sund&Baelt	Denmark

In addition to the already existing windfarms, some of the planned wind farms with available information were also taken into consideration to give an overview of future developments. The foundation and distance to shore conditions for the planned and existing wind farms were observed to be relatively similar. Considering advances in technology, some of the planned wind farms have larger capacities than the already existing. Figure 2 shows some of the planned wind farms.

Table 2: Planned offshore wind farms in Baltic Sea (Source: 4C offshore)

PLANNED

Sea	Wind farm	Capacity (MW)	Turbine capacity (MW)	Depth Range (m)	km to shore	Foundation	Country
Baltic	Bornholm	50	3-10	9-20	8,8	Monopile+ gravity	Denmark
Kattegat	Mejlflak	80	4	7-22	8	Monopile or gravity	Denmark
Baltic	Omo syd	200-320	3-8	8-13	11,3	Monopile	Denmark
Baltic	Smalandsfarvandet vest	200	3-10	5-20	13,2	Monopile or gravity	Denmark
Baltic	Blekinge	1000-2500	3	10-40	19,4		Sweden
Gulf of bosnia	Klocktarnan	660	5	1-44	20,7	Gravity	Sweden
Baltic	Kustvind	300		26-30	11,7		Sweden
Baltic	Oskarshamn	400		0-32	4,5	Anchored concrete rings	Sweden
Baltic	Wikinger	350	5	37-43	39,2	Jacket	Germany
Baltic	Arcadis ost 1	348	6	43-45	21	Jacket	Germany
Baltic	Arkona-becken sudost	385	6-7	21-28	37,5	Monopile	Germany

Considering 20-20 criteria and the commonly used foundations one case was selected from each category of foundation. Additionally, wind farms with at least 100 MW were considered.

As a result, Anholt wind farm founded on a monopile foundation and located in the Kattegat Sea in Denmark was selected as one of the case studies. Lillgrund based in Sweden and Rødsand II based in Denmark emerged as candidates for gravity foundations. In order to have a wind farms from different countries, Lillgrund based in Sweden and in the Öresund region was selected as the other case study in preference to Rødsand II.

Selection of participants

Interviews were conducted with selected professionals; most of them being project managers, from various companies involved in offshore wind farm development activities. The interviewees were involved in installation of Anholt and Lillgrund wind parks working for developers, contractors or service providers. Most of the interviewees were suggested by their respective companies. A total of six interviews were conducted with six experienced professionals in offshore wind farms particularly in North and Baltic Sea.

Interview guide

An interview guide was developed by the research team based on the research objectives, questions and hypotheses derived from theory. The research team was guided by the following principles and sought to ensure that the interview fulfilled the following requirements:

Relevance; ensure that the interview was conducted with the relevant actors i.e. the right person who was in charge of specific task during the installation of a predetermined wind farm.

Symmetry; the authors sought to achieve symmetry by interviewing people who held different positions on the same project.

Equivocality; this was intended to obtain the view of any person/party that had been alluded to by a previous interviewee hence facilitating the possibility of gaining different opinions on a given issue.

Saturation; this was achieved when the interviewees talked relevant matters and the information acquired was relevant to research objectives.

Data collection procedure

Mapping of general challenges collected from different academic research papers and reports constituted preliminary data. Preliminary data on challenges which generally occur during wind farm installation was partly used to set questions for semi structured interviews with the participants from developers and contractors at Lillgrund and Anholt wind farms.

To further obtain additional information on challenges faced at Lillgrund and Anholt wind farms, other project stakeholders such as service providers and experienced professionals in offshore wind farm were also interviewed. Semi structured interviews were selected to offer the interviewees the liberty to express their experiences on the projects while at the same time allowing the interviewers the opportunity to guide the discussions towards obtaining relevant information needed to meet the research objectives.

Analysis

Obtained results on challenges encountered in wind farm installation were gathered and discussed. The differences and similarities were highlighted and the most often occurring challenges were identified together with their causal effects and their current status. Depending on the status (mitigated/unmitigated) of the identified challenges, suggestions were made on what considerations can be made by developers and contractors to minimise their occurrence.

2 Trends in wind farm development

2.1 Wind turbine development

Simply stated, wind turbines are used to generate electricity from the kinetic power of the wind. The kinetic energy from wind turns the blades, which rotate a shaft, connected to a generator that converts the kinetic energy into mechanical power which is finally converted into electricity by the generator.

Wind turbines can be classified into two basic groups: the vertical-axis and horizontal-axis wind turbines. Both have advantages and disadvantages, modern wind turbines are mainly developed for large scale power production. The most popular turbine design is the horizontal axis wind turbine due to the fact that they are more efficient for large-scale production in low turbulent environments. Moreover vertical axis wind turbine is an old technology with low efficiency, less risk and silent and they are preferably in remote areas for private use. Furthermore vertical axis wind turbines can cause a navigation problem when located offshore (Óskarsdóttir, 2014).

Wind turbines can either be built onshore or offshore in shallow water or in deep water. Onshore wind energy has been utilized for power generation for a long time, around two thousand years. Due to various factors such as high speed and large availability of space offshore, the wind power sector has recently begun to expand to offshore wind power development. Offshore is growing faster and is the focus for development in many countries (Bilgili, Yasar and Simsek, 2010).

For the purpose of increasing installed capacity and generating large amounts of electric power, multiple wind turbines are grouped together in the same location to create a wind farm. Once placed in the same location the lower are installation and maintenance costs (Óskarsdóttir, 2014).

Although offshore wind turbines operate in the same manner as onshore wind turbines, the offshore wind farms are nowadays more developed and are the main focus for future development. The onshore wind farm development is mainly constrained by lack of space on land and the government support. Onshore wind turbines are also resisted by people when located closer to residential areas because of their noise and visual intrusion on the environment (Bilgili, Yasar and Simsek, 2010; Negro et al., 2010). On the other hand, the wind energy developers prefer offshore wind farms due to a number of technical advantages. The wind speed is usually bigger, stronger, more stable and much smoother in sea than over land, resulting in significant energy production. The less turbulence of wind can also increase the lifespan of the turbine generator (Bilgili, Yasar and Simsek, 2010).

As the capacities of the wind turbines increase with advances in technology, the size and weight of turbine components increase, consequently the capacity of installation equipment also increase. Bigger free areas in the sea facilitate the transport of larger turbine components moreover there is a huge area available for the installation of offshore wind turbines. Even though there is ongoing focus on offshore development, offshore wind turbines are more expensive and difficult to install and maintain compared to onshore wind turbines (Bilgili, Yasar and Simsek, 2010).

2.2 Wind turbine farm layout

As discussed earlier, in order to generate a large amount of electrical power and to lower the installation and maintenance costs, several wind turbines can be located in one place onshore or offshore.

A typical offshore wind farm consists of several wind turbines located in the water, offshore substation and onshore transformer. Wind turbines are connected by inter array cables to an offshore substation which in turn is connected by undersea export cable to onshore transformer connected to existing national grid (Koch, 2012 and Malhotra, 2011). An optimised wind turbines layout increases farm efficiency. A successfully optimised layout can; reduce operation and maintenance costs, provides solutions to production processes, quality control, logistics, transportation to the construction site and installation process.

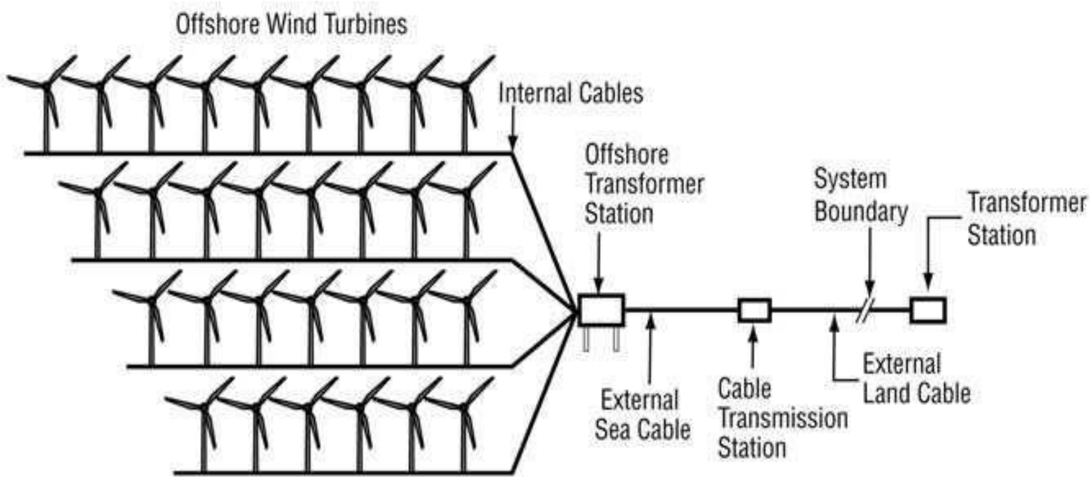

Figure 1: Typical wind farm components and their layout (Malhotra, 2011)

2.3 Wind turbine components

A wind turbine system consists of four main parts: the foundation, the tower, the rotor blades and the nacelle.

- The base or foundation, generally made of reinforced concrete or steel, supports the whole turbine upper structure in vertical position.
- The tower is, in some case, connected to the foundation by a transition piece, which is generally fixed to correct any misalignment between two components. The most common tower design is steel plate rolled into cylinder; most of them are cut, rolled and welded together into conical subsections. However there exist other turbines made of lattice tower. The tower also

provides access to the nacelle for maintenance with an inside ladder running up and it also contains the electrical conduits.

- The nacelle houses the key electro-mechanical components such as generator and gearbox; it is supported and directly fixed on top of the tower.
- The rotor blades, mostly made of fiberglass or carbon fibre composites capture the wind's energy. They are attached to the generator through a series of gears and spin the generator at a slow speed. The electric current thus generated is transmitted by a power cable from each turbine (Malhotra, 2011).

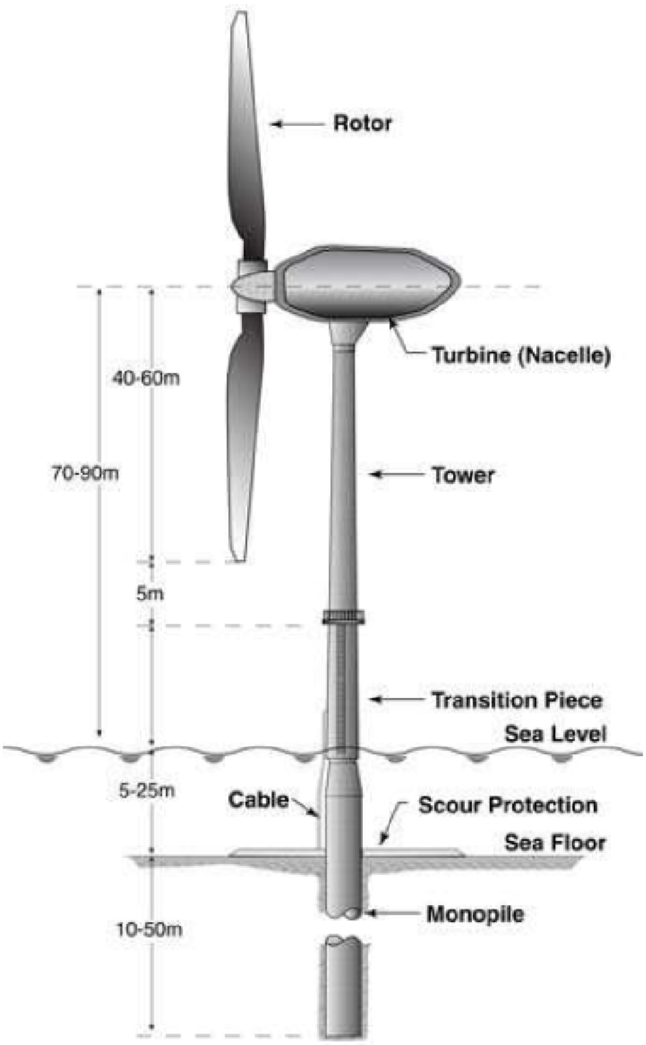

Figure 2: Typical wind turbine components (Malhotra, 2011)

3 Wind farm project development processes

3.1 Main steps in the planning and realisation of offshore wind farms

Gerdes (2010) has derived the standard project phases and grouped them into seven main steps required in planning and development of offshore wind farms as follows:

- Pre-project planning,
- Detailed project planning,
- Procurement and production
- Engineering, testing, installation and commissioning,
- Full operation,
- Repowering,
- Dismantling.

Pre-project planning,
In pre project planning, the feasibility study report and development strategies are generated. The feasibility report shows how technically and economically feasible the project will be. It for instance shows the most suitable areas for offshore wind farm installation, the wind farm technology to be used, geotechnical and environmental impact assessment, different stakeholder involvement, spatial planning, logistics and supply chain management as well as the impact of the project to the public.

Detailed project planning,
The development strategies and project structure are approved together with wind farm and grid technologies to be used. Following the approval of the project structure, detailed studies are done about the site, wind speed, chemicals in water and geography. Analysis of logistics issues, health, safety and environmental compliance is also done. Under this phase, designers describe the functional requirements of main elements of the wind farm such as foundation, turbine and electrical infrastructure. Concurrently, the planning of internal controlling system such as quality control, key performance indicators and reporting system to be used in project execution are developed.

Engineering, testing, procurement and production
This phase consists of tender process, contracting and financial arrangement plans. It also involves making more detailed engineering planning explaining the sequences of different steps like pre-testing, installation, commissioning, operation and dismantling. Training courses for personnel on operation and maintenance of main components are also provided at this stage. Following the hiring of contractors, production of turbine components starts and later transported to the installation site.

Installation and commissioning
Installation involves the installation of the whole wind farm infrastructure both offshore and onshore. The activities start by site preparation, pre-assembly of parts

followed by installation of foundation for wind turbines and offshore station. After foundation installation, inter-array cable laying and other components of wind turbines such as tower, nacelle and rotor blades are undertaken. Finally, the electrical infrastructure like offshore and onshore transformer stations are installed and connected to national grid. After installation the commissioning tests are done before project handover. The wind farm enters the operation phase in which the operator will ensure its service and maintenance as well as environmental monitoring until the wind farm is decommissioned.

As a complement, Thomsen (2014) adds that the installation of an offshore wind farm requires planning the entire project from start to finish. In planning an outline is done showing what is to be done, when, how, and by whom. For a successful planning and execution of any offshore wind farm, a logical plan of tasks together with allocated resources has to be done. Since the main focus of this study is the installation phase, the following section provides a detailed description of some of the decisions to be made, processes and challenges involved in the installation of offshore wind farm.

4 Operations management

4.1 Construction operation processes

Operations management is the activity of managing the resources that create and deliver services and products (Slack, 2013). Operation processes can be found everywhere in and between any organization that creates and deliver services and products. The principal is changing inputs into outputs using an input-transformation-output process. In the transformation process model, inputs are used to transform resources or are transformed themselves into outputs which can be services or products (Slack, 2013).

In construction projects, the general transformation process model is considered as construction processes that transform the resources into results. Construction sites are the points where the final products of the construction industry are produced, by using transforming resources like human force, equipment and technologies to transform resources such as materials. Managing a construction project needs to be done by considering various aspects involved in the construction industry such as human interaction, transformation of matter, institutions, lean and performance. The aspects of the construction processes have both tangible and intangible effects and also impact the economic efficiency and productivity of the process (Crawford and Vogl, 2006).

4.2 Elements of operation strategy

Slack and Lewis (2011) acknowledge the lack of consensus on the description of strategy and consequently operations strategy. They however, present four perspectives on operations strategy;

- Top-down perspective in which the operation strategy is a reflection of what the whole organization wants to do. Operation strategy is designed to match the overall strategic direction adopted by the organisation.
- Bottom-up perspective where operations improvements cumulatively build strategy. Within this perspective, it is appreciated that strategy emerges from an organisation's day to day experiences. The lessons learnt from operations are considered in the formulation of strategy.
- Market requirements perspective: this involves the translation of market requirements into operations decisions. Strategy is formulated with the intention of satisfying the requirements of an organization's market.
- Operations resources perspective which is concerned with the exploitation of capabilities of operations resources in selected markets.

Operations management is required for the satisfaction of market requirements. However, it is important not to simply follow the market since competitors also work towards satisfying the same market. As a result firms would end up doing the same things hence eroding any potential for long term competitive advantage (Slack and Lewis, 2011). In addition to satisfying the market, firms need to develop resource capabilities which cannot easily be copied by competitors. The reconciliation of the need to satisfy the market and to develop resource capabilities without causing unnecessary risk to the organisation is done through development of an operation strategy (Slack and Lewis, 2011).

Slack and Lewis (2011) define operation strategy as; ‘‘The total pattern of decisions which shape the long term capabilities of any type of operation and their contribution to overall strategy through the reconciliation of market requirements and operations resources.’’ In the management of operations resources, decisions have to be made in four areas which include; capacity strategy, process technology, supply networks and organisation development (Slack and Lewis 2011).

4.2.1 Capacity strategy

The capacity strategy is concerned with how capacity and facilities are organised and involves making decisions on; required capacity level, when changes in capacity levels should be made and by how much capacity should be changed (Slack and Lewis, 2008).

Capacity refers to the resources available to perform required activities within a given period of time. Capacity levels impact an organisation’s ability to meet and respond to customer demands and also affect the product lead time, ability to compete and cost of operation. Low capacity limits growth whereas high capacity levels lead to underutilisation of labour, machinery with consequent high costs and low profitability (Slack and Lewis, 2008; Ashwathappa, 2010). An appropriate level of capacity has to be maintained during operation through operation decisions on how much capacity to install, when and how much to increase the capacity. Capacity planning activities involve; forecasting capacity needs for products, identifying sources of capacity to meet needs and developing capacity alternatives, selecting from among the different alternatives for capacity (Ashwathappa, 2010; Slack and Lewis, 2008).

According to Slack and Lewis (2008), capacity can be adjusted by; working overtime, varying the size of the work force, using part time staff and subcontracting. In offshore wind farms, the capacity strategy covers issues such as contracts between wind turbine manufacturers, their suppliers and subcontractors since the manufacturers do not carry out installations themselves (Koch, 2012). Despite making plans for necessary capacity levels for projects, operations can still be constrained by failure of suppliers to deliver, machine failures, changes introduced by customers and failures in process technology (Slack and Lewis, 2008).

In addition to finding responses to capacity challenges, operations management is concerned with the coordination of manufacturing activities. This is done through production planning and control. Production planning and control refers to the planning and coordination of an organisation’s materials and facilities to attain the production objectives in a cost effective manner. It involves among other the functions of;

- Ensuring availability of materials components in right quantities to specification and at the right time.
- Choosing appropriate method for manufacturing the parts and building assemblies as well as selection of machines and equipment.
- Scheduling the utilisation of equipment, manpower and the duration of tasks.

Production planning and control activities therefore enable companies to gain a competitive advantage through, reliable delivery to customers, shortened delivery times and lower production costs (Ashwathappa, 2010).

According to Ashwathappa (2010), scheduling is one of the functions performed under production planning and control. It is concerned with setting the production time for production activities which include; setting start and completion times for operations as well as start and finish dates for assemblies. In offshore wind farm operations, scheduling is performed based on available labour and equipment. The schedule is developed based on the estimated time taken to install parts of the project and the processes involved in installation operation from pre-assembly to installation onsite (Thomsen, 2014). Scheduling of offshore installation activities is highly dependent on weather condition at sea consequently requiring planners to make attempts to find optimal schedules based on the installation scenario selected (Scholz-Reiter et al., 2010).

The installation scenarios available include;

- Pre-assembling the wind turbine components at a harbour located close to the construction site.
- Establishing an assembly area offshore from where elements are delivered to the site. The assembly area can be a construction vessel or platform and supplied by smaller vessels.
- Directly delivering pre-assembled components from the manufacturer's premises to site.

The scheduling function helps to ensure the effective utilisation of resources to produce products within established lead times and to prevent unbalanced use of time (Ashwathappa, 2010).

4.2.2 Supply network strategy including procurement and logistics

Lambert (2004) defined the supply chain management as ‘‘the integration of business processes from end user through original suppliers that provides products, services and information that add value for customers”. Logistics management is the part of supply chain management that plans, implements and controls the efficient, effective flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet the requirements of customers (Jonsson, 2008). Logistics can be done within one company or an integrated flow of materials through several companies. Logistics management deals with supply and demand planning, order processing, materials handling, storage, inventory management, distribution system, transportation management, storage as well as management of other involved stakeholders.

To effectively and efficiently take advantage of integrated markets, firms operate in a coordination and collaboration driven network in the areas of production and supply with the firms forming the key links between them (Borges, 2015). Wang et al., (2004) argued that companies should focus more on the supply chain approaches in order to acquire competitive advantages in terms of reducing costs, being flexible towards customers' demands and being time efficient. This can be achieved by adopting the just-in-time principle, where for instance in offshore installation, the component is just in the right place when needed without waste of time and resources (Thomsen, 2010).

The installation of offshore wind turbines is influenced by weather and the capabilities of the equipment used. By applying just in time principle, all components to be installed should be delivered and be ready to the point when needed to be installed. For instance, turbines are installed when the foundations are already completed and the latter take longer. Since turbine installation is faster than foundation there is a high demand in number of turbines whereas it takes time for the turbine to be ready for installation. Therefore, in order to meet the demand the supplier stores the turbines prior to the start of installation. This also happens to other turbine components and creates a mismatch between manufacturing time and installation time. Thus, due to this mismatch in delivery time, there is a need for a facility to store many components at one time. Turbine components are, sometimes; big and heavy thus require a large and well paved surface for preassembly, loading and unloading activities which is costly.

For the purpose of storing materials and resources in order to exploit good weather periods for intensive installation work, minimise delays in transport, handling and installation of offshore wind farms it is suggested to have logistical planning and renting an appropriate staging area in a port that is favourably close to the offshore site (Thomsen, 2010).

The offshore supply chain must be flexibly organised so that the installation is not delayed by material shortages. A continuous material supply must be guaranteed for the whole installation process. Scholz-Reiter (2010) suggests the offshore supply chain to be organised as supply chain in automobile industry which he considers to be efficient and flexible. Gerdes (2010) also emphasised on installation procedure and supply chain outline which allows a line production of wind farm and shows the process transparency in material process flow from production to offshore operation as shown in Figure 3. In regard to this, the scope of this report starts with assembly on land up to commissioning.

Figure 3: Material flow process for the installation of offshore wind farms (Gerdes, 2010)

In most cases, wind farms delivery falls under two contract forms either Engineering Procurement and Construction (EPC) contract which is between wind farm owner and a single contractor or a multi-contractual approach in which the owner places orders for individual building segments. In EPC contract the contractor bears all risks but tries to work with different subcontractors in order to share risks. In multi-contractual approach, risks are individually managed and hence cumulative risks become less to the owner (Gerdes, 2010).

Offshore installation processes face high uncertainties resulting in high risks. For economic benefits Gerdes (2010) recommends the use of multi-contractual approach rather than EPC contract. Since in EPC contracting the client has to take all risks or be able to pay the risk coverage the contract cost is high. However, multi-contractual approach requires the client to possess sufficient number of technically and managerially skilled personnel to follow up the project as well as managing interface.

4.2.3 Development and organisation

Koch (2014) argued that for operations to be running on a continuing basis there should be a long term decision on how the organisation should be organised and capability developed. The public judge the company to be good or not based on product quality and service delivered. Therefore the companies need to have a core operation strategy to develop products and services and make sure that they are successful in the marketplace. The product development is significantly affected by speed, scale of market and rapid technology change which in return determine the appropriate process to be used (Slack and Lewis, 2011). Based on resource usage and market requirement perspective, Slack and Lewis (2011) assert that due to high market competitiveness, the company should focus on the following; use of resource-based decisions to manage product or service development, meeting market requirement with new services and products, ability to justify the way the product is developed under such process and managing product or services as process.

Rapid technology changes have affected most industries including offshore wind power projects. As the number of competitors increase, the customers become more demanding in terms of wanting products and services that fit their specific needs. Therefore, the simple way to gain advantage over competitors is to introduce updated products and services (Slack and Lewis, 2011). A good planning technique of project tasks in terms of time and resources, management skills and tools combined with a proper organisation enable the achievement of performance objectives (Koch, 2014).

4.2.4 Process technology strategy

Process technology concerns the choice and development of systems, machines and processes that work on transformed or transform resources into finished products and services. The conversion of resources can be done either directly or indirectly by the technology. Process technology incorporates the technological aspects in the process of producing goods and services. It refers to the equipment and devices which deliver products and services. The process technology adopted by an organisation contributes towards achieving the market requirements in terms of speed, dependability, quality, flexibility and cost (Slack and Lewis, 2008).

Thomsen (2014) highlights the installation vessels as being important items in the balance of plant that are necessary for timely installation of offshore wind farms. The schedule of installation process is heavily reliant on the capacity and operation of the installation vessels such that a failure to procure them early for the project would most likely jeopardise the project schedule. A variety of vessels are available for use in the different phases of the installation process. A Trade-off however has to be made between the costs and risks imposed by the different combinations of vessel fleets available to perform the work (Kaiser and Snyder, 2010). Equipment available for offshore installation includes among others, lift boats, jack up barges, self-propelled installation vessels and heavy lift vessels. The vessels have different lifting and operating capabilities as different kinds of technologies to facilitate their operations.

4.3 Summary of theoretical framework

The installation of offshore wind farms involves the use of resources such labour, equipment and materials. The materials such as blades, tower pieces, rotors and foundation are assembled by the labour and equipment to form complete wind turbines. This conforms to the input-transformation-output description of an operation. In view of the foregoing model, the installation of offshore wind farms was considered as an operation. Consequently the theories on operations management and operation strategy specifically focusing on market requirements and operations resources were adopted for understanding the offshore installation process. Operation management theory was used to describe the components of an operation and what is required in order to successfully execute an operation. Additionally, it was used to identify the difficulties that can be encountered while running an operation. Based on the aim of this research and the research questions, the aspects of operations strategy in regard to capacity planning, logistics and supply, development and organisation as well as process technology were mainly used. The theory provided an insight on what considerations have to be taken while planning and executing an operation and the impacts of wrong decisions on the operation.

5 Wind turbine transportation and installation process

A wind farm consists of a number of wind turbines which are composed of foundations, tower, nacelle and blades which have to be fixed together to complete the installation. As part of the installation process, the components need to be moved from either the point of manufacture or fabrication port onshore to the installation site. The following section describes the vessels and other equipment needed for transportation and installation. Additionally, a description of the installation process for the different components forming a wind turbine structure is included.

5.1 Means of transportation

The installation of foundations and turbines of offshore wind farms requires the use of a variety of marine vessels the choice of which is dependent on system generation capacity, water depth, soil conditions at site, costs and risk exposure that result from the selection of a given set of vessels (Kaiser and Snyder, 2012). The installation vessels are used for: transfer of support structures and turbines to offshore sites, provision of stable platforms for lifting and installation operations and accommodation for ship crew and personnel (Attari et al., 2014). The vessels are of several types classified according to their purpose and they include among others; jack-up vessels, accommodation vessels, survey vessels, cable laying vessels, construction support vessels, diving support vessels, service crew vessels, heavy lift vessels, self-propelled installation vessels and tugboats (Attari et al., 2014; Kaiser and Snyder, 2012). According to Kaiser and Snyder (2012), maximum lift height and weight, speed and number of turbines carried are some of the critical characteristics of installation vessels.

5.1.1 Transportation vessels

The available vessels possess different capabilities. Some have both transportation and lifting functionalities whereas others can be used only for transportation. A brief description of some of the commonly used vessels is provided in the following section.

Jack-up platforms (JUP)/Lift boats

According to Attari et al., (2014), jack-up platforms are self-propelled or towed installation vessels that operate through jacking up and down of the hull to required operation heights. The vessels consist of a number of legs that provide stability by resting on the seabed. Jack up platforms are used for; installation of offshore structures, maintenance of offshore wind farms, offshore civil construction, site investigations and decommissioning of offshore oil and gas infrastructure to mention but a few. They are however, constrained by the time consuming jacking operations, length of the jacked legs and their need for feeder vessels during operation (Attari et al., 2014). The vessels are optimised for oil and gas operations in which they are capable of working slightly above the water surface unlike in the offshore installation where heavy loads are required to be lifted to greater heights. As a result, there are delays resulting from the slow operations of the jack up vessels (Doherty, 2014). The vessels are of different sizes ranging from small with capabilities of carrying and lifting 75 tonnes and 50 tonnes respectively to large with carrying and lifting capabilities of 750 tonnes to 500 tonnes respectively. They also operate at speeds of between 4 and 8 knots (Kaiser and Snyder, 2012).

Heavy Lift Vessels (HLV)

Floating vessels that are either self-propelled or towed and equipped with cranes specialised for lifting heavy loads. They are mainly designed for installation of pre-assembled modules making them widely used for the installation of foundations, assembled turbines and substations. The vessels are commonly used in the oil and gas industry hence making their availability limited and costly. Additionally, their mobilisation speed is low and their size often too big to be accommodated at some ports (Attari et al., 2014; Kaiser and Snyder, 2012).

Barges and pontoons

Non self-propelled vessels used to transport heavy wind farm components for example gravity bases, jackets and jacket piles, monopile and transition pieces. They are also used as production bases for gravity based structures away from the installation site.

5.2 Foundation installation

According to Kaiser and Snyder (2010), there are four basic types of foundations that can be used in offshore wind farms namely; monopile, gravity, tripods and jacket foundations. The choice of foundation used is dependent on specific conditions on site such as water depth and soil type. Figure 4 shows the typical structures for monopile and gravity foundations that are mostly used in shallow water.

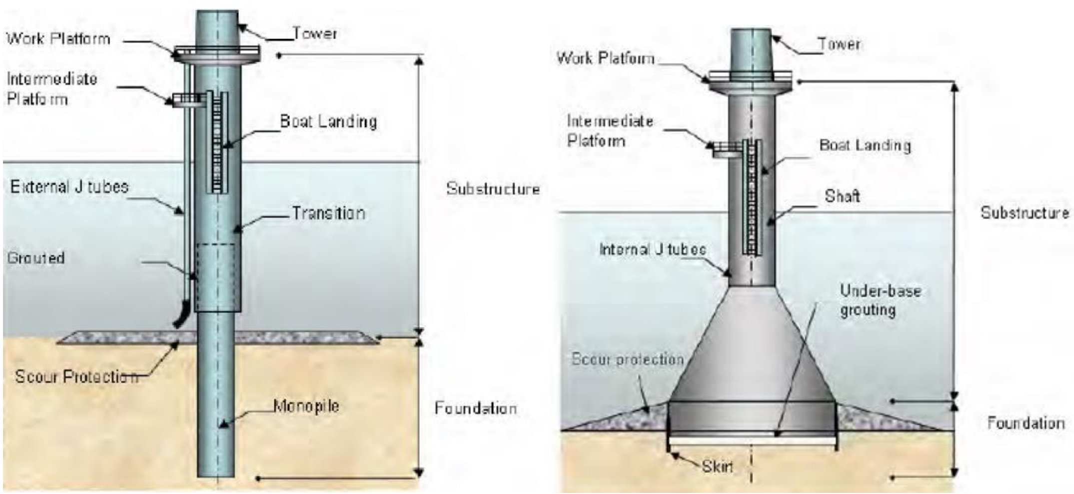

Figure 4: Typical monopile and gravity foundation structure respectively (Kaiser & Snyder, 2010)

Attari et al., (2014) indicated that the transportation and installation strategy for foundations is determined by, foundation type, weight, water depth, distance from port and met-ocean conditions. The transportation is also subject to approval of a marine warranty surveyor (Doherty, 2014).

5.2.1 Mono pile foundations

For the transportation of mono piles, the selected method partly depends on installation vessels selected and infrastructure available at the port. The monopiles can be transported by floating, carried as cargo on an installation vessel and on a barge or offshore supply vessel (Conconi et al., 2014). Once they arrive on site; the monopoles are upended by cranes or other gripping devices and driven to the seabed by a hydraulic hammer. A transition piece is then grouted or bolted to the top of the mono pile (Doherty et al., 2014). Different combinations of vessels can be employed for the installation of mono pile foundations and these according to Attari et al., (2014) are:

One installation vessel – transportation and installation of foundations is done by employing only one vessel. Foundations can either be installed first followed by transition pieces or foundation and transition pieces installed in sequence.

One installation vessel and one feeder vessel – In this case the installation vessel is stationed at site and supplied by feeder vessels. Therefore the installation vessel is not required to make several trips to and fro the port.

Two or more installation vessels – More than one installation vessels are used to either transport and install the foundations or one installs the foundations and the other install the transition pieces. The strategy leads to reduction in installation times but does not necessarily halve the total equipment time for the task.

5.2.2 Gravity based foundations (GBF)

Gravity based structures resist loads by self-weight and ballast and resist overturning through wide bases. GBF are mainly installed in shallow water depth ranging from 1-27 m (Conconi et al., 2014). The installation of gravity based foundations typically requires deployment of: a large floating crane (Heavy lift Vessel) to lift the structures, large barge to transport the foundation structures and tugboats to tow the barge and crane in case they are not self-propelled (Esteban et al., 2015; Thomsen, 2014).

Gravity based foundations can be produced in number of ways including; construction on barges or pontoons, onshore construction on a quay, construction on a dry dock and construction at a floating dock (Doherty et al., 2014). In constructing directly on the barge, the foundations are constructed directly on the barges which are thereafter used to transport the completed foundations to the installation site. Construction at a quay involves the construction of foundation on an onshore quay from where they are transported to the launching area by means of self-propelled modular transporters.

Dry dock construction consists of the construction of bases at a dry dock which is flooded to float out the completed bases. Installation of the gravity based structures involves the preparation of the seabed for purposes of ensuring soil with sufficient bearing capacity at the base and levelling for substructure stability (Esteban et al., 2015). The GBS support structures are transported to site, lifted off the transportation vessel and placed to the prepared seabed. Depending on the design of the gravity substructure, ballasting is done to further increase the foundation stability (Esteban et al., 2015).

5.3 Turbine installation

Installation of turbines comes after the installation of foundations. Turbine installation is highly sensitive to weather conditions and wind speed, requires lifting of heavy components up to the height of the hub. As a strategy to minimise the challenges of offshore lifting operations, some of the components are pre-assembled onshore. Vessel requirements for turbine installation are dependent on; turbine weight, size, hub height, and installation method adopted (Attari et al., 2014; Conconi et al. 2014).

Depending on the number of lifting operations intended to be performed offshore, six common installation methods are available (Doherty et al., 2014) and shown in Figure 5 below.

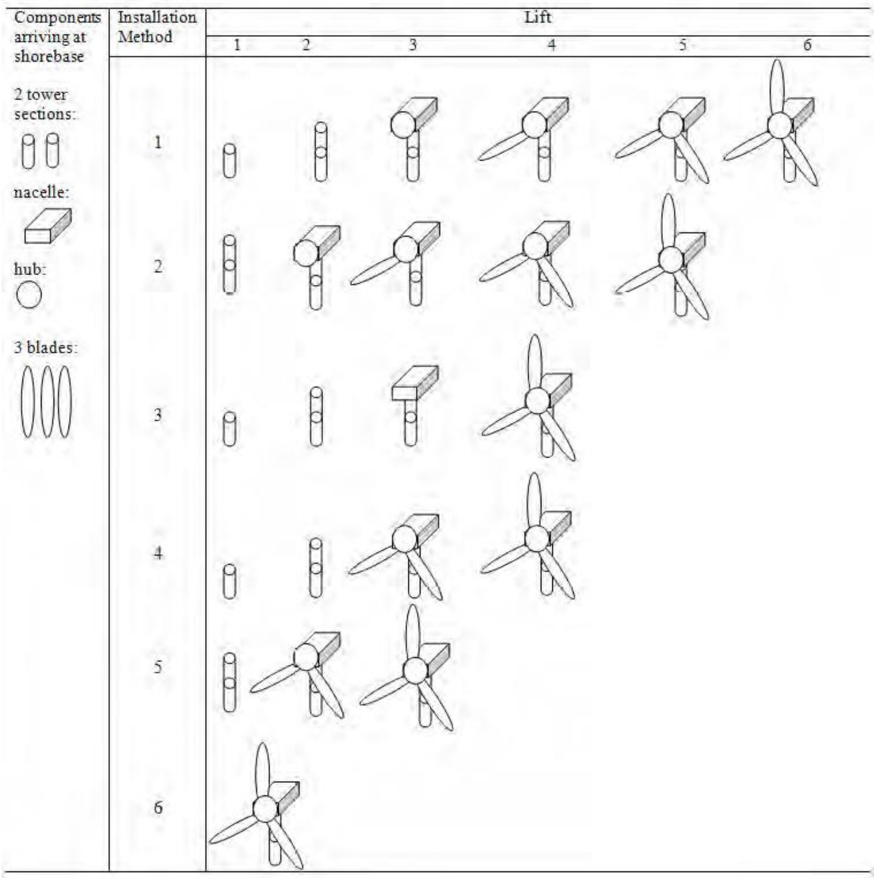

Figure 5: Installation methodologies for turbines (Kaiser & Snyder, 2010)

The installation methods range from method 1 which involves the lowest degree of onshore pre-assembly and a large number of onshore lifts to method 6 which involves pre-assembly of the entire turbine onshore and one offshore lift. The methods are described by Kaiser and Snyder (2010) as;

- The first method involves the least degree of offshore pre-assembly and consists of separate installation of the tower sections, nacelle and separate installation of each blade. The method allows maximum use of deck space of transport and installation vessel since more components are loaded onto the vessel. This reduces the number of trips the vessel has to make to and from the offshore site.
- In method two, the two tower sections are pre-assembled onshore and lifted as a unit offshore. At the offshore site, the pre-assembled tower is fixed followed by the nacelle and finally each individual blade installed separately.
- Method three consists of the onshore pre-assembly of the rotor and results in a total of four lifts. The tower is transported as two separate pieces which are installed in two lifting operations followed by installation of the nacelle and finally the pre-assembled rotor.
- In method four, the rotor and two blades are pre-assembled onshore into a bunny ear configuration and installed offshore in one lifting operation. The two unfastened tower pieces and one blade are transported and installed individually offshore.
- The fifth method involves the onshore pre-assembly of the tower pieces. The rotor and nacelle are also pre-assembled into a bunny ear configuration. The tower is installed in one lifting operation followed by rotor with two blades and the last blade installed separately.
- The last installation method consists of the fully onshore pre-assembly of the tower, nacelle and blades. The completed turbine is transported from an onshore harbour and fixed in one lifting operation over the foundation. The method requires employment of heavy lift vessels.

The degree of pre-assembly affects the number of offshore lifting operations, transportation means and equipment required. Method 1 is often suitable for sites located far away from shore to maximise use of space on the transportation vessels. On the other hand, method 6 involves a single offshore lift but transporting the assembled turbine can be challenging and requires employing heavy lift vessels with large capacity cranes.

5.4 Electric cable installation

According to Kaiser and Snyder (2013), inter-array cables and export cables are part of the electrical infrastructure of an offshore wind farm and are usually buried in the seabed.

A number of methods are available for the installation of cables. The installation can be done by either Remote Operated Vehicles (ROVs) or under water ploughs which lay and bury the cables at the same time. Water ploughing involves the insertion of the cable in a plough which uses a high pressure water jet to create a trench into which the cable sinks. The plough is pulled on the seabed by means of an installation vessel or barge (Doherty et al., 2014, Kaiser and Snyder, 2013). Another employable method involves first excavating the trenches and using divers or a cable laying vessel to guide the cable into the pre-excavated trench followed by backfilling with excavated material (Doherty et al., 2014). The installation process also requires the employment of divers at other stages such as feeding the cable through the J-tube. The operation is susceptible to weather and tidal waves which can potentially lead to time overruns.

5.5 Offshore substation

An offshore substation can be incorporated in the offshore wind farm infrastructure to collect and convert generated electricity for transmission to the onshore grid (Barlow et al., 2015). An offshore substation is employed to reduce power losses before the power is exported to shore. Depending on seabed conditions, water depth and weight of the substation structure, a suitable foundation is selected to support the substation. The installation sequence for offshore substations is similar to that for the installation of turbine and involves the loading of substation components onto the installation vessels which transits to the installation site and installs the substation at the designated location. Since the substations are significantly heavier than other offshore wind farm components, heavy lift vessels are used for substation installation (Kaiser and Snyder, 2013).

6 Results

6.1 General challenges in installation process

The installation of offshore wind farms consists of different activities in which various contractors and service providers are involved. To implement the installation requires extensive planning and use of resources. Despite the planning effort, offshore installation is hindered by a number of constraints. After reviewing different literature and reports, the following challenges were generally identified.

6.1.1 Installation vessels

The installation of offshore wind farms has been constrained by a number of factors. MacAskill and Mitchell (2013), point to the insufficiency of installation vessels required to meet the demand for installation of cables, substructures and turbines as a major challenge in the European offshore industry. According to Flower (2013), availability and suitability of vessels for installation still constrain the installation process. The vessels lack capabilities to jack up in deep water, lack dynamic positioning capabilities and are slow. Ian (2011) adds that there still exists a shortage of suitable vessels for the installation of export and inter array cables despite the offshore wind industry responding to the shortage of suitable vessels by building purpose built vessels for offshore installation.

Marine vessels for offshore wind installation are also used in sectors such as civil construction, telecoms, and pipeline as well as in the oil and gas industry. As a result, there is uncertainty on the availability of vessels due to variability in demand from the different sectors. Additionally, turbine manufacturers set strict requirements for motions to which nacelles can be exposed during installation hence limit the installers' choice of installation vessels (Flower, 2013). In periods of high activity in the aforementioned sectors, high competition for vessels arises consequently leading to high day rates for the vessels (Roberts et al., 2013; Ian, 2011; Snyder and Kaiser, 2010).

6.1.2 Personnel and regulatory limitations

Roberts et al., (2013), cite the shortage of credible suppliers and competent crew especially for cable installation as a constraint that has been responsible for problems during the installations of cables. In line with cable installation, the operation often requires the use of divers- an activity that is considered highly risky and requires strict monitoring. The diving operation is also dependent on weather and sea conditions hence rendering it a bottleneck to the installation process in some instances (Doherty et al., 2014).

6.1.3 Installation harbours

According to the European Wind Energy Association (EWEA), offshore installation activities require the establishment of a number of specially adapted harbours. The facilities need to have deep water, reinforced quaysides, sufficient space for laydown areas for organising components and to allow free crane movement, areas for assembling wind turbines as well as space for production of wind farm components (EWEA, 2009). The installation ports are used to reduce the logistical risks on projects through storage of components close to the offshore wind farm site (Roberts et al., 2013). There are still a few suitable harbours for offshore wind activities. The slow development in dedicated harbours is according to Roberts (2013) a result of; high cost involved in upgrading port facilities on the basis of singular projects and long lead times involved in the establishment of dedicated harbours. However, as a result of contracts signed between contractors and ports and on-going developments of harbours in UK, Belgium, Denmark and Netherlands a sufficient number of harbours could be secured for future projects (Roberts et al., 2013).

6.1.4 Health and safety challenges

Offshore installation works take place in extremely challenging environments such as work at sea in deep water and lifting heavy weight components. These types of works require strict health and safety procedures thus safety is a very important issue in any engineering work particularly in an offshore environment. Working in offshore environment is more risky and it is more difficult to get help when an accident occurs. The installation of offshore wind turbines faces almost the same challenges as in the oil and gas industry. However the oil and gas industry has faced these challenges for many years about forty years thus the safety procedures has been developed and keep updated according to the experience gained from previous projects (Ian, 2011 ; Skiba, 2010). These safety procedures are available to the public particularly offshore wind power developers to adopt and adapt. However some accidents occur due to fact that some people either fail to follow procedures or attempt to take short cuts in order to save time. Skiba (2010) indicated that out of the major offshore incidents that happened between year 2004 and 2008 in the UK, a high number was due to the failure of following safety instructions during deck operations and construction and maintenance. Because the overall objective is to bring everyone back safely from the offshore site works, Thomsen (2010) emphasised that a company has the responsibility to safeguard its employees from any danger that might arise from unsafe work practices while ensuring safety through installation, operation and maintenance techniques.

6.1.5 Weather conditions

The installation of offshore wind turbines is greatly affected by the weather conditions. The transport and installation of wind components take a long time since it consists of pre-assembly, loading, unloading, water transport of turbine components and installation process itself. Some turbine structures like foundation and transition piece can be installed in conditions of higher wind forces and waves whereas others like blades and nacelle require tranquil air conditions. This means that the number of installed components increases under good weather conditions and that bad weather can considerably delay the entire project (Scholz-Reiter, 2010).

The scheduling for installation and choice of equipment to be used are strongly dependent on the current weather conditions on sea. This limitation in choice and weather dependent scheduling influence the logistic and supply chain of materials, installation method as well as affect the installation process in terms of time. Because of the seasonal weather variations, most of the companies prefer to maximise the vessels' utilization thus substructures are installed from autumn to spring and installation of nacelle and blades in summer period (Scholz-Reiter, 2010).

According to Skiba (2010), the installation works are seriously hindered by a low number of working days in winter season. In a bid to increase production time, the foundation structures are sometimes fabricated outside of the project location hence requiring transportation over a large distance between the manufacturing point and the offshore wind farm location. The transportation process is however also weather dependent thereby requiring development of a detailed report about weather window and data on significant wave heights for both transportation and installation (Esteban et al., 2015).

6.1.6 Water depth and distance to the offshore wind farms

The development of offshore farms is also dependent of water depth; the water depth is one of the factors that limit the location of offshore wind farms. The proposed offshore wind farm location has influence on; the design considerations, cost, project duration and equipment and materials to be used. Water depth and seabed conditions are the two most important parameters for selecting the appropriate foundation to be used.

The installation of any kind of foundation such as monopile, gravity, jackets, tripod or tri-pile in deep water requires giant component dimensions which are difficult to handle. Foundations are considerably more expensive component for offshore turbines. Additionally, water depth impacts the cost of the foundations since the foundation cost increases with increase in water depth. The deep water limits the number of available installation vessels in the market; since the choice depends on their operational water depths. The installation operation time takes longer in deep water compared to shallow water which results in an increase in the project cost (Kaiser and Snyder, 2010). EWEA (2013) reports that on both existing and under construction offshore turbines, the average water depth of different offshore project locations such as in Baltic Sea, North Sea, and Irish Sea region, is up to 40 m deep.

Apart from deep water, as the wind farm is located far away from the coast the more the offshore transformer station is required as well as a long sea transmission cable which could also pose technical problems. Thus installation cost increases due to both increasing distance to shore and water depth. Therefore locating the offshore wind farm at greater distance to shore and at higher water depth has a significant effect on design, construction and project costs (Bilgili et al., 2010).

On the other hand, shallow water also becomes an obstacle to offshore wind turbine installation. It is quite difficult for a vessel to move in an area where the water depth becomes less than the maximum draft of the vessel (Uraz, 2011).

6.1.7 Component weight

The power capacity of the turbine increases as the sizes of the turbine increase thus turbines get larger and heavier. The increase in turbine components like hub height, nacelle and weight of other components requires greater lifting capacities and sufficient boom length of the on-board cranes which must install the turbine components at the desired height.

As the size and weight of the parts of wind turbines have increased, the capacity and the size of the machines have increased consequently. As most of the vessels currently used are not specially designed for wind turbine installations, this increasing in size of the machines becomes an added challenge to the offshore installation. Since the lifting capacities and the reachable height of the cranes determine the size and the weight of the component to be lifted, the weight of the turbine piece must be less than the safe working load of the crane. The bigger size and weight of the turbine components also reduces the number of components that the vessel can carry at time (Uraz, 2011).

The service speed of the vessels can be slow as well as the jack up speed due to weight of the components on board. The same challenge arises when offshore transformer and support structures like gravity foundations have to be transported on barge that can only transport a limited number of components depending on the weight and dimensions.

6.1.8 Component logistics and transport

Offshore wind farms consist of several wind turbines located in the water, power transmission cable, offshore substation and onshore transformer. The wind farm contains a large number of turbines and foundations and each turbine has main components such as the tower, the rotor blades and the nacelle. The installation of turbine consists of transport and fixing all components together to start generating energy. The considerations related to procurement, logistics and transportation are discussed in detail in section 4 of this report. According to Skiba (2010), the main challenges associated to the logistics and supply chain can be summarised into: limited availability of installation vessels, lack of vessels specially designed for offshore wind turbine installations and need of costly facility to store many components for pre-assembly, loading and unloading activities. In the end these challenges result in significant project delays.

6.1.9 Sea bed conditions

Sea bed condition is one of the factors that affect the installation of turbines particularly foundation and sub marine cable. The choice of type of foundation to be used is highly dependent to the seabed conditions. Since gravity foundations resist the overturning loads by means of its own gravity, they are preferable at sites where underlying seabed is difficult to penetrate, such as on a hard rock or in relatively shallow waters. However the foundation has to be placed on the prepared seabed, a seabed preparation consists of removing obstacles, low bearing capacity soils, levelling and or placement of granular materials or rip-rap rock bed.

The removal of unsuitable soil layers or dredging requires additional time and need of special equipment depending on the water depth, type of soil, weather conditions etc. (Esteban et al., 2015). On the other hand monopile foundations also require removal of some seabed obstacles like boulders. Driving piles into the ground requires heavy equipment, and usually takes a considerable time and the noise generated during pile driving in the marine environment has been accused to be challenging to aquatic life.
The installation vessel must be able to jack up and stay stable during installation process thus the stability of the jack up unit is highly dependent on the seabed conditions around the turbines. Moreover there should be a careful selection of boat with appropriate operational seabed penetration (Uraz, 2011).

6.2 Project description and installation process

6.2.1 Lillgrund project description

Lillgrund wind power plant is located in the Öresund area 7 km off the southern coast of Sweden as shown in Figure 6 and in water depth ranging from 4 to 12 m. The wind farm has a capacity of 110 MW generated from 48 turbines each rated at 2.3 MW. The shallow water and close proximity to the coast were advantageous in a way that they enabled easy access during construction and during maintenance, use of a short export cable and control of the foundation cost.
The wind farm owned and operated by Vattenfall Vindkraft was constructed between 2006 and 2007 with support from the Swedish Energy Agency. The permit process for Lillgrund was however started in 1997 by Eurovision from which Vattenfall purchased the development authorisation in 2004 (Jeppsson et al., 2008).

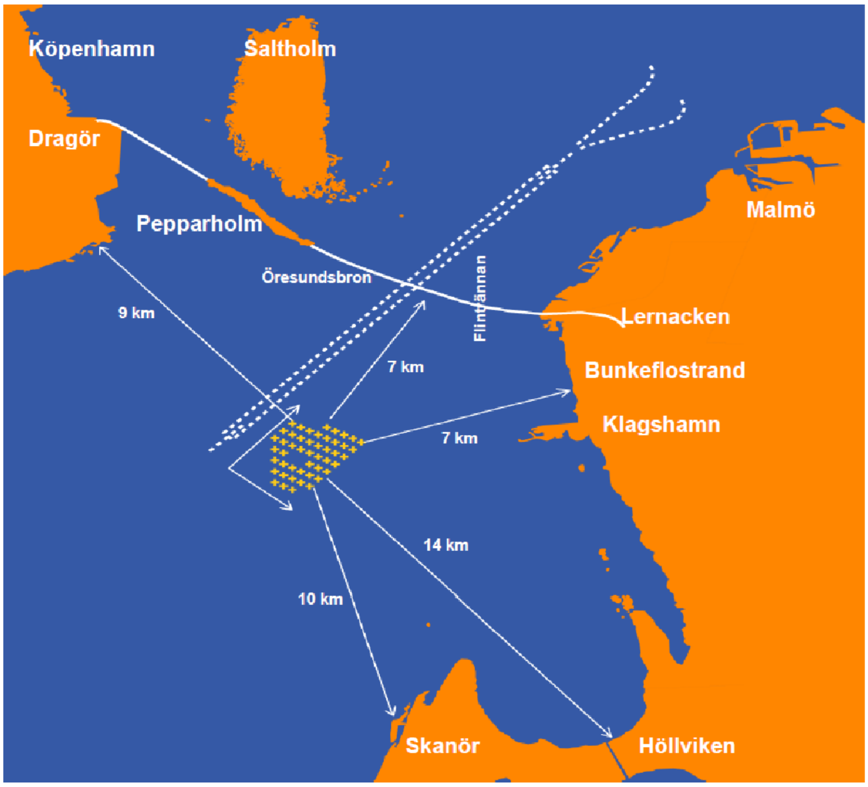

Figure 6: Lillgrund project location
(Source: Vattenfall 2008)

The project was executed under two major contracts; one for foundation and seabed preparation and the other for wind turbines and electrical system by Pihl-Hochtief joint venture and Siemens power respectively. Vattenfall purchased all risk construction insurance to cover the works for all the contractors, subcontractors and consultants. Lillgrund is founded on gravity based concrete foundations and also consists of an offshore substation (Flodérus, 2008). Additional information on Lillgrund is summarised in Table 3 below.

Table 3: Lillgrund Project facts

FACTS			
Wind turbines	Siemens 2.3 MW Mk II	Foundation Height	19 m
Number of wind turbines	48	Water depth	4-13 m
Wind turbines capacity	2.3 MW	Distance to shore	11.3 km
Total capacity	110 MW	Wind farm area	6 km^2
Hub height	68 m	Construction period	2006-2007
Rotor diameter	93 m	Location	Öresund
Total height	114.5 m	Developer	Vattenfall AB
Weight, Rotor	60 tonnes	Ownership:	100% Vattenfall AB
Weight, tower	134 tonnes		
Weight, nacelle	82 tonnes		
Total weight,foundation	2,254 tonnes		

6.2.2 Lillgrund installation process

Foundations

Lillgrund is founded on gravity based reinforced concrete foundations which are filled with ballast to increase their mass. The contract for the foundations was executed by Pihl-Hochtief joint venture (Flodérus, 2008). Due to the varying water levels on site, five different heights of foundations were produced ranging from 10.3 m to 14.3 m and a base width of 19 m. The foundations filled with ballast weighed between 2,102 and 2,254 tonnes. The foundations were prefabricated directly on the transportation barges in Poland at a harbour that was rented by the contractors (Jeppsson et al., 2008). According to Larsen (interview, 2016-03-10) , who was a site manager in charge of wind turbine generator on behalf of Vattenfall AB, the choice of production areas was based on the consideration of an area with sufficient bearing capacity, risk analysis and assessment of the flight path while production costs would be low in Swinoujscie.

Figure 7: Transportation of foundations
(Source: Vattenfall, 2008)

Foundation production works were carried out simultaneously with dredging works on site. The dredging works were performed by Peter Madsen Rederi A/S which involved cutting the seabed to required profiles until a base with sufficient bearing capacity was attained and filling the voids in unlevelled surface with hard rocks. Divers were employed to check that the dredging works were properly done before the foundations could be placed. The manufacture of the foundation was done off site and was performed directly on transportation barges with the intention of facilitating production, lifting and transportation to site. After concrete had cured, the barges were towed to the installation site as shown in Figure 7; an operation that required a weather window of twenty four hours. On site, the foundations were placed on the prepared seabed by means of a crane barge supplied by Eide contracting AS as shown in Figure 8. The placed foundations were protected from scouring due to ocean currents by placing a layer of rock fill around the placed foundations (Jeppsson et al., 2008).

Figure 8: Installation of foundation
(Source: http://www.tech-marine.dk*)*

Turbines

The installation contract for turbines at Lillgrund was entrusted with Siemens wind power A/S which was selected based on the consideration of factors such as profitability, proven technology, previous experience, interface information, aesthetic information, environment and noise from the turbines (Flodérus, 2008). Lillgrund wind farm is made up of the Siemens 2.3 MW Mk II wind turbines. Each turbine consists of a 73 m high cylindrical tower weighing 134 tonnes, an 82 tonnes nacelle and 60 tonnes rotor. Additionally, the rotor consists of 3 blades with a diameter of 93 m. The turbine components (nacelles, blades and tower) were transported by road from the Siemens' factory and its subcontractors' premises in Jutland in Denmark to the installation port at Nyborg. Some degree of onshore pre-assembly was performed specifically the attachment of the three blades to the hub at the installation port. The preassembled blades, the tower pieces and the nacelle were transported to the installation point by A2SEA using a jack up vessel called Sea power shown in Figure 9. The vessel consists of four jack-up legs and is capable of operating in marine conditions with wave heights up to one meter. The vessel is also fitted with a mobile access gangway and has the capacity and sufficient area to accommodate enough components to install three wind turbines from one trip (Jeppsson et al., 2008, Flodérus, 2008).

The installation sequence on site was such that the lower part of the tower was fixed in place followed by the upper part, the nacelle and lastly fixing the pre-assembled rotor as shown in Figure 10. The installation method used at Lillgrund corresponds to method number 3 explained in Figure 5. A total of four lifting operations were employed during the installation. The installation time for the three turbines that the sea power would carry was five days. The installation time included the transit time to and fro the installation site by the installation vessel. The actual installation time for three turbines on site was however two days (Flodérus, 2008). According to Larsen (interview, 2016-03-10), the installation sequence described above has since become obsolete due to the fact that it requires a large space on the installation vessels to transport a fully assembled rotor. At the time of constructing Lillgrund, it was problematic to lift a single blade while offshore since it was highly weather sensitive. However, according to Johannsen (interview, 2016-05-03) , who is Vice President, in charge of Projects at A2SEA, the method adopted for installation is sometimes dictated by the turbine manufacturers depending on turbine configuration. In early days, it was not possible to turn the rotor shaft while the turbine was not balanced by 3 blades, but nowadays it is possible to turn the unbalanced shaft to allow the installation of single blades.

Figure 9: Transportation of turbine components
(Source:Vattenfall, 2008)

Larsen (interview, 2016-03-10) added that with the introduction of the blade gripper, lifting of single blades offshore can now easily be done and the common practice now is to transport the wind turbine components without any preassembly. This ensures optimum use of space on the installation vessel and minimises the number of trips between the wind farm and the installation harbour.

Figure 10: Turbine Installation
(Source:Vattenfall, 2008)

Cables

Lillgrund consists of 130 kV electrical system that is composed of 7 km of export cable at sea and 2 km of cable on land that is connected to E.ON's station at Bunkeflo near Malmö (Jeppsson et al., 2008). The contract for the supply of turbines including the installation of the electrical system was awarded to Siemens wind power. Siemens in turn subcontracted the cable supply and installation work package to ABB high voltage cables which also split the works among four subcontractors namely; Seløy Undervannsservice A/S, SvenskSjöentreprenad AB (SSE), Peter Madsen Rederi A/S and Baltic Offshore AB which were responsible for; export cable installation, diving, transport and inter-array cable installation respectively (Unosson, 2009).

The installation of offshore cables involved surveying the proposed route for the cable using a marine survey vessel MV sound seeker. The survey activity was carried out to obtain information on amounts of boulders and other obstructions that could have been lying along the seabed. On completion of the survey, pre excavation of 1 m deep trenches was performed by the dredging vessel Grävlingen and finally followed by laying and burying the cables. To minimise the risk of grounding, the excavated material was placed on one side of the excavated trench. The vessels Nautilus maxi and C/S Pleijel were used for laying the export cable and inter array cables respectively. A Remotely Operated Vehicle (ROV) and divers were employed to ensure that the cables were properly laid in the excavated trenches (Unosson, 2009).

Offshore substation

Lillgrund wind farm consists of an offshore substation shown in Figure 11. The 520 tonne substation is 22 m in diameter and reaches up to 25 m above sea level. The steel works for the substation were performed in Poland by Montostatal-Chojnice a subcontractor to Bladt Industries A/S. The steel frame was transported from Poland by a barge to Aalborg where the rest of the electrical works were performed by other Siemens subcontractors including; Siemens AG, Siemens Ballerup, and Semco Maritime A/S (Jeppsson et al., 2008).

Figure 11: Substation installation
(Source: http://www.bladt.dk)

6.2.3 Anholt project description

Anholt wind farm is located between Djursland and the island of Anholt located in Kattegat Sea in Denmark as shown in Figure 12. The wind farm covers an area of 88 km^2 and consists of 111 wind turbines. The wind farm is located in sea water with a depth of between 15 and 19 m. The total farm capacity is 400 MW in which each turbine generates approximately 3.6 MW, a rotor of diameter 120 m turns the gear box housed in nacelle mounted at 81.6 m above sea level. A transition piece connects the tower and a monopile foundation of a diameter of 5 m driven into the seabed. The nearest wind turbine is accessible from Grenaa port at a distance 20 km away. The port was used during both installation works and maintenance of the offshore wind farm (DONG energy, 2016).

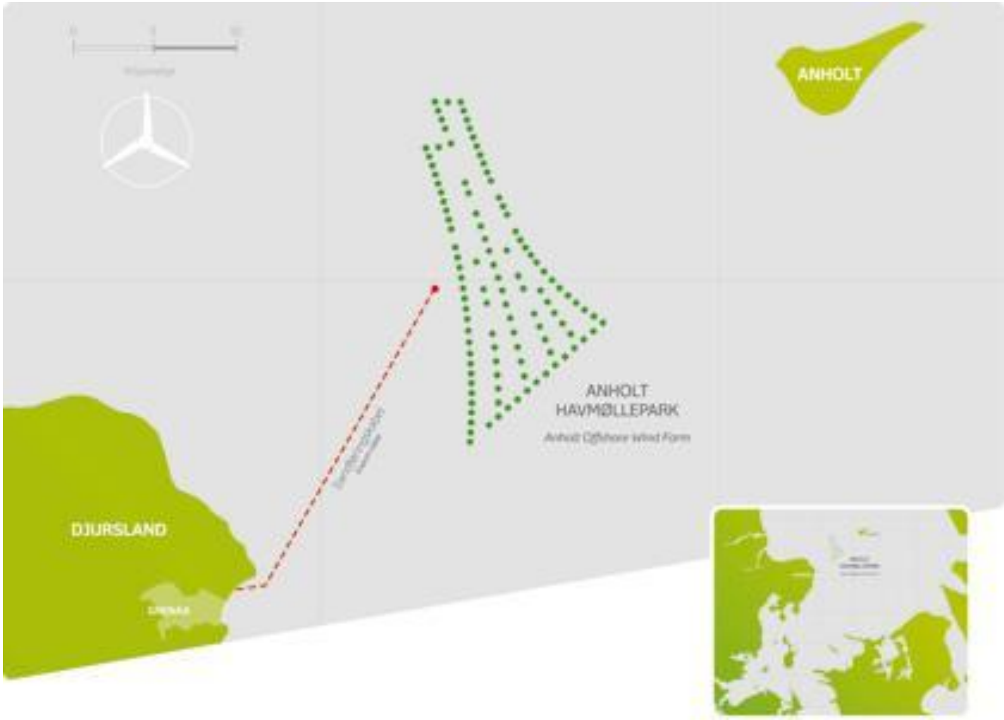

Figure 12: Anholt wind farm location
(DONG energy, 2016)

The project also includes the offshore transformer platform with dimensions 37.5 x 23.4 x 139 m (LWH) and submarine cable to transport the generated electricity to shore at Grenaa. A geophysical survey of the wind farm area and the cable corridor was conducted before the installation begun .The major soil types encountered were mainly gravel, sand, clay and in some areas small organic content - which are preferable for driven steel monopile foundation. In 2010, DONG Energy was awarded the licence for construction and operation of the Anholt offshore wind farm for 25 years. The construction works took place between 2012 and 2013. The wind farm has been in operation since 2013 and can supply electricity corresponding to the annual consumption of 400,000 households (Pau, 2015). A summary of information on Anholt is presented in Table 4.

Table 4: Anholt Project facts

FACTS			
Wind turbines	Siemens 3.6 MW-120	Length,monopile	33-37 m
Number of wind turbines	111	Start wind	4 m/s
Wind turbines capacity	3.6 MW	Full production from	13 m/s
Total capacity	400 MW	Stop wind	25 m/s
Hub height	81.6 m	Distance to shore	20 km
Rotor diameter	120 m	Wind farm area	88 km^2
Total height	141.6 m	Construction period	2012-2013
Weight, blade	18 tonnes	In operation	Autumn 2013
Weight, tower	200 tonnes	Location	Anholt in the Kattegat sea
Weight, nacelle	205 tonnes	Developper	DONG Energy
Total weight,foundation	460 tonnes	Ownership:	50% DONG Energy
Pile driving depth	20-30 m		30% PensionDanmark
Water depth	15-19 m		20% Pensionkassernes Administration

A part from the principal contractor DONG energy, Energinet.dk, the Danish national transmission system operator for electricity and natural gas was responsible for establishing an offshore substation, for the power export cable to shore, and the connection to the main power grid on land. Anholt wind farm is one of the big projects in Denmark, in addition to DONG energy other main sub-contractors were involved in project execution such as Siemens Wind Power A/S for wind turbines and rotors supply, Siemens A/S for offshore substation electrical equipment, MT Hoejgaard for Civil engineering, AH Industries for wind mill towers and nacelles and Nexans Deutschland GmbH for array cables. Furthermore, about 23 other sub-contractors were contracted by some of the main sub-contractors (Pau, 2015).

During the construction of Anholt, various professional services provider were involved. The involved services provider were; Ballast Nedam Equipment services for the foundation installation vessel, A2SEA for Wind turbine installation vessels, Visser & Smit Marine was contracted by Dong Energy to install infield cables and Hvide Sandes Skibsbyggeri for two service vessels. GEO Engineering Consultant was hired to carry out geotechnical and geophysical investigations and Ramboll made detailed designs for offshore substation and foundation, environmental and maritime studies. The project reports indicate that about one hundred vessels were involved in the construction and a total of 3,000 employees of which 1,000 staff was employed fulltime (Pau, 2015).

6.2.4 Anholt installation process

During installation period the wind turbine components were stored at Grenaa port and transported to site by support of barge and the installation vessel itself. As shown in Table 5, the actual construction activities started in 2012.

Table 5: Key dates and activities for Anholt wind farm construction project

	Time	Activity
	February 2008	Political agreement of the establishment of a wind farm
	April 2009	Danish Energy Agency released tender specifications
	April 2010	Danish Energy Agency received tender
Construction period=3 years	2 July 2010	Concession granted to DONG Energy
	July 2010	Geological surveys started
	Autumn 2011	Shore landing cable work started
	January 2012	Offshore construction started
	January 2012	Foundation construction started
	March 2012	Transformer platform work started
	June 2012	Laying-out of cables in the wind farm started
	September 2012	Erection of wind turbines started
	October 2012	First electricity generated
	Summer 2013	Entire wind farm in operational
	October 2013	Inauguration by Queen

Foundation

Foundations consisting of round steel pile with a diameter of approximately 5 m, a wall thickness of 5 cm and weighing up to 460 tonnes were driven into the seabed. The pile length varies depending on location from 37 m to 54 m. The monopiles foundations were installed by MT Højgaard A/S using Ballast Nedam heavy lift vessel-Svanen, and the transition pieces by the heavy-lift vessel Jumbo Javelin rented from A2SEA Company. A2SEA also used its sea power and flagship sea installer for the installation of Siemens turbines.

The steel monopiles were manufactured by Bladt Industries and MT Højgaard A/S had the contract for supply and installation of 111 foundations. To install the monopile, the first step was to install plugs and rigging at harbour then launch the plugged monopile to the water using sheerlegs as shown in Figure 13. The plugged monopile was able to float on water surface and towed to site for installation by means of vessel. Reaching the point of installation the monopile was installed by MT Højgaard A/S technicians by use of Svanen vessel shown in Figure 14. It took about 7-8 hours to drive the monopile into the seabed and afterwards a transition piece was installed.

Figure 13: Lifting monopile at Grenaa
(Source: DONG Energy 2016)

The transition piece installation vessel, capable of carrying 9 pieces on each load, was used for loading the transition pieces directly from the harbour. On arrival to site the 170 tonne transition was lifted and grouted on top of the monopile. Once the transition piece had been placed access was provided for grouting and completion works such as paint repair, after which the substructure is ready for handover (MT Højgaard, 2012).

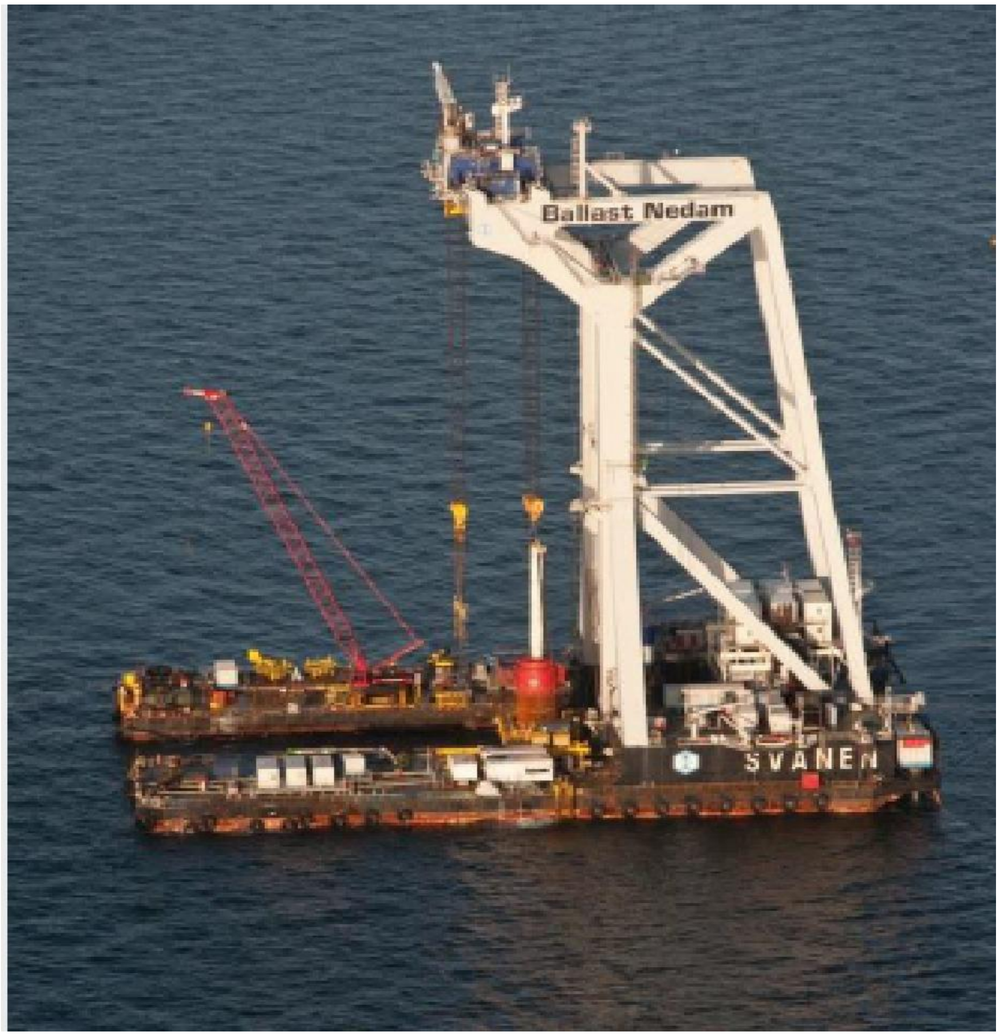

Figure 14: Driving monopile foundation into seabed
(Source: DONG Energy 2016)

Turbine

The wind turbines were supplied and installed by Siemens wind power A/S, each wind turbine has a capacity of 3.6 MW and the weight of 200 tonnes. Turbine installation includes the installation of nacelle and three blades. The total height of the wind turbine is 141.6 m to the tip of the blade. The air gap between mean sea level and the lower tip of the blades is approximately 23 m above mean sea level. To erect wind turbines, a crane mounted on the jack-up vessels was used to lift the wind turbine components into place in six lifting operations. As explained in Section 5.3 the lifting operation consists of 2 pieces of tower, 1 nacelle, 3 blades and no pre-assembly is done onshore. The jack-up barges or installation vessels, during installation stand on the seabed and create a stable lifting platform by lifting themselves out of the water body (DONG energy, 2016).

Figure 15: Loading turbine components
(Source: DONG Energy 2016)

A2SEA provided installation vessels, around four different turbine installation vessels were deployed at the same time during turbine installation period. Sea Power, a semi jack-up vessel with the capacity of one turbine per load installed 45 turbines. The other 39 turbines were installed by Sea Worker, a jack-up barge but non self-propelled, with the capacity of 2 turbines per load out. Sea Jack also a jack-up and non-self-propelled barge with the capacity of two turbines per load-out installed 13 turbines. Lastly the 14 turbines were installed by Sea Installer, purpose built for wind industry with the capacity of two turbines per load-out.

Figure 16: Installation of turbine components
(Source: DONG Energy 2016)

Turbine installation phase is carried out in following processes: The vessel loads components for one to two turbines at the port transports them to the site as shown in Figure 15. At the site the vessel jack-up and start installation of one turbine starting from lower part of the tower, upper part, nacelle and three blades are installed separately as shown in Figure 16. Once the first turbine is completed the vessel goes down to the floating level starts sailing to the next turbine location and jack-up again to installation of the second turbine. Having repeated the same installation procedures and finished the carried components, the vessel takes voyage from site back to port for new loading (Thomsen, 2013).

Substation

Energinet.dk was responsible for establishing an offshore substation and power export cable to shore. Siemens AS was awarded the contract for supply and installation of offshore electrical substation equipment and control system (SCADA). Strabag offshore wind GmbH signed a contract with Energinet.dk to design, build and install a concrete gravity base foundation and steel support structure for the transformer substation. The electrical and technical systems on the transformer platform started at Bladt Industries in Aalborg and the transformer platform floated from Aalborg to Anholt. Semco Maritime that was in charge of electrical, security and safety installation completed the installation later after the transformer arrived at Anholt.

The whole structure, made of concrete gravity base of 4,000 tonnes from dry dock near Copenhagen together with steel jacket structure of 800 tonnes from Spanish subcontractor, was floated and towed to Anholt site. The concrete foundation structure has been placed on sea bed 3 m below the sea surface with the steel structure rising up to 12 m above sea water level. In the end, the main rectangular steel platform structure of 1,710 tonnes was fixed to the rising steel jacket by Seaway heavy lifting- the 2,500 tonne crane vessel ‘‘Stanislav Yudin’’ as shown in Figure 17 (Strabag, 2013 and Offshore WIND, 2012).

Figure 17: Lifting and installation of Anholt substation
(Source: Energinet.dk)

Cables

An offshore transformer platform contains three transformers, collects the power from the wind farm and increases the voltage. Since the wind turbines produce power at a voltage of 33 kV and in order to reduce power loss the voltage is transformed to 220 kV in the substation before the power is transmitted to shore. Thus 160 km buried submarine array cables, connects the turbines to offshore substation, and transmits the power generated by the 111 wind turbines to offshore substation placed on a platform in the western part of the wind farm. From offshore substation, the 25 m long submarine cable or export cable of diameter of 27 cm buried in 1 m into the seabed by means of advanced remote-controlled robots transmits the power to Grenaa. And a further 56 km high-voltage land cable transmits the power from Grenaa to an existing onshore substation at Trige where a 400 kV main power grid distributes the power to the customers (DONG energy, 2016; Pau, 2015; Energinet, 2016).

The inter-array cables were manufactured by Nexans Deutschland and Visser & Smit Marine Contracting (VSMC) contracted to execute the array cable installation. The cable transport was organized from Nexans’ factory in Hannover to Anholt where it was installed by both Stemat 82 and Toisa Wave DP2 cable installation vessels (VBMS, 2012).

6.3 Specific Installation Challenges

In this section the results from specific project reports and interviews with developers and contractors involved in the case studies are presented.

6.3.1 Lillgrund specific challenges

The construction of Lillgrund was considered successful by the developer. According to Larsen (interview, 2016-03-10), the 2.3 MW turbines selected was a proven technology that had been used on several other windfarms. Also in an interview with Johanssen (interview, 2016-05-03), the vessels and methods adopted for Lillgrund had earlier been applied at Horns Rev I, a wind farm within North Sea with conditions harsher than in the Baltic Sea. Despite the success of Lillgrund construction, some challenges were experienced and are discussed in the following text.

The export cable installation was delayed as a result of bad weather conditions at sea and the breakdown of the thrusters/propellers of the vessel Nautilus Maxi after hitting what is presumed to have been excavated material or sandbar (Unosson, 2009). Aronsson (interview, 2016-04-14), a project manager at Baltic Offshore Kalmar AB, recalled the failure and remembered talk of the machine grounding in excavated masses. He also added that the thrusters are delicate parts whose functionality can be impaired by even minor dents. Even after repairing the broken thrusters, harsh weather conditions at sea prevented immediate resumption of operations by Nautilus Maxi. This resulted in a delay of two months and need to re-open the trenches which had consequently been refilled with mud during the period of inactivity (Jeppsson et al., 2008; Unosson, 2009). Also, according to Jeppsson et al., (2008), the layout of Lillgrund was made with an unutilised space close to the centre of the park. This was due to the too shallow water in this part which could prevent vessels from easily manoeuvring in this part of the park.

The installation vessel was loaded so that it could be unloaded in a given sequence. In case an error was discovered in works on site, installation could not proceed but rather the entire vessel would have to be moved back to the installation harbour to be unloaded and have the error fixed. In a bid to minimise errors at the tower and foundation interface, tight tolerances were set for the bolts since a mismatch in connection during installation would require sending the installation vessel back to harbour for unloading and reloading – a process that would significantly increase installation time and consequently costs. The narrow tolerances set presented constructability challenges for the foundation manufacturer. Even when the contractors managed to achieve tolerances for each bolt, there was unevenness in the concrete when the whole tower was installed rendering some bolts too short to allow for ease in placing the jacket for bolt pre-tensioning. Therefore, local cutting of the concrete had to be done to achieve the required bolt height (Jeppsson et al., 2008).

According to A2SEA (2016), the company that transported and installed the turbines at Lillgrund, the challenges faced at Lillgrund involved the limited space between the turbines. Johanssen (interview, 2016-05-03), stated that the transportation of pre-installed rotors to site complicates the installation process since lifting the wide rotors is likely to result in collisions with the already installed structures at site as well as at the installation harbour. Additionally, the hit and run technique was employed during turbine installation. The technique means that in case the weather became unfavourable, the entire installation vessel had to be moved to safety at the installation harbour. However, the distance from the installation harbour at Nyborg to the windfarm was long hence making it difficult for timely movement of the vessel to safety. However, according to Johanssen, with the currently available vessels which are able to withstand harsh offshore conditions, distance is no longer a problem.

6.3.2 Anholt specific challenges

Anholt wind farm is said to have been successful according to the parties involved in its execution. Despite these assertions, a number of challenges were encountered during installation and they are highlighted in the following text.

When asked about the most challenging part of the project, the DONG Energy project director said that it was the project complexity. He added that, to meet the project goal in short and strict time frame, it was mandatory to have a robust and efficient installation set-up. It was crucial to choose the optimal installation strategy and ensure the availability of the specialised installation vessels in order to avoid delays and their effects on the installation sequence. It was also necessary to cope with natural challenges such as seabed conditions and weather conditions. Since the installation phase of Anholt took place during two winters and one summer, weather conditions put pressure to material supply and personnel working on site (DONG Energy, 2013).

Geotechnical survey showed that the northern part of the wind farm was challenged by soft seabed in some turbine positions and the presence of boulders zone in the southern part. In respect of the installation process and future use of vessels with jack-up function, the detailed depth profiles were carried out for all turbine positions which finally necessitated the abandonment of some turbine positions. These abandoned positions caused the change of the final park layout and a non-optimisation of a given area (DONG energy, 2013).

In an interview with Ms Bente Østerbye (interview, 2016-04-15).a senior project director at MT Højgaard that was in charge of supply and installation of foundations, the company did not encounter any problems caused by boulders during monopile installation. However, as different precautions had to be implemented to eliminate the risk from boulders the client provided for more than expected quantities that had to be paid for regardless of whether they were executed or not.

Gas presence was also found during the surveys at position of turbine number 21 in the northern area of the farm; it was shallow gas since it was entrapped between 4 and 8 m below seabed. The gas was probably methane and hydrogen sulphide which are flammable and harmful to human respiratory system. A number of options were known to eliminate the hazard. The gases were expected to be released during the first minutes when driving the monopile in seabed. Additionally by dropping an anchor to the seabed at the gas position and applying a load to the anchor the gas could be released. Considering that the installation vessel would be positioned at about 300-400 m from the gas location, it was expected that the released gas could dilute to an extent in which it is harmless before reaching the installation vessel and this was considered the most favourable solution. Additionally as a precaution, Bente (interview, 2016-04-15) said that gas detectors were installed at the pile gripper, a gas detector with suction pump and hose was connected to the hammer sleeve for continuous monitoring of the gas which flowed out of the monopile during pile driving.

MT Højgaard used various tools and equipment for the installation of monopile. The various tools and equipment such as jack-up vessel and floating vessel both equipped with a crane, hydraulic hammer and a pile gripper were used by MT Højgaard for installation of the monopile. In addition, drilling and cutting equipment and jetting tool for pulling were used in case of pile driving refusal.

The pile installation involved driving the pile between 20-30 m into the seabed using a hydraulic hammer. The penetration depth was determined as a function of the turbine loads, water depth, wave loads, ice loads and soil conditions. The expected time for driving each pile was between 7 and 8 hours depending on soil properties. During monopile driving, the risk of pile refusal before achieving full penetration– primarily due to the risk of boulders was considered. In this situation, a combination of both driving and drilling activities was planned as general solution. The drilling equipment is used to drill out the soil inside the pile and remove the obstruction before pile driving is resumed. Bente (interview, 2016-04-15) stated that due to the way Svanen– the installation vessel operates, it was not possible to shift the hammer with the drilling equipment without releasing the pile from the pile gripper. If the pile refusal occurred in the transition zone between shallow penetrations, it would be possible to pull the pile up again using the trunnions. Considering the case of deep penetration where the pile was stable it would be necessary to cut the pile at seabed level and abandon it. Therefore MT Højgaard has developed the procedures for cutting a failed monopile and retrieval of an unstable monopile, the total cutting duration was around 8 hours. She also mentioned that in order to avoid the risk of standstill of up to 14 days due to damage of the hydraulic hammer during pile driving, a spare hammer was mobilised to installation site.

It has been reported by Energinet.dk that at several areas, it was not possible to bury the array cable at a sufficient depth due to stones or hard seabed. Therefore it was recommended to place a protecting layer of stones in the identified areas to ensure protection of the cables (subseaworldnews, 2013).

Due to a tight schedule, the harsh weather conditions posed great challenges to some installation activities such as the erection of turbines that were done in eight and a half months including intense turbine installation over the cold and icy winter. Monopiles were transported floating on water surface and being pulled to site by vessel, since the installation of foundation also took place during winter it was then challenging to move freely. Therefore special equipment was designed and used for icebreaker; special oil was also used for hydraulic system during the towing of the monopile to site.

Despite the robust installation set-up and a close dialogue with suppliers, irregular supply was also one of challenges highlighted by some contractors. Irregular turbine delivery was one of the challenges mentioned by A2SEA that was providing the transport and installation services of turbines (A2SEA, 2013). The turbine supplier, Siemens increased the turbines delivery rate thus requiring A2SEA to change the vessel planning accordingly. Bente (interview, 2016-04-15) also mentioned that they encountered the challenge of inability of some suppliers to produce to required specifications; one manufacturer was not able to produce foundation to accuracy and specified requirements.

DONG Energy reported the presence of Subsea Mines while performing detailed geophysical surveys of the seabed. Two old mines from World War II were located on the seabed in the wind farm area, one of the mines was located close to the substation, and the other mine was located in the centre of the wind farm area. The mines were inspected and classified as high-risk mines thus the Admiral Danish Fleet blasted the mines before the installation begun (subseaworldnews, 2012).

Owing to the good planning, preparation and readiness during the installation of Anholt, the problem of appropriate equipment was not experienced. Additionally, Bonefeld (interview, 2016-04-06) mentioned that there were a number of available vessels than before especially cable laying vessels coming from oil and gas because of low oil price at that time. The problem of limited supplier especially turbine suppliers and export cable manufactures, this result in limited choice of supplier. Both Bonefeld and Staffan (interview, 2016-04-15) said that Siemens is the main player among the turbine suppliers.

6.3.3 Cross-cutting challenges

Despite the focus of this research being on case studies, a number of crosscutting challenges that affect the installation process were identified from interviews conducted. Most of these are a result of attempts to improve the wind farm performance whereby attempts to optimise output of the windfarms results in new challenges. From a developer’s perspective, Larsen (interview, 2016-03-10) from Vattenfall and Bonefeld (interview, 2016-04-06), working as Senior Director at DONG Energy both stated that in an attempt to optimally harness the wind energy and to reduce the number of turbines installed, large size turbines and longer blades were being produced. As the turbines become larger, they also require massive foundations. This view was also shared by Sjölander (interview, 2016-04-05) working as Project manager at E.ON. While talking to contractors, Bente (interview, 2016-04-15), she also emphasised on the challenge of lifting heavy and big size components.

The heavy weights render the currently available vessels insufficient for lifting such heavy components. Additionally, logistical challenges arise since the components can no longer easily be transported by road. As a way of reducing the logistical challenges, some manufacturers have started locating production facilities close to the shore to enable direct load out of the components onto transportation vessels. Concerning the installers, when asked whether they are involved during the early stages of the projects, Johanssen (interview, 2016-05-03) stated that they always work cooperatively with the turbine manufacturers.

7 Discussion

From the analysis of interview results, the challenges could be categorised as site specific and crosscutting challenges. The site specific challenges were those specifically experienced at the cases studied, Anholt and Lillgrund whereas the crosscutting challenges were those that were raised similarly by interviewees at both case studies. The general challenges found in literature and different reports gave the general view of most occurring challenges in offshore wind park installation. The interviewees in some instances raised similar challenges such as delays as result of harsh weather conditions at sea and the challenges related to transporting and installing heavy weight components. These challenges validated the results from previous reports and studies.

From the obtained results it was noticed that some of the general challenges arise from nature like weather conditions and difficulties in fully predicting ground conditions whereas other technical challenges such as heavy weight components resulted from among others the production of larger turbines with the aim of improving the efficiency of turbines and reducing construction costs. The site specific challenges such as irregular supply and inability to produce in accordance with the required standards are attributable to among others supply chain constraints such as limited number of suppliers.

Gerdes (2010) highlights the main steps required in the planning and development of offshore wind farms. The installation process is among the main steps in wind farm development. In the installation process, different resources are managed to deliver products by the principle of getting outputs using an input-transformation-output process. Thomsen (2014) asserts that for a successful planning and execution of any offshore wind farm, a logical plan of tasks together with allocated resources as well as countermeasures for challenges has to be done.

The managers involved in the installation phase of Lillgrund and Anholt considered preparation and planning as vital elements required to keep projects on time and budget. The planning involved making decisions on the type of vessels that were appropriate for the installation task at hand, deciding the form of contract to use, the interpretation of both weather forecasts and geotechnical investigations to guide the scheduling , procuring contractors and selecting appropriate installation harbours to mention but a few. The planning activity was also guided by among others knowledge and the experiences gained from previous operations. In order to minimise ambiguities the planners attempted to use methods that have been proved for instance the selection of wind turbines used at the Lillgrund wind farm.

Since the installation of wind turbine involved various contractors and service providers, both developers and contractors agreed to work in close cooperation. Such kind of cooperation was highly needed from design phase to facilitate the early identification and mitigation of problems that could arise in the later phases of the project. For instance to avoid lifting challenges that might occur, the designers would need to be aware of the availability of appropriate lifting vessels on the market. Given that the installation was carried out by different contractors the master planning was jointly done and regularly updated by all parties involved. The cooperation among the different parties was necessary to improve coordination, communication and consequently minimizing conflicts during construction.

Both Lillgrund and Anholt had an installation period that was, according to interviewees, short and with a strict time frame therefore they were forced to use any available weather window for installation activities. A number of decisions need to be made for the successful installation of offshore wind farms. The offshore wind industry is expanding according to market demand hence the required resources need to be planned accordingly. By focusing on market requirements and operations resources, Slack and Lewis (2011) suggest that in the management of operations resources, decisions have to be made in four areas which include; capacity, process technology, supply networks and organisation development.

Capacity refers to the resources available to perform required activities within a given period of time, it also influences an organisation’s ability to meet and respond to customer demands as well as project lead time and operation cost (Slack and Lewis 2011). All interviewees agreed that the choice of right installation vessels was the first step during a planning of a wind farm installation. For example to avoid the heavy lifting challenges that could occur, at Anholt, the contractor chose to tow the foundation to site instead of loading them on vessels because it was not quite easy to lift the 460 tonne monopile whereas at Lillgrund, the gravity foundation were directly manufactured on barges and transported to site by the same barges.

The choice and planning of an installation vessel was generally based on vessel capacity in terms of size and efficiency, seabed conditions and water depth. Therefore, due to favourable sea conditions, it was necessary at Lillgrund to use one type of vessel (sea power) for the whole installation process. The planning and selection of equipment was not quite problematic since the contractor deployed the same equipment that had just been used in harsher conditions at Horns Rev 1 in the North Sea. Contrary to Lillgrund, vessel selection and planning at Anholt was highly demanding. The planning for Anholt was based on the challenging conditions of the site and it was necessary for the contractor to find a unique and flexible solution to these challenges. One of the fascinating solutions was using a flexible fleet where the contractor planned and achieved turbine installation using four different installation vessels namely sea power, sea worker, sea jack and sea installer. According to A2SEA (2012), adopting this flexible fleet of vessels shielded the customer from paying huge costs for vessel capacity that is not really used.

Slack and Lewis (2008) define process technology as the choice and development of systems that contribute towards achieving the market requirements in terms of speed, dependability, quality, flexibility and cost. In agreement with this theory Kaiser and

Snyder (2010) also mention that a trade-off has to be made between the costs and risks imposed by the different combinations of vessel fleets available to perform the work. The interviewees confirmed that they had a variety of vessels available for use in the different phases of the installation process. The vessels of different lifting and operating capabilities with different kinds of technologies to facilitate their operations included; lift boats, jack up barges, self-propelled installation vessels, heavy lift vessels and different cable laying vessels as well as remote controlled robots.

Literature reviewed pointed out the shortage of purpose built vessels. However, from the interviews conducted, the interviewees asserted that there was sufficient capacity of vessels able to sufficiently meet the ongoing offshore development demands. Notwithstanding this assertion, the vessels were also in demand from other sectors such as telecommunication and oil and gas sectors. Consequently, there was uncertainty on the availability of vessels due to variability in demands from the different sectors. There was also concern over low installation speed due to the fact that the non-purpose built vessels are specifically made for oil and gas industry.

Concerning the six installation methods of turbines, advances in technology especially for turbines, vessels and the introduction of the blade gripper, method one (i.e. installation of individual components without prior pre-assembly onshore) has become the most preferable. The method enables the optimisation of space on the transportation and installation vessels. One of the challenges expressed in an interview that differed from the general challenges in literature was related to the limited space between the turbines hence making the installation process difficult. This challenge could be attributed to the installation method employed at Lillgrund i.e. transporting fully assembled rotors to site. However, this problem will most likely not be frequently experienced in the future since the rotor components are nowadays transported as single units and installed individually.

As far as logistics is concerned, Jonsson (2008) indicates that logistics can be done within one company or as an integrated flow of materials through several companies. Companies should focus more on the supply chain approaches that help them to reduce costs, to be flexible towards customers' demands and being timely efficient (Wang et al., 2004). Linking this strategy to the wind turbine installation, Thomsen (2010) argues that the appropriate supply chain approach is to adopt the just-in-time principle, where the installation of offshore components is done just in the right place when needed without waste of time and resources.

The interviewees strongly emphasised that the installation harbour was problematic. The absence of sufficient numbers of purpose built harbours for offshore operation hindered the installation process since priority was given to commercial vessels over offshore vessels. As such it is preferable to use a purpose built harbour located further away from site than a non-dedicated harbour located close to site. In the Baltic Sea region, attempts have been made to resolve the harbour problem by building purpose built harbours such as Nyborg and Grenaa. The question that remains is whether they will remain suitable for handling heavy turbine components for future developments as well as to accommodate large size vessels. As the construction of offshore wind farm requires onshore space for pre assembly, loading, unloading and lifting activities of heavy and larger components for a long period it is challenging to find the big space of rigid pavement with appropriate facilities that can be occupied for a period up to three years. According to some of the interviewees, it is expensive to build purpose built harbours for every wind farm activity. As a result it is not economical to construct a harbour for each wind farm; a more appropriate solution would be to develop a number of strategically located harbours that can be used as need arises.

Slack and Lewis (2011) argue that rapid technology changes affect most industries including offshore wind power projects. As the number of competitors increase, the customers' demands become more sophisticated .Consequently; the simple way to gain advantage over competitors is to introduce updated products and services. The contractors organise themselves to have the capability of running their operations on a continuous basis while meeting customer demands. The ability to work in this changing environment on a continuing basis determines how the competences develop. Highly competent and well organised contractors are more and more needed as both turbine capacity and water depth increase. As a long term decision, most interviewees recognised the need for development and organisation in their respective companies in order to compete with future challenges that may arise. The interviewees were aware of the fact that future offshore installations would be in more challenging conditions than they did before, the reason for continuous development of processes and equipment to overcome the expected challenges.

The installation of offshore wind farms is highly weather dependent and harsh weather conditions at sea have been stressed as a common constraint. Installation activities can only be done under conducive weather windows. This was highlighted as one of the major constraints by all the interviewees contacted. Contractors and developers have attempted to overcome the weather constraints by among others scheduling of highly weather dependent activities in autumn and summer. For instance turbine installation and cable laying are done in autumn and summer. In recent times however, purpose built vessels and technologies such as the blade gripper have been developed to facilitate offshore installation works in harsh weather conditions.

8 Conclusion

The offshore wind sector is continuously growing regardless of its lower competitiveness compared with other energy sources. The rapid growth originates from the need by developers to maximally tap the large energy resource offshore.

The sector is continuously improving its processes and finding solutions to some of the challenges that the sector has previously faced. Generally during the installation of offshore wind farms a number of decisions need to be taken to foster smooth operation. Decisions need to be taken on selection of the right vessels for the anticipated work at right place and in right time. For unhindered progress of works contractors competent to perform the works need to be hired. As such decisions have to be made on what method of procurement has to be used in order to get the right contractor who can implement the project economically. The aforementioned decisions need to be supported by proper planning of operations where it is clearly defined who, when and how the task will be performed.

However, through this research a number of challenges have been identified and discussed. The installation of offshore windfarms is faced with a number of challenges such as failure of mobilized machines to perform work and presence of unknown items on the seabed such as unexploded objects left in the sea due to earlier human activities. Turbine sizes are increasing as the industry players seek to effectively tap the wind resources offshore. This however results in larger and heavier components which require larger vessels equipped to handle heavy loads and render road transport unfeasible thus requiring alternative means of transportation. These rapid changes necessitate cooperation between the players that participate in this highly fragmented sector. Some challenges are site specific for instance seabed conditions thus requiring each project to be carefully planned as a unique case. Solutions to site specific challenges may also come from experiences and lessons learnt from similar projects completed.

The installation activities are highly weather dependent whereas harsh weather conditions like frozen water in winter, high wind speed and sea tide are still encountered. The weather related phenomena are natural events and outside human control and were considered as persisting. For these persisting challenges, the authors recommend that their impact should be considered during the planning of activities, having appropriate risk sharing and allowing time contingency in scheduling. Since the turbine components are getting bigger, the logistical challenges involved in transporting over road can possibly be minimised through the location of turbine manufacturing facilities close to the water bodies.

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