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Report

HSE challenges related to offshore renewable energy

A study of HSE issues related to current and future offshore wind power concepts

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(Hywind tow. Source: statoil.com)

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ABSTRACT

This report presents the results of a study of hazards and HSE challenges within the offshore renewable wind energy industry. The various offshore wind power concepts that exist today, as well as developments that may result in future concepts are listed and described in terms of technical solutions and operational philosophy. A brief, categorised summary of actors in Norway is presented. Equally briefly the regulations and standards that we have found for offshore renewable energy are listed. The report presents a qualitative analysis of the hazards that exist for different stages and phases of offshore wind farms. Furthermore, several potential accident scenarios are presented, with possible consequences for humans, the environment and materials. Some issues, such as construction safety and helicopter transport, are presented in more detail. The project has been carried out by an interdisciplinary team of SINTEF and NTNU (the Norwegian University of Science and Technology) researchers and professionals.

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HSE challenges related to offshore renewable energy

Executive summary

The study has been conducted in order to demonstrate the important HSE factors related to offshore renewable energy. The offshore renewable energy industry is immature and this limits the study's ability to present valid HSE information. The HSE challenges described in this report may be used as a basis for developing regulations for the industry. The study has been carried out by a SINTEF project group together with a reference group consisting of representatives from authorities, employee unions, research communities and companies active within the industry. The study covers potential serious incidents and major accidents (including environmental issues) as well as work-related accidents.

The first part of the report evaluates different concepts for planned offshore wind farms. Usually a pre-feasibility study is carried out covering all aspects of the project. Following this concept phase, an extensive site investigation is performed. Data about wind and wave conditions at the location has to be gathered. The next step involves engineering of the main components. This is usually done by subcontractors. Then, all the components have to be constructed and installed. In detail, the installation comprises the substructure, the wind turbines (nacelles and blades), and the electrical infrastructure. The general operational lifetime of an offshore wind farm is around 20 years. The wind farm can be operated remotely from shore, but yearly services and maintenance of the turbines has to be performed offshore. The main challenge is access to the turbines in adverse weather conditions. In addition, breakdowns can lead to the need to replace heavy components. This involves larger logistic operations. At the end of its lifetime the wind farm components have to be removed.

In general, seven different foundation/substructure concepts are currently available for offshore wind turbines. The main difference between these concepts is whether they are bottom fixed or floating and the water depth they are suitable for. Each concept has its advantages and disadvantages, and some (such as suction bucket and floating substructures) are still in the test phase. Even though current offshore wind turbine concepts are quite similar, several new concepts are under development. The new developments address mainly the number of blades, the orientation of the axis and replacement of components (for example the gearbox).

The installation of wind turbines offshore is performed with a crane vessel (usually a jack-up barge). Transport of the components can take place directly on the crane vessel or on additional transport vessels. Floating substructures are easier to install than bottom fixed foundations. In general, floating structures and turbines are preassembled close to the construction port and then towed out to their final position as a complete unit.

One of the main challenges in the operational phase of an offshore wind farm is access to the turbines. Wind and especially wave conditions can make access and egress impossible. Access methods can be divided into four main categories: (1) direct boat landing, (2) boat landing with motion compensation,

(3) crane hoist and (4) helicopter. All access methods have their advantages and disadvantages. Three methods are available to transfer equipment to the wind turbine: (1) carried by crew, (2) crane and (3) helicopter. The choice of method depends on the weight of the equipment and the weather conditions. A typical offshore wind farm requires approximately four to six visits per wind turbine per year. Of these, there are one or two planned visits for regular service/maintenance and two to four unplanned visits for corrective repairs. It is also common practice to perform major overhauls at 5-yearly intervals. Replacement of small parts and normal inspections are responsible for the majority of maintenance operations. The practice (found in the North Sea) of using helicopters to access the nacelle from a suspended basket is regarded as very risky, although at least one European helicopter operator is in the process of developing “a safe, flexible and cost effective method of helicopter access” to offshore wind turbines.

A large number of Norwegian actors are active within the offshore wind power industry, although no offshore wind farm has yet been constructed in Norway. The Hywind pilot is the only offshore wind turbine constructed so far. However, concessions have been awarded for several offshore wind farms and there are other farms still in the concept stage. Several Norwegian actors are involved in foreign offshore wind farm projects, for example in the UK and Germany.

Several laws, regulations and specifications apply to offshore wind farms in Norway. These include: The Energy Act, The Ocean Energy Act, the Employment Protection Act, the Petroleum Activity Act, and the Pollution Act, as well as a large number of additional regulations. There is also the question of whether the EU Directive 2006/42/EC on machinery should apply to offshore wind turbines considered as a whole, as well as the mechanical parts of the turbine. Some detailed standards and specifications for offshore wind turbines are also currently being developed abroad.

We would like to point out that the offshore renewable energy industry is as immature in Norway as it is in other parts of the world. This limits the ability of this report to give a broad perspective on HSE challenges. The publicly available information on accidents and incidents, as well as accident and incident scenarios on offshore wind farms is scattered and lacks detail. Nevertheless, the material gives some indication of the most critical and frequent HSE incident scenarios, namely lifting operations, access to and egress from turbines, maritime operations and emergency handling:

- There are several reports of incidents related to lifting operations during installation of offshore wind farms.
- Severe sea conditions threaten safety during installation.
- Repairs to essential equipment (such as installation vessels) can lead to maintenance tasks being delayed (due to the distance travelled). One accident report indicates that such delays can put increased pressure on personnel to meet installation deadlines within the summer time window.
- Corrosion is a possible challenge to the technical integrity of offshore wind farms.
- There are structural safety issues related to seabed connections.

Some structural failures are intrinsic to the marine environment as they affect components which are not present in onshore wind turbines. Other categories of failure (such as lightening or corrosion damage) also apply to onshore wind turbines, but the probability of such failures increases in the offshore environment. The most frequent incident scenario for offshore wind farms seems to be related to crane and lifting operations during installation, heavy maintenance work, transport of equipment and parts, and access. Maritime operations are also frequently involved in incident scenarios. Major accident scenarios with the most severe outcomes (in terms of fatalities and material loss) are related to maritime vessel and helicopter transport, and structural damage during operation. There are some scenarios that are specific to offshore wind turbines. These include ice throw, blade failure (and possible consequent structural damage), and some other aspects related to access to the turbine and the tower.

The following issues have been identified as important for emergency operations in offshore wind farms:

- In current offshore wind turbines access to areas safe from fire is difficult. If personnel are present when fire starts, there are few alternative escape routes and few safe areas to wait for rescue.

- Helicopters may not be able to get close enough to rescue personnel in the sea or stranded at a turbine. A marine vessel may be the only solution, and there are limits on when vessels can be deployed (depending on wave height etc.).

- Evacuating a sick or injured person from the nacelle may be challenging as ladders inside and outside the tower are steep and may require both hands when climbing.

- Evacuating personnel from wind turbines because of changed weather conditions can be a challenge.

- In case of blade failure or other structural damage, it may be difficult to capture floating objects using boats, especially if the object is large.

- Possible differences in emergency handling for petroleum workers, fishermen and other maritime workers and workers in the offshore renewable energy industry should be considered.

- Many actors are involved in the different phases of an offshore wind farm. It is important to identify who is responsible for emergency preparedness and handling.

The current HSE situation for offshore wind farms appears to be very different to that of other offshore operations. HSE procedures, use of protective equipment, safe working practices etc. seem to be lacking, or at least incomplete. The actors involved are unfamiliar with offshore operations, authorities do not work closely together and they do not have clear roles and responsibilities. Emergency situations are not prepared for unless this is a requirement from one of the companies involved. There is also a general lack of regulation and coordination between authorities within the HSE area internationally. The findings from this project indicate that several measures should be taken to ensure good HSE practice for offshore wind energy operation in Norway and internationally. There is a need for regulation that respects Norwegian HSE interests and traditions when working on the Norwegian Continental Shelf and internationally:

- The responsibility for HSE regulations, inspections and audits should be clear and coordinated.
- Appropriate inspections and audits should be conducted.
- The phases in offshore wind energy farms should be regulated to ensure that HSE aspects are taken into account at an early stage. This includes the fact that responsibility for HSE should be clear and unambiguous at all times and in all phases.
- There is a need for HSE requirements in the design phase to ensure that sufficient attention is given to ergonomic considerations in manual work areas. This may require an international standard or guideline as most concepts from international industry are ‘off the shelf’.
- The wind energy industry is international. Cooperation between the relevant authorities in different countries is necessary.
- An offshore wind farm for research, testing and learning should be established. All experience of operation, maintenance, reliability and HSE development in the Norwegian offshore wind industry should be collected from an early stage. Databases for this purpose should be established. Contribution to, and use of data from such databases should be open to all actors and the authorities.
- Emergency preparedness plans and training sessions should be established.

Finally, the report identifies a need for further work. This comprises the need for research farms and pilot projects where HSE issues can be studied, as well as the need for a safety management system for offshore wind farms.

1 Introduction

This report presents the results of a study of hazards and HSE challenges that exist in the offshore renewable wind energy industry as well as planned and possible activities within offshore wind production in Norway.

The report lists the various offshore wind energy concepts that exist today, as well developments that may result in new models. Both fixed and floating concepts are included and they are described in terms of technical solutions and operational philosophy. The map of actors in this industry is rapidly changing, but a brief, categorised summary of Norwegian actors is presented. Equally briefly, regulations and standards that apply to offshore renewable energy are listed.

The main part of the report presents a qualitative analysis of the hazards that exist for different stages and phases of offshore wind farms. Furthermore, several possible accident scenarios are presented with possible consequences for humans, the environment and materials. The discussion includes a qualitative prioritisation of these scenarios. Issues related to risk mitigation and regulation of HSE risks are also identified.

1.1 Assignment definition

The background to the project was the fact that a study of HSE factors related to offshore renewable energy production does not exist elsewhere. The HSE challenges described in this report may be used as a basis for developing regulations for the offshore renewable energy industry.

1.2 Approach

We visited some of the actors working in the offshore wind industry in Norway. They shared their experience of HSE work on offshore wind farms in Germany and the UK, as well as their experience of projects in development in Norway. In addition, we used HSE reports from various organisations and institutions related to the development of offshore wind farms internationally and in Norway. The FME[1]s Nowitech and Norcowe contributed their knowledge of research and development activities in the industry. Discussions with the various companies are not reported in detail in this report, but the information provided is included in the HSE analysis. Findings have been partly validated by the fact that different actors point to the same HSE challenges. The HSE challenges noted are also supported by data from reports and webpages.

1.3 Conditions and limitations

The study has been carried out by a SINTEF project group together with a reference group consisting of representatives from authorities, employee unions, research communities and companies active in the industry. The study covers possible serious incidents and major accidents (including environmental issues) as well as work-related accidents. Security aspects are briefly addressed. Although the term ‘offshore renewable energy’ is used in the title of this report, the study is limited to offshore wind turbine energy production. The study includes selected developments in the North Sea, but areas under development in the Norwegian and the Barents Sea are also briefly considered. The study does not cover HSE challenges posed by accompanying infrastructure and adjacent constructions onshore.

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[1] the Norwegian Research Council's Centres for Environment-friendly Energy Research (FME)

1.4 Acknowledgements

The project group would like to thank all that have participated in the project and those that have provided information in telephone calls, meetings and visits. Contributions have come from contractor companies, operating companies, unions, the authorities, researchers and experts. We especially wish to thank the reference group and our employer for their cooperation in the project.

2 Current offshore wind farm concepts

The chapter describes current offshore wind farm concepts as they are applied both to existing offshore farms, and to farms in development (for example Round 3 offshore wind farm projects in the UK). Concepts under development are mentioned briefly in the corresponding sections to show possible evolutions and future trends. However the main focus of this chapter is on current concepts as they can be expected to determine the development of offshore wind farms for at least for the next 10 years.

First, the typical life-cycle of an offshore wind farm is briefly described. Second, the state-of-the-art in design and different concepts for the construction of an offshore farm are presented. The third section focuses on typical offshore operations since most of the health and safety-related hazards occur during these operations. The last two sections look at Norwegian actors and participants in the supply chain for an offshore wind farm, and possible locations in Norway.

2.1 Life-cycle of an offshore wind farm

The typical offshore wind farm has a life-cycle of more than twenty years which can be divided into several phases.

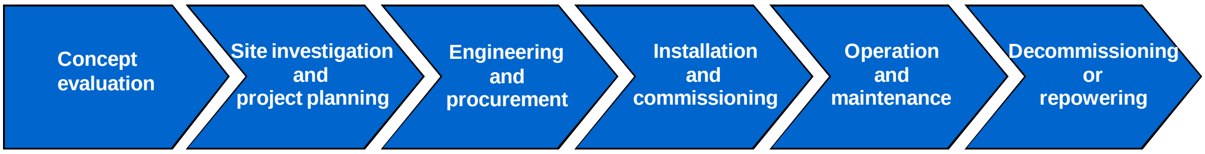

Figure 1: Project phases of an offshore wind farm (based on Deutsche WindGuard et al.)

2.1.1 Concept evaluation

The first phase is the evaluation of different concepts for the planned farm. Usually a pre-feasibility study is carried out which covers all aspects of the project. In detail, the wind farm technology and the grid connection have to be decided. In addition, an economic assessment of the main suppliers and construction work has to be undertaken. The feasibility of logistics and supply chain management have to be checked. Thought has to be given right at the beginning of the project to the possible environmental and public impact, in order to be aware of potential obstacles or protests. Strategies for financing, handling media and public opinion, stakeholder involvement and the approval process have to be developed. The structure of the project and possible partners has also to be decided upon.

2.1.2 Site investigation and project planning

After the concept phase, an extensive site investigation has to be performed. Data about the wind and wave conditions at the location has to be gathered. In addition, seabed surveys have to be carried out. These give valuable information about the appropriate type of foundation and possible routes for subsea cables. Data about the possible environmental impact on sea life and birds has to be collected. This is also a requirement for obtaining project approval from national authorities. Approval has to be obtained for both the wind farm and the grid connection. The time schedule of the project has to be planned, as well as the involvement of possible subcontractors. Tendering and negotiation with subcontractors is a crucial part of this phase.

2.1.3 Engineering and procurement

Engineering of the main components is performed in the next step. Usually this is done by subcontractors. The various components will be produced at different locations and by several subcontractors. It is therefore important to have control of the supply chain, and good interface and work flow management. The components produced are transported to the logistical centre, which is usually a port near to the site. The port has to fulfil several requirements. For example, there must be enough space available for onshore construction works, logistics and the high number of vessels active in the installation phase.

2.1.4 Installation and commissioning

In this phase all the components have to be installed. In detail, the installation comprises the substructure, the wind turbines, and the electrical infrastructure. The site has to be prepared before the final installation of the components can take place. Several components will be preassembled at the construction port (such as the offshore substation and parts of the wind turbines). After installation the wind turbines have to be connected with the substation and an export cable to shore has to be laid on the seabed. The installation of the different components is highly weather dependent and involves huge logistics operations both offshore and quayside. The installation phase is complete when the wind farm and the Supervisory Control And Data Acquisition system (SCADA) are tested and commissioned.

2.1.5 Operation and maintenance

The general operational lifetime of an offshore wind farm is around twenty years. It can be operated remotely from onshore, but yearly services and maintenance of the turbines have to be performed offshore. The main challenge is access to the turbines in adverse weather conditions. In addition, the breakdown of crucial parts can lead to the need to exchange heavy components and involves larger logistical operations.

2.1.6 Decommissioning/repowering

At the end of the lifetime of the wind farm, the components have to be removed. This again involves large logistical offshore operations. But due to the newness of offshore wind farms, no data on these operations is available. Another alternative is to use the existing infrastructure and to replace the existing turbines with more up-to-date and powerful parts, also called repowering.

2.2 General concepts/design

An offshore wind farm consists of several main components and different concepts are available. In general a farm consists of the foundation and the substructure (1), which holds the wind turbine (2). The wind turbines are connected via the inter array cable (3) with the offshore substation (4). The substation transforms the generated electricity and sends it through the export cable (5) to the onshore grid.

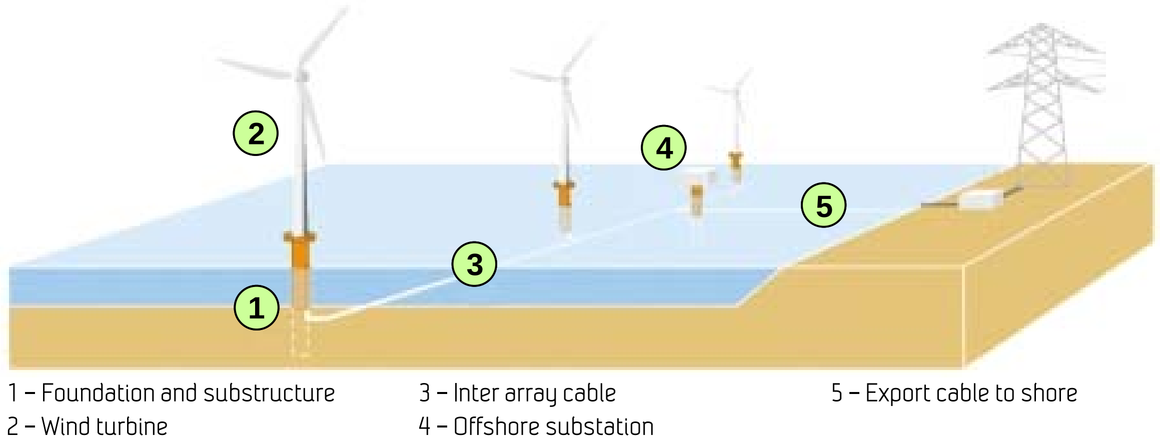

Figure 2: Layout of an offshore wind farm showing the main components (Source: www.bwea.com)

In the following sections the state-of-the-art of the various concepts for the main components of an offshore wind farm are presented. The main focus is on concepts currently in use and concepts which can be expected to be in use until 2020. In addition, newer concepts under development are presented to show how development may progress in the future.

2.2.1 Foundation, substructure and the wind turbine

The IEC (International Electrotechnical Commission, 2005) has defined the various parts of an offshore wind turbine shown in Figure 3.The foundation, the substructure and the wind turbine form one unit after installation. The foundation fixes the substructure to the seabed, while the substructure is the interface between the seabed and the wind turbine. A transition piece is installed at the top of the substructure. It provides the connection between the substructure and the wind turbine and enables correction of any deviations from the vertical in the substructure. The transition piece assures that the wind turbine is installed perfectly vertically. In addition, the foundation has to be protected against scour[2]. Sandbags and stones laid around the foundation can counteract the process.

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[2] Ocean currents and the continuous swell wash out sediment from under offshore foundations. This process is called scour. Scour causes offshore wind turbines to lose their purchase on the seabed and thus their stability (Source: www.offshore-wind.de)

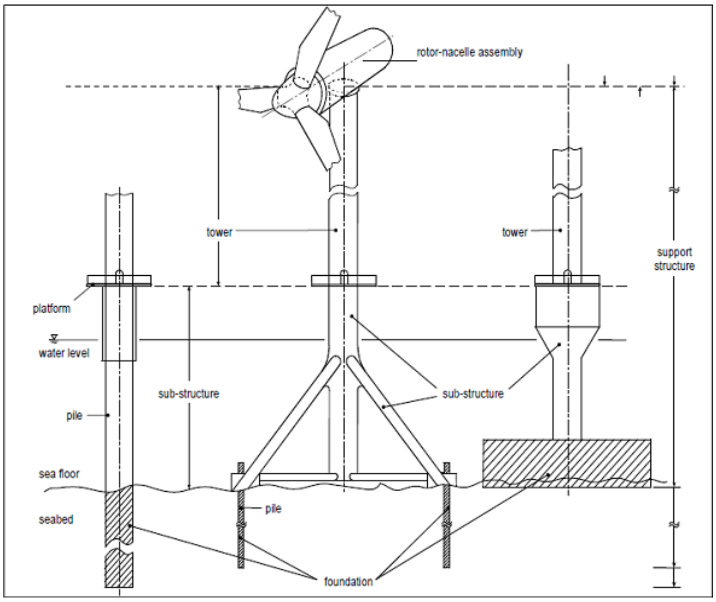

Figure 3: Nomenclature of an offshore wind turbine (Source: IEC, 2005)

2.2.1.1 Foundation and substructure

In general, seven different foundation/substructure concepts are available for offshore wind turbines. The main difference between the concepts is whether they are bottom fixed or floating, and the depth they are appropriate for. The following figure gives an overview of available concepts[3].

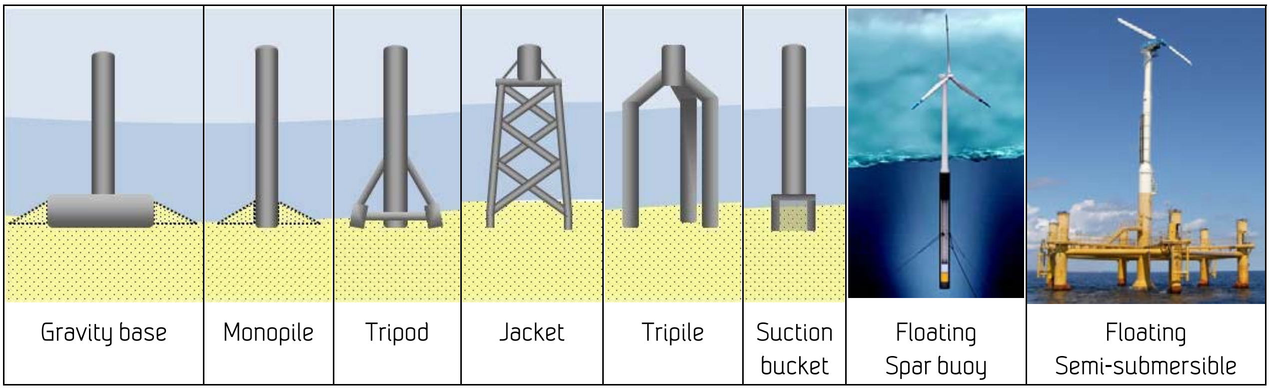

Figure 4: Available substructure concepts for offshore wind turbines (Source: www.offshore-wind.de and EWEA, 2009)

Each concept has its advantages and disadvantages, and some of the concepts such as suction bucket and floating substructures are still in the test phase. The following table summarises the main advantages and disadvantages, as well as applied examples for the various concepts.

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[3] Information about foundations and substructures is mainly based on www.offshore-wind.de; EWEA, 2009; Eggen et al., 2008; Douglas Westwood, 2010

Table 1: Characteristics of the different substructure concepts (Source: www.offshore-wind.de and EWEA, 2009)

Type	Depth	Example of application	Advantages	Disadvantages
Gravity base	up to 40 m	Nysted, Lillgrund	Needs little steel, no pile driving	Expensive if used at great depths
Monopile	up to 20 m	Horns Rev	Can withstand scour	Large pile hammer
Tripod	20-50 m	Alpha Ventus	Dimension of piles is small	Cannot be used in a stony seabed
Jacket	20-50 m	Alpha Ventus	Already in use in the oil industry	Needs large quantities of steel
Tripile	25-50 m	BARD I	Lightweight construction	Only one test facility to date
Suction bucket	up to 30 m	Test phase	No pile driving	Little experience
Floating	80 -700 m	Test phase, Hywind	Suitable for deep water	Little experience

Gravity based foundations

Gravity based foundations are made of concrete and are already used for bridges and in some European wind farms in a water depth of up to 10 metres. They are held in place by gravity, which is why no piling is needed (but the seabed must be prepared). High initial costs have been reduced by changing their shape. It is also now possible to install them in deeper water. Gravity foundations are not dependent on steel prices and are therefore inexpensive. On the other hand, their sheer weight can lead to transportation problems.

Figure 5: Gravity based foundation of the Nysted offshore wind farm (Source: www.nrc-cnrc.gc.ca)

Monopile

The design of the monopile consists of a cylindrical concave pile. Monopiles are used in many European near-shore wind farms in a water depth of up to 20 metres. They can be quickly and easily installed, but heavy pile hammers are needed. Monopiles can easily be protected against scour, but are dependent on seabed conditions and cannot be installed on a stony seabed.

Figure 6: Transport of the monopile for Fino 3 (Source: www.fino3.de)

Jacket

The jacket is a frame construction made of steel in the form of a lattice. It is pinned to the seabed with four extra piles. The offshore installation period is quite long due to the time needed for pile driving. Jackets are already in use in the oil industry and are appropriate for heavy, large-scale turbines. Due to the piling, it cannot be used on a stony seabed. Norwegian companies have experience in the design of jackets, for example the jackets for the Alpha Ventus wind farm are designed by OWEC Tower.

Figure 7: Transport of the jackets for Alpha Ventus (Source: www.alpha-ventus.de)

Tripod

The tripod is a three-legged steel frame which supports the main pile under water. It is pinned to the seabed with three small piles, which have to be hammered. It is possible to use piles of a smaller diameter than the monopile. The tripod can be applied in a water depth of up to 30 metres or more. Another advantage of the tripod is good scour protection. But because of the need to drive piles, tripods cannot be used on a stony seabed. The first tripods in operation at an offshore wind farm were produced by Aker Solutions in Verdal (Norway).

Figure 8: Transport of tripods for Alpha Ventus (Source: www.offshore-stiftung.de)

Tripile

The tripile consists of three steel piles which sit on a three-legged structure above the water level. As for the jacket and tripod, the tripile has to be pinned to the seabed. The production of the tripile is relatively cost-effective due to its compact construction. The first tripiles are in operation in an offshore wind farm. According to the manufacturer, tripiles can be used in a water depth of 25-50 metres.

Figure 9: Tripile at the offshore wind farm Bard 1 (Source: www.bard-offshore.de)

Suction bucket

The bucket foundation is sucked into the seabed by means of a vacuum and is held in place in sandy subsoil by suction. It is important that the construction is adjusted evenly and that it creates an upright and safe foundation. No pile driving is needed to install the bucket foundation, but it is very sensitive to seabed conditions. So far, no suction bucket has been successfully installed for offshore wind turbines. One test by Enercon to install a suction bucket failed.

Figure 10: Concept outline of a suction bucket (Source: www.energyengineering.co.uk)

Floating

Several concepts for floating substructures are available. However, they are all still in the development or prototype stage. The main two concepts are spar buoys (Hywind, Sway) and semi-submersibles (WindSea, Blue H, Windflo, Windfloat). The Hywind concept consists of a metal spar buoy filled with ballast. The floating element is fastened to the seabed by three anchor piles and is 100 metres long. A Hywind prototype has been installed by Statoil off the coast of Norway.

Figure 11: Hywind concept (Source: Statoil)

The Sway concept consists of a spar buoy tube with bottom ballast. The system remains stable as the centre of gravity is far below the centre of the spar buoy. It is anchored at only one point and can rotate around this point. Since the whole structure can rotate, the nacelle of the wind turbine does not have to rotate and can stay fixed. Another special characteristic of the Sway concept is that the wind rotor is placed downwind. Sway is designed for water depths of 80-300 metres.

Figure 12: Sway concept (Source: Sway)

The WindSea concept consists of a semi-submersible platform with three columns. A wind turbine is placed on each of the three columns. Two are orientated upwind and one downwind. The whole platform is self-orientating towards the wind. The WindSea platform can be easily disconnected from the turret that is connected to the mooring lines and contains the cable for power transmission. By doing so, it is possible to tug the platform to port for larger maintenance tasks.

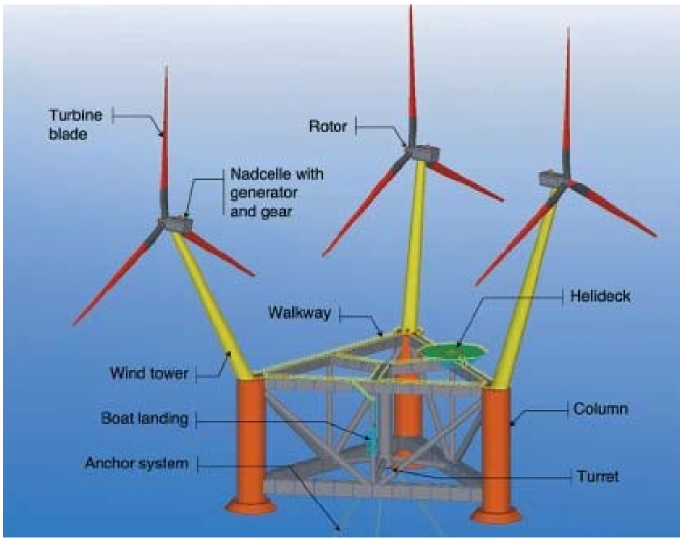

Figure 13: WindSea concept (Source: WindSea)

The Blue H concept is also based on a semi-submersible platform. The platform is connected to a counterweight on the seabed with several chains. Blue H is designed for water depths of 30 metres and more. A prototype was recently tested.

Figure 14: Blue H concept (Source: Blue H)

Other concepts are also available for floating offshore wind turbines with semi-submersible platforms. These are quite similar to the concepts already presented and will be only mentioned briefly here: the French concept Windflo and the Windfloat of Principle Power.

Figure 15: Windflo concept (Source: www.nassetwind.com)

Figure 16: Windfloat concept (Source: www.principlepowerinc.com)

2.2.1.2 Wind turbines

Early offshore wind turbines were adapted from onshore designs. But in recent years, more turbines have come to the market, which are specially designed for offshore conditions. The main problem for the design of offshore wind turbines is their reliability since they have to withstand a harsh environment. A clear trend is the use of wind turbines with production capacity of 5MW and above. The general design of all offshore wind turbines is quite similar and is shown in principle in Figure 17.

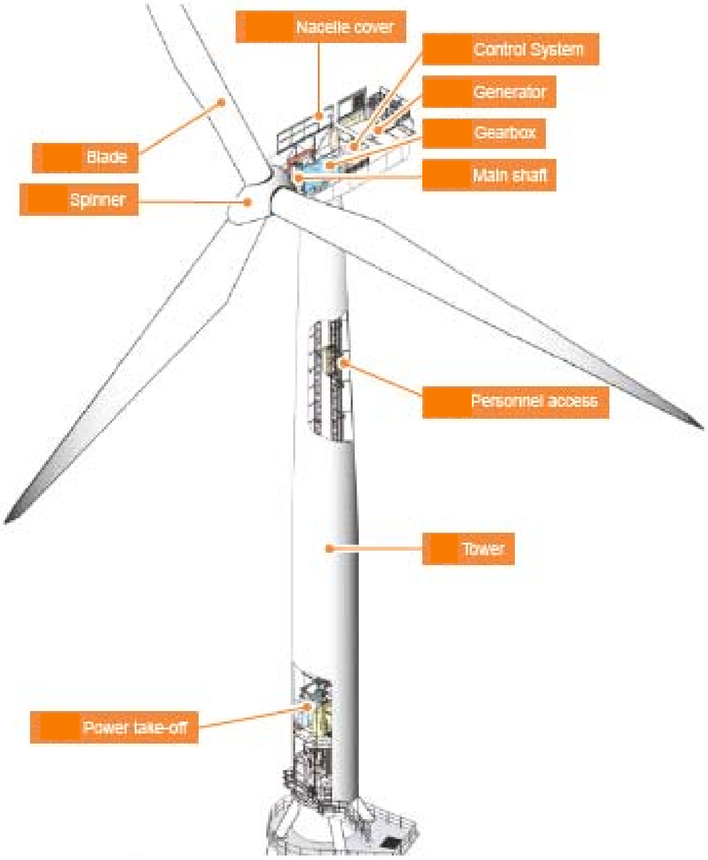

Figure 17: Configuration of an offshore wind turbine (Source: Siemens Wind Power and the Crown Estate, 2009)

The main components of a wind turbine are the tower, the nacelle and the blades. The tower is used by personnel to gain access to the nacelle. For this reason, ladders and a lift are typically installed inside. The tower can also be equipped with facilities for longer crew stays, in case weather conditions do not allow them to leave. Typically, this comprises a simple toilet and survival equipment. The nacelle is placed on top of the tower, and contains the main mechanical and electrical components. An overview of the main components inside the nacelle is presented in Figure 18.

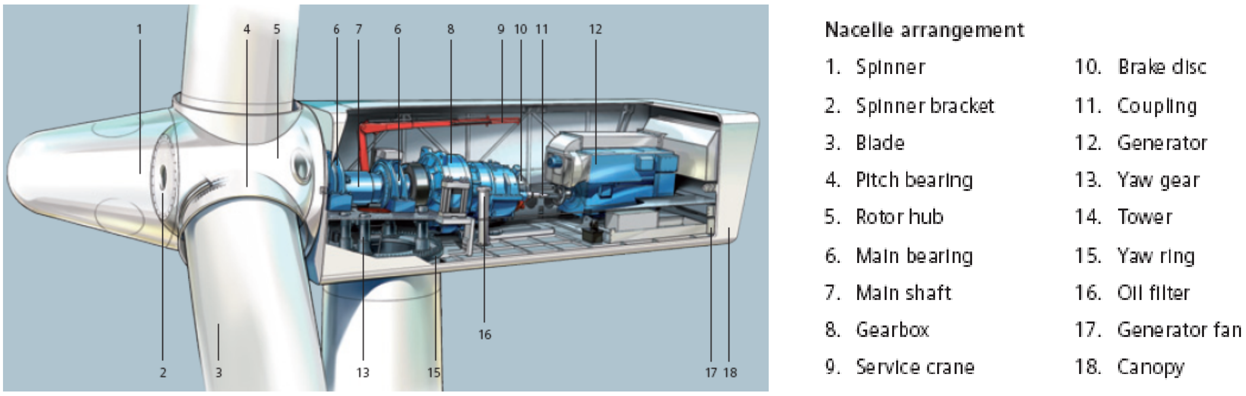

Figure 18: Main components inside the nacelle of a wind turbine with gearbox (Source: Siemens Wind Power)

The main difference in the current design of wind turbines is the gearbox. Some of the newer concepts do not have a gearbox and use a direct-driven generator, since a lot of failures have been experienced with the gearbox. The enormous size of the nacelles of the 5MW turbines allows personnel to enter and to work inside without problems. Figure 19 illustrates the size of the nacelle of 5MW wind turbines compared to a person.

Figure 19: Size of the nacelle of a 5MW wind turbine compared to a person (Source: Multibrid M5000, GE 4.0 - Scanwind)

A large number of offshore wind turbines of the multi-megawatt class are currently available. Producers are mainly located in Germany and Denmark. Offshore wind turbines currently available are summarised in Table 2.

Table 2: Overview of available offshore wind turbines (Source: EWEA, 2009; Windenergie Report Deutschland, 2009; Wind turbine manufacturers)

	BARD 5.0	Multibrid M5000	Repower 5M/6M	Siemens SWT-3.6	Vestas V90/V112	Nordex N90	GE 3.6	GE 4.0	Darwind: DD115
Power output [MW]	5	5	5/6	3,6	3	2.5	3.6	4	5
Manufacturer	Bard Engineering	Areva	REpower	Siemens	Vestas	Nordex	General electrics	General electrics (former Scanwind)	XEMC - Darwind
Number of turbines operating (offshore)	1	6	14	79	96	1	7	13 (but onshore)	2 (test turbines)
Concept	Variable speed (Gearbox)	Variable speed (Gearbox)	Variable speed (Gearbox)	Variable speed (Gearbox)	Variable speed (Gearbox)	Variable speed (Gearbox)	Variable speed (Gearbox)	Direct-drive (no gearbox)	Direct-drive (no gearbox)
Rotor diameter [m]	122	116	126	107	90 / 112	80	111	110	115
									

2.2.1.3 New wind turbine concepts

Even though current offshore wind turbine concepts are quite similar, several new concepts are under development. New developments address mainly the number of blades, the orientation of the axis, and replacement of turbine components (for example the gearbox).

Current wind turbines use three blades. In theory, wind turbines with two blades or even one blade with a counterweight (see Figure 20 and Figure 21) should be more cost-effective. However, there is one main disadvantage of fewer blades, and that is the higher noise level due to the higher speed of the blade tip. Noise is mainly a constraint onshore and far less important offshore, thus it can be expected that future offshore wind turbine concepts may have only one or two blades.

Figure 20: Two bladed wind turbine (Source: www.nordicwindpower.com)

Figure 21: One bladed wind turbine with counterweight (Source: www.wind-energy-the-facts.org)

Current offshore wind turbines use a horizontal axis; however several concepts are under development to design a vertical axis turbine (see Figure 22). The British NOVA (Novel Offshore Vertical Axis) project looks into new concepts and has a goal to provide 1GW of power from offshore vertical axis turbines by the year 2020.

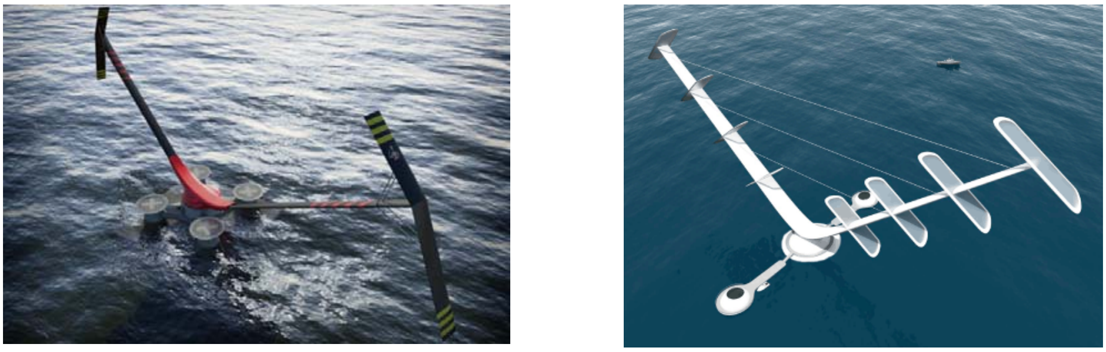

Figure 22: Vertical axis offshore wind turbine concepts from the NOVA project (Source: www.windpower.ltd.uk; www.nova-project.co.uk)

Other concepts under development aim to replace and reduce the number of components in the wind turbine. The Norwegian ChapDrive concept replaces the mechanical gearbox with a hydraulic pump which is connected to a hydraulic motor with a closed-loop hydraulic circuit (see Figure 23). In addition, a variable speed control system is implemented. The main advantage of the concept is that the majority of the components are moved from the nacelle down to the base of the wind turbine. This leads to easier installation because of the reduced top weight, and simplifies access. Furthermore there is no need for a mechanical gearbox and frequency converters.

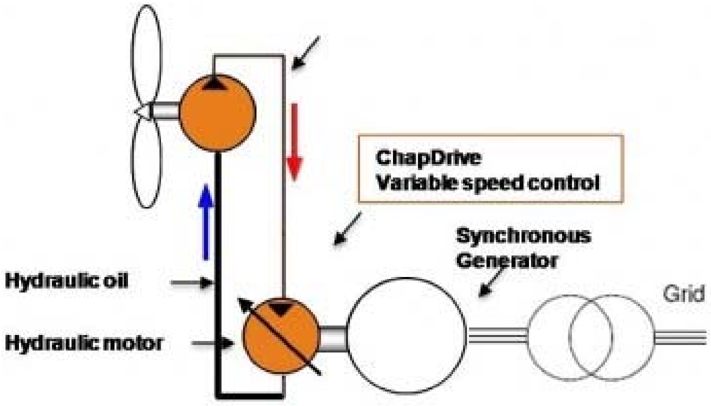

Figure 23: The ChapDrive concept

TU Delft has developed a similar concept to ChapDrive which is even more radical. In their concept the wind turbine drives a water displacement pump and pressurised water is channelled to a single offshore transformer platform, where pressurised water coming from several wind turbines is converted into electricity.

2.2.2 Electrical infrastructure

The electrical infrastructure of an offshore wind farm consists of the offshore substation, the inter array cable, and the export cable to shore. Two main concepts are available which depend on the distance from shore. The current standard is to use High Voltage Alternating Current (HVAC). At transmission distances longer than 50 km High Voltage Direct Current (HVDC) is cost competitive due to lower electrical losses. The main difference between the concepts is that a converter is needed at both ends of the cable for converting alternating current to direct current (offshore) and back to alternating current (onshore).

2.2.2.1 Offshore substation

Generally, if HVAC is used, the substation can be placed onshore or offshore, depending on the size of the wind farm and the distance to shore. An offshore substation increases the voltage of the generated electricity before it is transmitted to shore, to reduce electrical losses. It has to contain a converter if the transmission to shore uses HVDC. The substation is installed on a supporting sub-structure and contains facilities to allow access, which may be a helicopter platform if the structure is far offshore (see Figure 24).

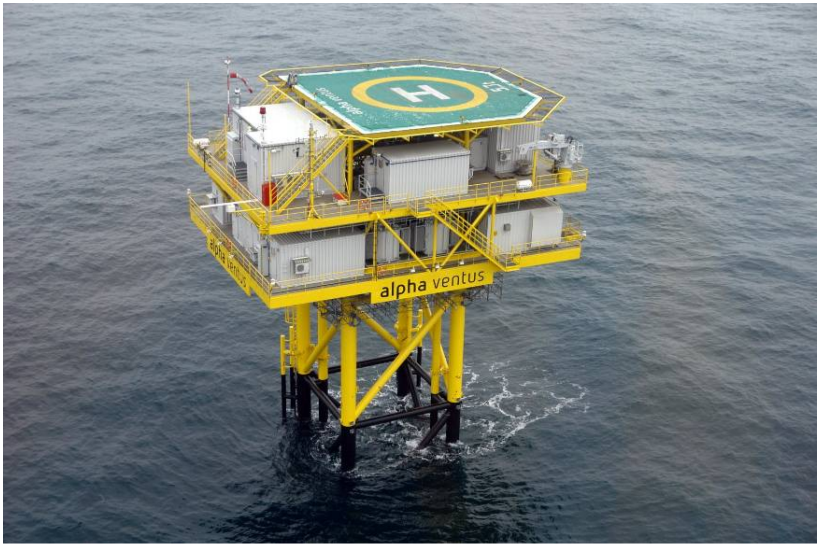

Figure 24: Offshore substation at the Alpha Ventus wind farm

Normally a substation can support a wind farm around the size of 500MW. But it is also possible to have several substations to improve supply reliability. As the transformers are oil-cooled (and also contain other coolants) they present a fire risk which has to be controlled with fire protection measures. Substations will in the future also be used as service platforms and house a workshop to support the maintenance of wind farms a long way offshore. Therefore, the safety of personnel working and/or accommodated at the substation has to be guaranteed, for example with escape routes for evacuation. In addition, an on-board crane is usually available at the substation to lift material from vessels onto the structure.

2.2.2.2 Subsea cables

The inter array cable connects the wind turbines to the offshore substation, where electricity is collected from all turbines and transformed/converted before it is sent to shore through the export cable. The export cable is a HVAC or a HVDC cable depending on the technology used. HVDC cables are lighter which makes installation easier and is a lower material cost. However, the HVDC converter stations are quite expensive, which makes HVDC more cost effective than HVAC only for distances to shore of about 50 km.

2.3 Offshore operations

The main focus of this report is on offshore operations. It should be noted that not all life-cycle activities are performed offshore, and that the following section will focus exclusively on offshore activities. The three main offshore operations are: site investigation surveys; installation and commissioning of foundations/substructures, wind turbines, the offshore substation and subsea cables; operation and maintenance. In addition, decommissioning or repowering is performed offshore at the end of the life of the wind farm. However no data is available for this phase due to the newness of the technology. The first offshore wind farms were installed in the 1990s and have still not reached their end of life. It can be expected that decommissioning is quite similar to the installation phase only in reverse order and that repowering also can be compared to the installation phase. For these reasons the phase of decommission and repowering is not described in this report. The main offshore operations and the equipment needed are illustrated in

Figure 25. Each of the three phases (site investigation, installation and commissioning, operation and maintenance) will be described in more detail later[4].

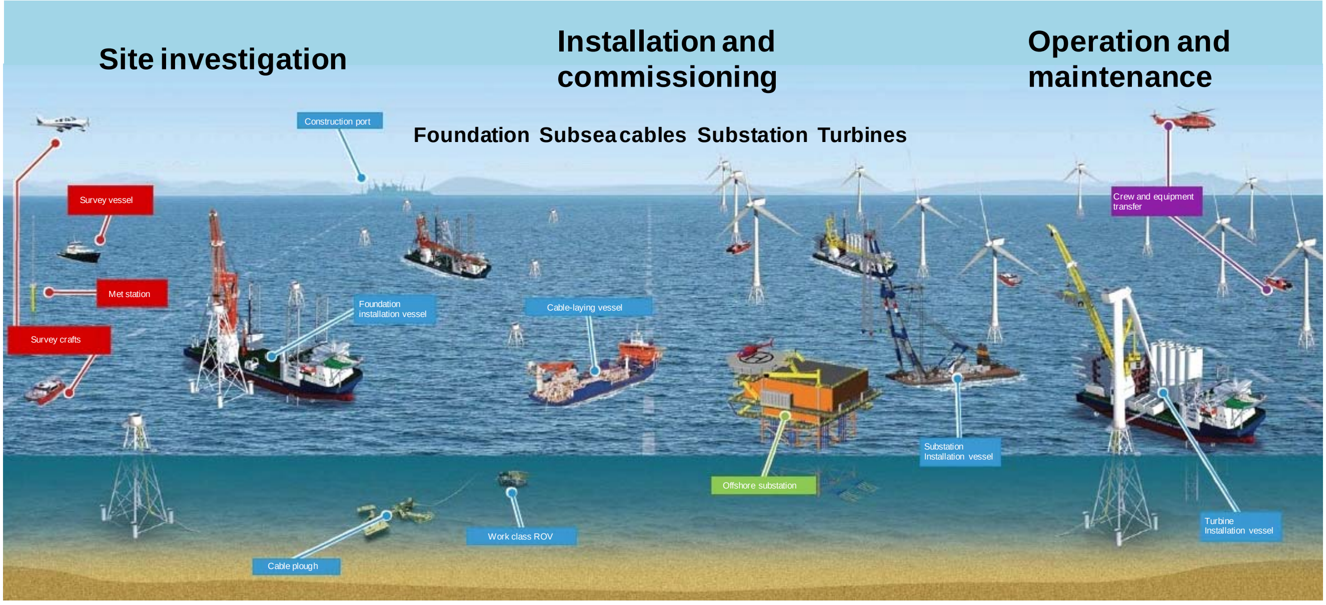

Figure 25: The main offshore operations and the equipment involved (Source: The Crown Estate, 2009)

2.3.1 Site investigation

Extensive site investigations have to be carried out at the proposed location. The information and data collected during site investigation is essential for design decisions and to estimate the potential environmental impact. Therefore, three main types of survey have to be carried out, covering all the external conditions (above and below the waterline, on and under the seafloor) at the site: environmental surveys, meteorological and oceanographic surveys using a meteorological (met) station, and seabed surveys.

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[4] The main sources for the description are The Crown Estate, 2009; EWEA, 2009 and Douglas Westwood, 2010

2.3.1.1 Environmental surveys

The objective of environmental surveys is to collect data on the distribution, diversity and number of different species and it can take over two years to collect adequate information. The data is used for environmental impact assessments. Environmental surveys are usually a requirement to apply for consent to construct the wind farm. The species surveyed are marine animals and birds.

Species that live on the seafloor and in the sediment are often surveyed using locally-based fishing boats. These surveys are often carried out at the same time as surveys for fish. A common method is to collect samples by dragging a net along the seafloor behind the fishing boat. Fish are collected by trawling. In addition, sea mammal surveys analyse whales, dolphins, porpoises and seals. A priority is to assess the acoustic impact of offshore activities (as is done in seismic studies on sea mammals). Sea mammals (unlike other marine species) are only observed from boats and aircraft and are not caught. The sea mammal survey is often carried out together with bird surveys to save money.

Bird surveys aim to assess the impact of the wind farm on sea birds, both resting and migrating. The main concerns are that the wind farm can act as a barrier to migration routes and increase bird mortality due to collisions with the turbine blades. It takes at least two years to gather reliable data on the population and flight patterns. The results of the bird survey can have a significant impact on the design of the wind farm. Methods used for surveying birds range from boat or aircraft-based visual surveys to radio tagging. Boats used for bird and mammal surveying are typically around 30 metres long.

The weather and sea conditions have to be considered in the planning of all surveys. The crew on the survey vessel normally work rotating shifts which alternate between observing, recording and resting. In addition to survey vessels and aircrafts, the met station can also be equipped with instruments for surveying bird and sea mammal activity.

2.3.1.2 Meteorological and oceanographic surveys using a met station

Met stations are used for monitoring of all aspects of meteorological and oceanographic conditions. The met station has to be constructed in advance at the planned site. Usually, they are placed within, or upwind of the farm area in order to gather reliable data on wind conditions. A common design is a mast with a height equal to the height of the planned turbines. The masts are typically designed using a steel lattice construction with climbing facilities such as ladders to reach the measuring instruments (see Figure 26). Met mast foundations are generally monopiles, or jackets for deeper water. The met station can contain a helicopter platform for easy crew access, but other access methods (similar to those found on the turbine itself) are also feasible (see section 2.3.4., Access methods). Instruments are located all around the met station to measure wind speed, wind direction, temperature, pressure, humidity, solar radiation and visibility. Metocean sensors collect data about waves, sea level and currents. In addition, bird radar and hydrophones can be installed to observe bird and sea mammal activity and to support environmental surveys. Oceanographic data can also be collected using instrumented buoys, which are less costly than a met mast. In this case, it is only possible to collect oceanographic data.

Figure 26: German met mast Fino 3 (Source: www.fino3.de)

The installation of a met station is done in two steps. First the monopile (or jacket) has to be installed, and then the met station can be lifted onto the substructure. The installation of the substructure is done in a manner similar to that used for the turbines, and is explained in more detail in section 2.3.2. The met station is preassembled onshore and placed on the substructure using crane vessels. This can either be done in one step, or the met mast can be constructed offshore from several components (see Figure 27).

Figure 27: Construction of the met station Fino 3. Transport and installation of the platform with helideck and lower mast section (left). Construction of the mast (right) (Source: www.fino3.de)

2.3.1.3 Seabed surveys

Seabed surveys analyse the characteristics of the seabed at the proposed location. The surveys comprise geophysical surveys to analyse seabed features, and geotechnical surveys that penetrate the seafloor to map the characteristics underground. Seabed surveys give valuable input for choosing the design of the foundation and the layout of the farm. In addition, this information is needed to plan the installation of the foundations, which may involve penetrating the seabed.

The geophysical survey establishes a map of the area with data on water depth, seabed features and special areas on the seafloor. Special areas can contain hazardous substances or munitions as well as areas of marine archaeological interest. Geophysical surveys are performed using specialised vessels using various methods such as echo soundings, sonar, magnometer readings and acoustic seismic profiling. According to the Crown Estate, vessels used for surveying are typically around 50 metres long and have to withstand unfavourable weather conditions. The operational period of the vessel is up to a month and multiple crews have to rotate to enable effective surveys.

The geotechnical investigation of the site is conducted after the geophysical survey and the scope of the survey is dependent on the foundation concepts being considered. In general, the target is to obtain data about the characteristics of the strata below the seafloor. The investigations are carried out by drilling a number of boreholes and by cone penetration tests. These operations are dependent on specialised survey vessels over 90 metres long. The vessels have to be this size to be able to carry large pieces of equipment (such as drilling rigs and cranes) on-board. In addition, vessels have to be stable at specific locations in order to drill boreholes and obtain samples. Jack-up barges are similar but smaller, and can be used for foundation and turbine installation (for a more detailed explanation see section 2.3.2). These vessels have sleeping quarters to allow an operational time of over a month at sea.

2.3.2 Installation

The installation phase is logistically challenging. Components have to be transported to the construction port and re-assembled on the quay. A lot of space is required at the port due to the size of the wind turbines when lying down on the ground. The foundations with the corresponding substructures are the first components that have to be constructed. The installation of the wind turbines, the substation and the laying of the subsea cables can be done partly in parallel. The subcontracting of the different tasks differs from project to project, but there are generally separate tenders for the installation of the foundation/substructure, the installation of the wind turbines, the installation of the offshore substation and the laying of the subsea cables.

A large number of vessels support the actual installation process. These can include crew and anchor handling vessels, barges, dive support and ROV (Remotely Operated underwater Vehicles) support vessels. Installation vessels vary in size, but recently built vessels designed for installation of offshore wind turbines range in length from 70-140 metres. Subsea ROVs are mainly used for visual inspections of the subsea structures and for monitoring installation operations. Many of the installation tasks are executed with jack-up barges. This kind of vessel is equipped with several legs that can be lowered down to the seabed (see Figure 28). After all the legs are lowered, the vessel is jacked up above sea level and is therefore independent of wave conditions. This allows the jack-up barge to remain in a completely stable position and to perform precise lifting operations. When jacked-up the vessel is not affected by waves. However, the process of lowering the legs down to the seabed is quite sensitive to waves and can only be performed in calm waters.

Figure 28: A jack-up barge used for installing offshore wind farms (Source: www.alternative-energy-news.info)

The different tasks are described later, and in more detail for each part of the installation (bottom fixed foundations/substructures, wind turbines, floating wind turbines, the offshore substation and the laying of the subsea cables).

2.3.2.1 Bottom fixed foundations and substructures

The process of installing the foundation and substructure is highly dependent on the foundation chosen. The installation of the three main bottom fixed concepts (gravity foundations, monopiles, and tripod/jacket) will be described in more detail. In general, bottom fixed substructures have to be transported to the offshore wind farm with transport vessels before they are fixed to the seabed. The installation of bottom fixed foundations has usually to be performed with jack-up barges, but installation using floating cranes is also possible depending on the weather characteristics of the location.

Gravity base structures can be significantly heavy (up to 3000 tons) and can be floated or transported on barges to their position. If floated they can be sunk directly when they arrive at their final position, otherwise a crane vessel has to move the foundations to the right position (see Figure 29).

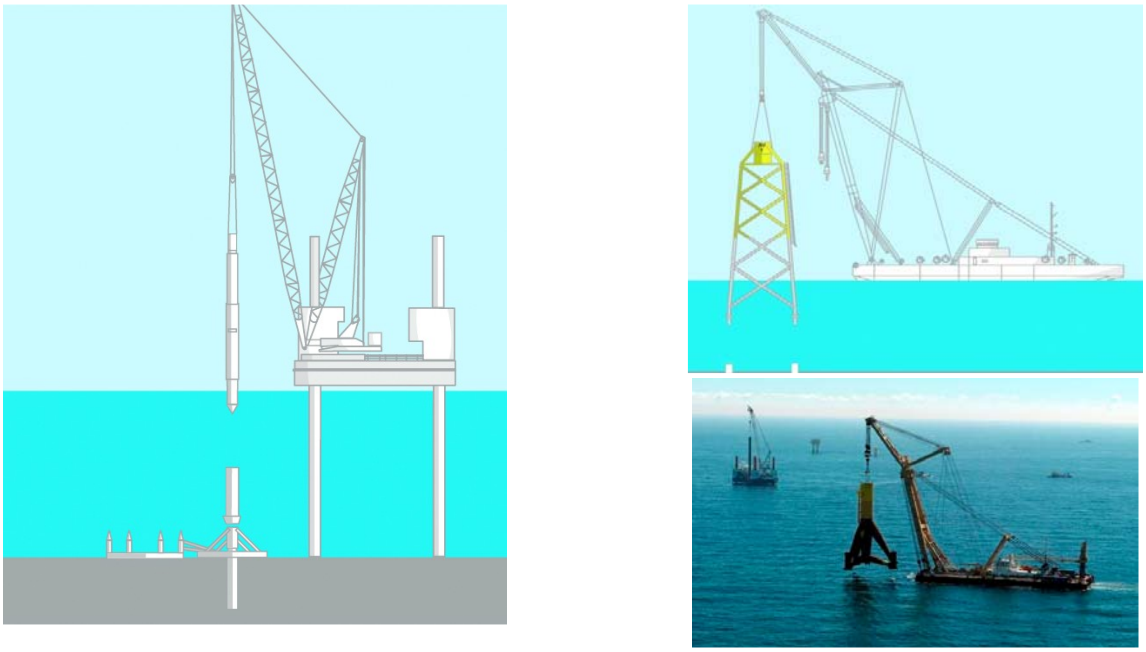
Photo: Jan Kofod Winther

Figure 29: Installation of the gravity base structure at the Nysted wind farm (Source: Danish Energy Authority)

Monopiles are typically installed from a jack-up vessel, but can also be installed by using a floating vessel. The monopiles are driven into the seabed by hammering. This is done using a hammer and anvil system and driving the pile slowly into the seabed with hammer movements (Figure 30). If hammering is not possible due to ground conditions or environmental restrictions, the monopiles can be fixed into position with drilling systems.

Figure 30: Hammer driving a monopile without anvil system (Source: www.nor-trade.dk)

Jacket and tripods have first to be fixed to the seabed with several pin piles. The installation of the piles is similar to the procedure for installing monopiles by hammering or drilling. When these piles are installed, the jacket or tripod substructure can be lowered onto them.



Hammering of the pin piles

Lowering of the jacket or tripod onto the pin piles

Figure 31: Installation of the jacket (Source: www.alpha-ventus.de)

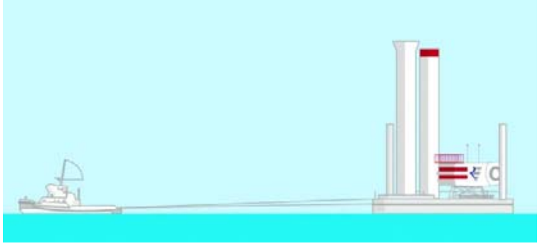
When the substructures are in place a transition piece is installed at the top of the substructure. This enables correction of any deviations from the vertical in the substructure. This ensures that the installation is perfectly vertical.

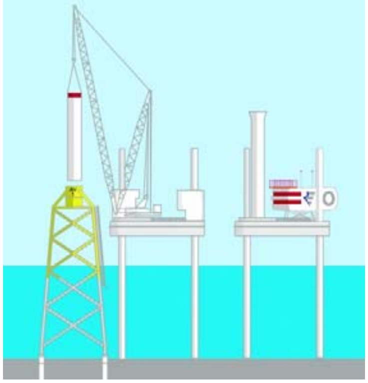
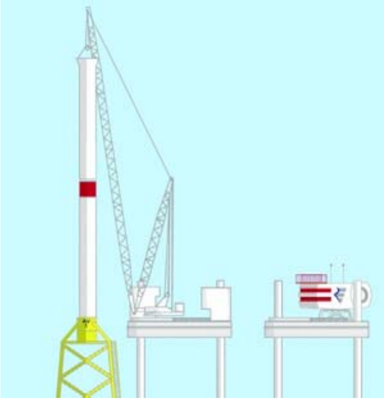
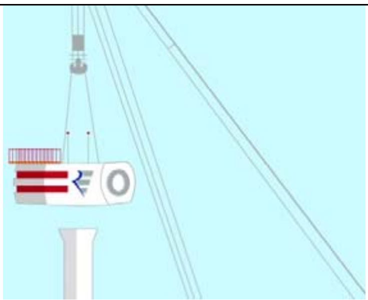
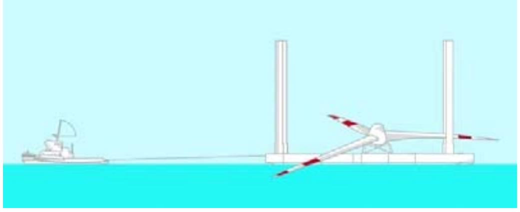
2.3.2.2 Wind turbines

Several concepts are available for the installation of wind turbines. The main differences between them concern how much preassembling is done onshore at the construction port and therefore how many installation steps are needed offshore. Variations range from assembling almost everything offshore - which involves installing several tower sections, the nacelle and the three blades one by one onto the nacelle - to transporting a fully constructed wind turbine to the offshore location and setting it up in one step onto the substructure (Figure 32). When not installed offshore the individual components have to be transported to the assembly location. The most common installation approaches lie between these two extremes.

Figure 32: Transport and installation of a wind turbine constructed onshore at Beatrice (Source: www.scaldis-smc.com)

The installation of the wind turbine offshore is performed with a crane vessel (usually a jack-up barge). Transport of the components can take place directly on the crane vessel or on additional transport vessels. In the following example a typical installation procedure is shown based on the installation of the Repower wind turbines at the Alpha Ventus offshore wind farm. In that installation an individual crane jack-up barge and an extra transport jack-up barge were used.

Transporting of the tower sections and nacelle on a towed transport jack-up barge.	

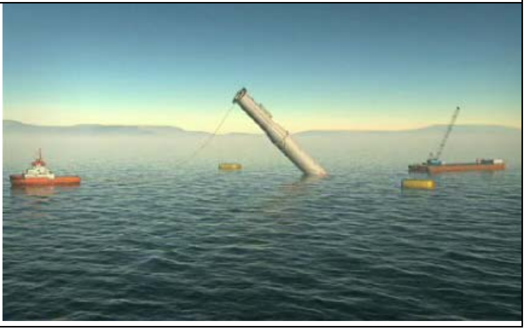
Installation of the first tower section with the crane jack-up barge.	 
Installation of the second tower section with the crane jack-up barge.	 
Installation of the nacelle.	 
Transporting the blades which are already completely joined to the rotor hub.	 

Installation of the rotor hub with joined blades.	

Figure 33: Installation concept of the Repower wind turbine at Alpha Ventus (Source: www.alpha-ventus.de; Windenergie Report Deutschland, 2009)

2.3.2.3 Floating wind turbines

Floating substructures are easier to install than bottom fixed foundations. In general, floating structures and the turbine are preassembled close to the construction port. They are then towed out to their final position as a complete unit. When they have arrived in position, they are fixed with a mooring system to the seabed. The installation of floating wind turbines is similar to that of bottom fixed wind turbines with the exception that they are assembled at, or close to the construction port. The following figures show the procedure for the installation and assembly of the first floating offshore wind turbine (Hywind).

Towing of the floating substructure to assembly position	
Up-ending of the substructure	

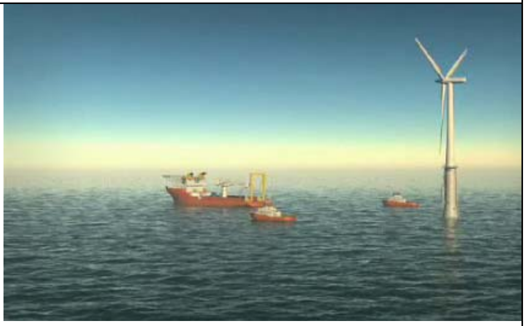
Filling the substructure with ballast	
Installation of the tower with nacelle	
Assembly of the rotor	
Towing to offshore position	
Installation of the mooring system	

Figure 34: Installation of Hywind (Source: www.statoil.com)

A new Norwegian concept for installing floating wind turbines is called WindFlip. WindFlip is a specialised vessel that transports offshore wind turbines. It can transport a completely assembled turbine lying in a nearly horizontal position on its deck. WindFlip has to be towed to the offshore location. When in position, its ballast tanks are filled with water, which causes it, and the attached turbine to flip 90 degrees into a vertical position. Finally, the anchor handling vessel used to tow WindFlip is connected to the wind turbine and tows it to its final position. The WindFlip concept should reduce installation time (and therefore installation costs) significantly. Currently the WindFlip concept is still under development and has not been fully tested.

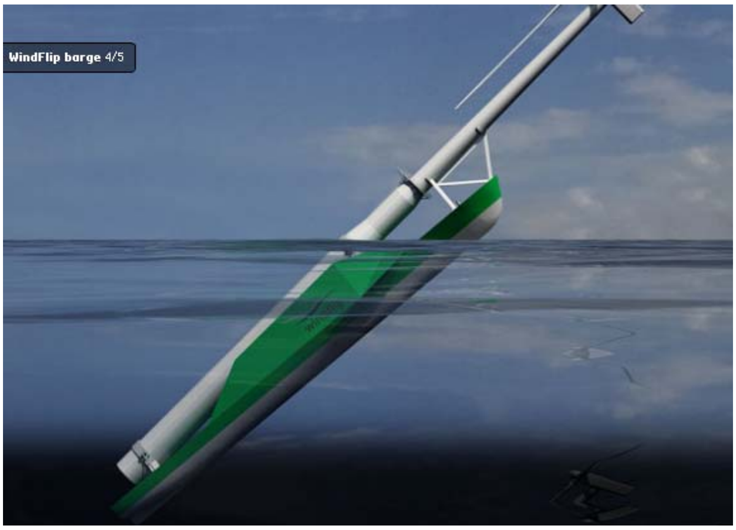


Figure 35: WindFlip in 45 degrees position (Source: www.windflip.com)

2.3.2.4 The offshore substation

The offshore substation is completely preassembled onshore. The assembly is similar to that of the wind turbine substructures, the only difference is that the substation substructure is significant larger. A barge transports the substation to the offshore location. A heavy floating crane (1000 tons or more) then lifts it directly onto the substructure (Figure 36).

Figure 36: Installation of an offshore substation (Source: Deutsche WindGuard et al.)

2.3.2.5 Subsea cables

The installation of the subsea cables has to be separated into 1) the installation of the export cable from the substation to shore, and 2) the installation of the inter array cable from the wind turbines to the substation. Export cables are laid in sections up to 70 km long to avoid subsea connections. The cables are buried in the seabed at a depth of 1.5-3 metres to avoid damage from fishing vessels or ship anchors. Two general methods are available for cable laying. In the first, the cable is laid and buried simultaneously using a cable plough. This method is applicable for a variety of seabed conditions. The second method uses a two-step approach. First, the cable is laid on the seafloor and then it is buried with a trenching ROV. The trenching ROV fluidises the seabed and allows the cable to sink down. The export cable is lowered down from a cable-laying vessel that is equipped with a carousel and a tensioning device. The carousel stores the export cable, while the tensioning device holds the cable under tension (Figure 37).

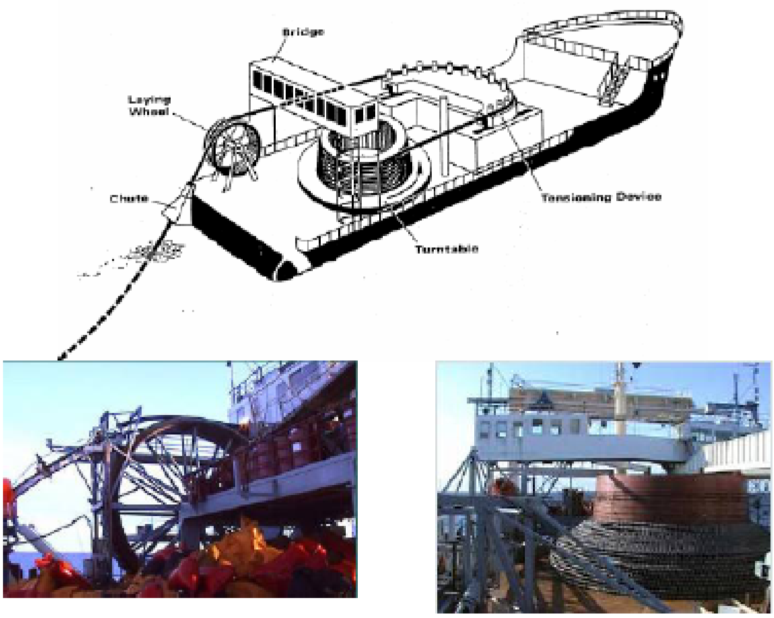


Figure 37: Cable laying vessel (Source: Deutsche WindGuard et al.)

Several designs for the layout of the inter array cabling between the wind turbines and the substation are available. Chain, or spider topologies are common, but other layouts are also possible. In principle, the method for laying the inter array cables is the same as for the export cable. However, it is often not possible to use a cable plough close to the turbines. Therefore, a trenching ROV is used for burying the cable close to the structures. The inter array cable laying vessel does the same job as the export cable vessel, but is smaller because the inter array cable is shorter. The cables are fed into the turbine through a J-tube and subsea ROVs can be used to observe and control this process.

2.3.3 Commissioning

After installation of all the components, the wind farm has to be thoroughly tested. This includes visits to, and inspections of the various offshore structures as well as different tests. The main steps for commissioning the offshore substation and cabling are (The Crown Estate, 2009):

- Visual inspections
- Mechanical testing
- Protection testing
- Electrical insulation testing

- Pre-energisation checks
- Trip tests and load checks

The main steps for commissioning the wind turbines are (The Crown Estate, 2009):

- Check of installation activity and documentation
- Energisation of all subsystems
- Testing of each link in safety and emergency system chains
- Exercising of all safety-critical and auxiliary systems
- Slow rotation of the rotor to confirm balance and smooth operation of the drive train
- Overspeed sensor and other safety-critical checks
- First generation and checks on normal operation of all systems.
- Checks on critical components and connections after a period of attended operation, then after a longer period of unattended operation.

2.3.4 Operation and maintenance

The operation of the wind farm is mainly performed remotely from an onshore operations centre. However, maintenance tasks have to be carried out continuously, which means that personnel have to access offshore structures, and that equipment has to be transported offshore. Depending on the task, heavy logistics can be required. The following sections describe different access and transport methods. In addition, typical maintenance operations will be explained in more detail.

2.3.4.1 Access methods for personnel

One of the main challenges in the operational phase of an offshore wind farm is access to the turbines. Due to the wind and especially the wave conditions, access or egress can become impossible. Therefore, it is very important to have an access solution that allows personnel a safe transfer most of the time. Several alternatives for accessing bottom fixed and floating offshore wind turbines as well as the substation are available. Floating wind turbines are expected to move slightly, but not to the extent that access to them is hampered. The different access methods can be divided into four main categories[5]:

- Direct boat landing
- Boat landing with motion compensation
- Crane hoist
- Helicopter

All these methods have their advantages and disadvantages. The main characteristics of the different methods are summarised in Table 3. A more detailed description of the different variants in the four main access categories follows in the section below.

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[5] Information on access methods is mainly based on Eggen et al. 2008 and Offshore Center Denmark, 2004

Table 3: Characteristics of the different access methods

Type	Significant wave height in metres	Average wind speed in m/s (1hr at 10 m height)	Example of application	Advantages	Disadvantages
Direct boat landing	0.5 - 1.5 (rubber boats) 2.5 (SWATH)	10	Nysted (rubber boats) Bard 1 (SWATH)	Simple	Sensitive to marine growth and icing
Boat landing with motion compensation	2 - 2.5 (OAS) 2 - 3 (Ampelmann)	11.5 (OAS) 14 (Ampelmann)	Tested	Not sensitive to marine growth	Installation of additional equipment on the vessel required
Crane hoist	2.5	?	None	Not sensitive to marine growth	Remote control of crane Maintenance offshore required
Helicopter	-	15 - 20	Horns Rev, Alpha Ventus	Not sensitive to waves Fast transport	Expensive

Direct boat landing

One of the most frequently used access methods is a direct boat landing. The transfer vessel normally approaches the structure on the lee side to avoid unnecessary wind and wave disturbance during transfer. This advantage is not available on traditional pillar mounted wind turbines as access is usually only possible from a defined part of the structure and monopiles are too small in diameter to give significant protection against wind and waves. Boat landings come in all forms, but usually they are pipe-structures welded directly onto the platform (Figure 38). The transfer vessel maintains contact with the boat landing by using engine power to press constantly against the structure (Figure 39). If contact with the structure is established personnel can access the wind turbine directly from the deck of the transfer vessel via a ladder or gangway which is installed on the wind turbine. The maximum wave height for this kind of transfer is quite low as the boat starts moving with the waves. The critical wave height depends on the size of the boat. Another problem with this access method is marine growth and possible icing on the ladder that leads to slippery conditions. Any marine growth or icing has to be removed, otherwise, safe access cannot be guaranteed.

Figure 38: Boat landing with direct access (Source: Offshore Centre Denmark, 2004)

Figure 39: Direct boat landing (Source: www.southboatssp.co.uk)

Boat landing can be performed with normal vessels, but usually special designed vessels are used which are less sensitive to waves due to the shape of their hull. The most common design concepts are the catamaran and the SWATH (Small Waterplane Area Twin Hull). These vessels have a twin hull and are therefore more stable in waves. One example is the S-Cat service vessel built by the Måløy shipyard (Figure 40) which can fill its hull with water to increase stability when alongside the wind turbines. It can carry up to 24 passengers and has a loading capacity of 10 tonnes. This vessel is currently being tested as an access possibility for the Hywind offshore floating wind turbine. Other hull concepts are also under development to improve the resistance of boats to waves.

Figure 40: S-Cat from Måløy shipyard (Source: www.maloy-verft.no)

In addition to these main methods for direct boat landing access, other variants are available. Fenders are one alternative (Figure 41). Additionally, the ladder which enables access to the wind turbine, and usually is installed on the wind turbine structure, can be replaced by a stair access directly mounted on the vessel (Figure 42). This shortens the transfer time since personnel do not have to climb up the ladder at the main structure.

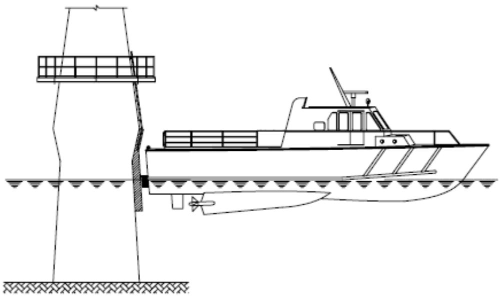

Figure 41: Direct landing with fender (Source: Offshore Centre Denmark, 2004)

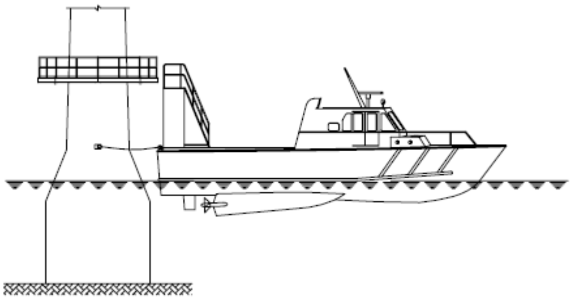

Figure 42: Ladder mounted on transport vessel (Source: Offshore Centre Denmark, 2004)

Other possibilities for accessing the working platform without the use of a ladder are hydraulically managed methods. The gangways are expandable and are either supported directly by the working platform (Figure 43) or the main structure (Figure 44). Hydraulically managed access methods can include a motion compensation system. These systems are described in more detail in the next section.

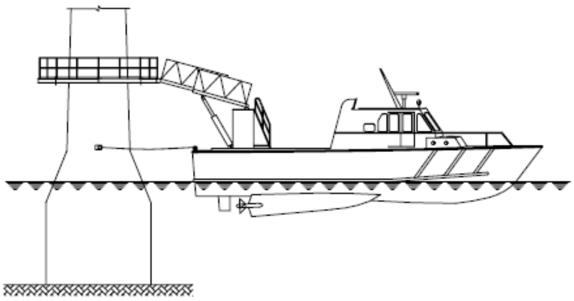

Figure 43: Hydraulically managed access supported directly on work platform (Source: Offshore Centre Denmark, 2004)

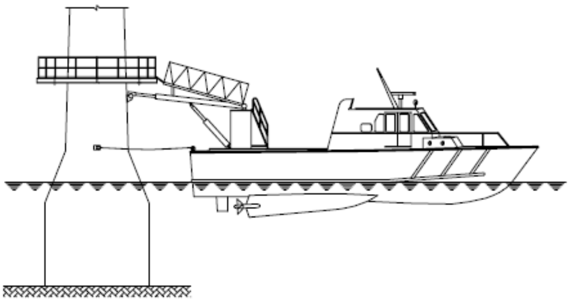

Figure 44: Hydraulically managed access supported on main structure (Source: Offshore Centre Denmark, 2004)

Boat landing with motion compensation

In addition to specially designed boats, several concepts have been developed to compensate actively for the movement of the waves. The compensating equipment is usually mounted on the vessel. Various concepts are presented here as examples. The Seabridge, the Viking Selstair, the Offshore Access System (OAS) and the Ampelmann are described in detail.

The Seabridge concept is based on the idea that service vessels can be moored with ropes to the wind turbine as if it was being towed. The system consists of a telescopic ladder which is freely supported by the supply vessel, and which is pushed to a docking station mounted on the wind turbine (Figure 45). During the pushing operation, the ladder is guided by ropes that connect the vessel to the wind turbine and which are held under tension due to the towing mode of the vessel. This access concept should allow personnel to enter the turbine in wave heights of up to 3 metres.

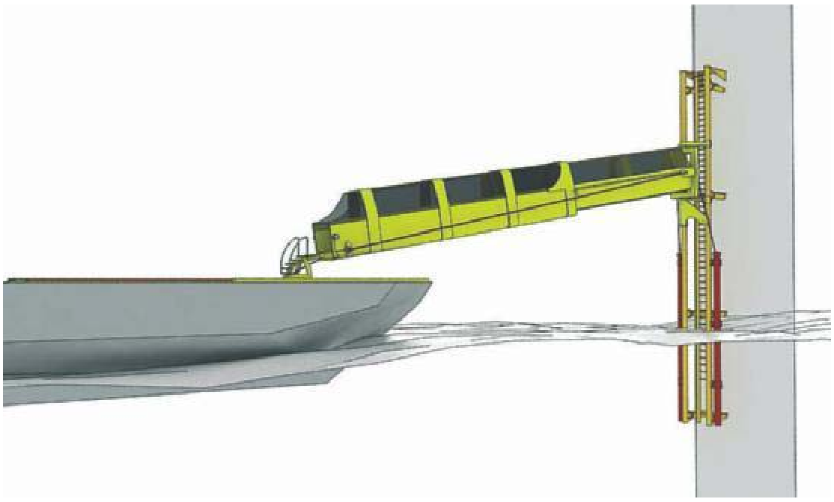

Figure 45: The Seabridge concept (Source: Fjordenes Tidende, 2009)

Viking Selstair is based on an emergency rescue system using a tube. The tube is equipped with an internal collapsible winding stairway that is used for transferring personnel. The system needs a fixed platform on the wind turbine to work. The tube with the collapsible stairway can either be lowered via remote control from the fixed platform, or constructed on the deck of the support vessel.

Figure **46** shows the latter variant. The support vessel must have good handling characteristics in order to position the tube at the correct location on the platform to ensure a safe connection between the vessel and the wind turbine. The system can be used in wave heights of up to 3 metres.

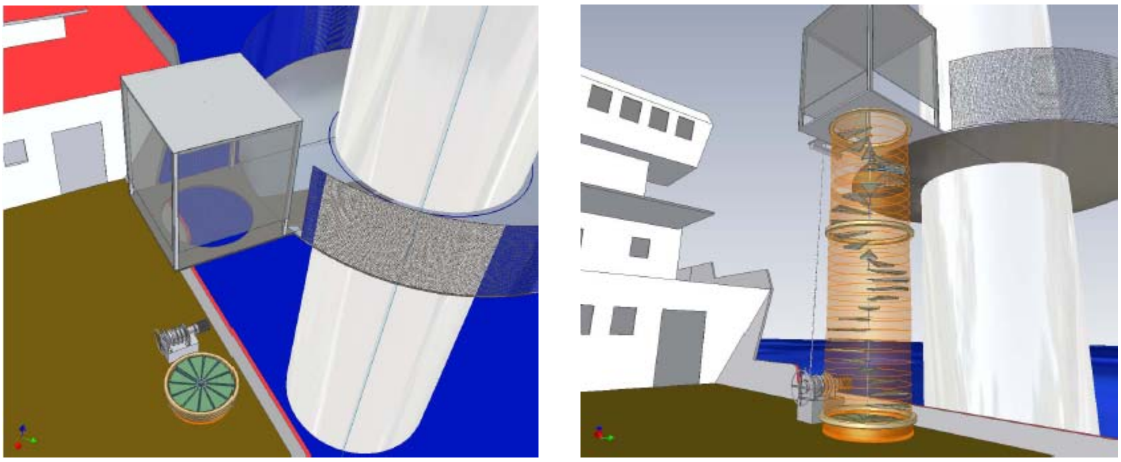

Figure 46: The Viking Selstair access concept (Source: Viking)

The Offshore Access System (OAS) from Fabricom uses a telescopic gangway that is installed on the boat. When the gangway is extended towards the wind turbine, a heave-compensation system maintains the end of the gangway at a constant height. This system incorporates a motion reference unit in its active hydraulic system, which maintains the gangway tip at a constant height relative to the horizon. This allows the gangway to be safely connected with the turbine structure in wave heights of up to 2.5 metres. A latching mechanism is engaged on contact with the wind turbine. Once secured, the heave-compensation system is disengaged. This allows the gangway to move freely between the vessel and the structure. At this point, the gangway is robustly connected to the fixed structure and compensates automatically for vessel motion. This guarantees a safe transfer of personnel to the wind turbine.

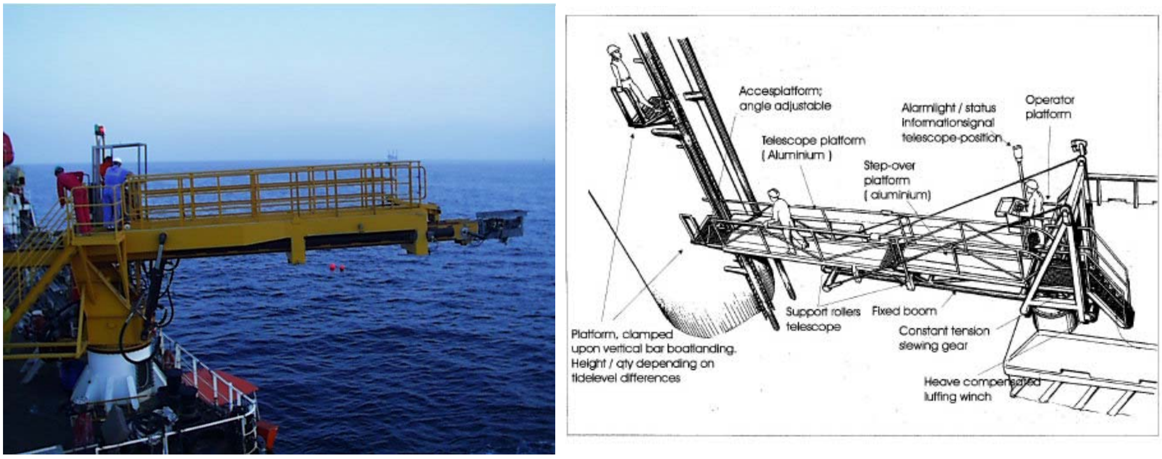

Figure 47: The Offshore Access System (OAS) from Fabricom (Source: Fabricom)

Ampelmann is a vessel-based self-stabilising platform that actively compensates for all motion due to waves and wind. The base of the Ampelmann system is mounted on the deck of the vessel and handles motion compensation with hydraulics. The topside of the Ampelmann is therefore stationary relative to the horizon. The gangway, which is mounted on the topside, can be deployed onto the offshore structure. The connection between the tip of the access gangway and the offshore structure is maintained through constant pressure, because the gangway is pushed against the structure. This prevents a gap appearing between the gangway and the offshore structure and enables crew transfer. When the Ampelmann is installed on a 50-metre multi-purpose vessel, a wave height of up to 2.5 metres can be safely managed.

Figure 48: The Ampelmann access system (Source: www.ampelmann.nl)

Hoisting by crane

The Danish company Grumsen has suggested installing a crane on the wind turbine that lifts the boat out of the water and enables the crew to climb onto the wind turbine. The boat is hooked onto the crane wire before approaching the structure. A crane operator sits on the boat and controls the crane remotely. When connected, the crane operator activates the heave compensation system that ensures that the wire is taut at all times. This enables the operator to hoist the boat out of the water safely. When the boat is in its final position at the wind turbine, personnel can access the turbine directly.

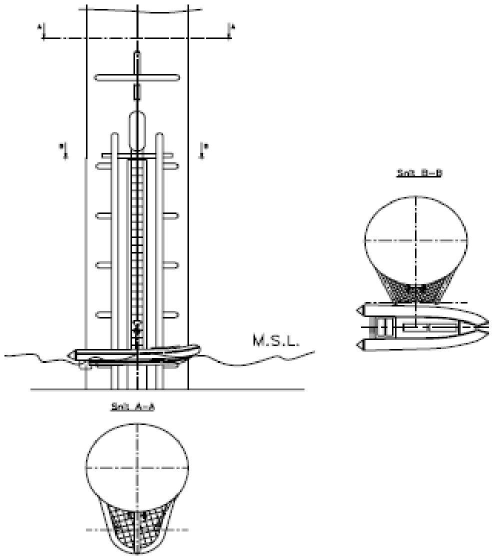

Figure 49: Illustration of the hoisting system proposed by Grumsen (Source: Grumsen)

Helicopter

Helicopters can be used for airborne transfer of personnel to offshore wind turbines. This requires the addition of a fixed landing platform to either temporarily set down the helicopter or to lower personnel and equipment by winch. The latter option is most widely used today, as landing platforms for helicopters tend to be large and heavy structures and platforms usually have to be installed on top of the nacelle. Use of helicopters for transfer of personnel and equipment in the North Sea, Norwegian Sea and other harsh environments is discussed in section 4.6.

Figure 50: Landing on the nacelle by winching down from a helicopter (Source: Repower)

2.3.4.2 Transfer of equipment

In general, three methods are available to transfer equipment to the wind turbine:

- Carried by crew
- Crane
- Helicopter

Carried by crew

Equipment can be carried directly by the crew on the wind turbine, if it is not too heavy or bulky. Transfer takes place using the same access methods for crews.

Crane

Cranes are an alternative to transfer more heavy and bulky equipment from the vessel to the wind turbine. This saves time, if a large amount of equipment has to be transferred. The crane can be installed directly on the wind turbine (

Figure 51) or on the vessel (

Figure 52). If the crane is installed on the wind turbine, it can be mounted on the working platform or in the nacelle. A crane in the nacelle has the advantage that equipment can be lifted directly into the nacelle. While a crane on the working platform can do more precise lifting operations, equipment still has to be transported (using the lift in the tower) up to the nacelle. It is also possible to use mobile cranes on the turbine, which are installed temporarily. Cranes on vessels are available in different sizes depending on the weight of the components to be lifted and whether the load needs to be lifted up to the working platform or the nacelle. The vessels used can be normal floating vessels or jack-up barges depending on the lifting operation.

Figure 51: Crane on wind turbine, on working platform or in the nacelle (Source: www.vessel-sales.com)

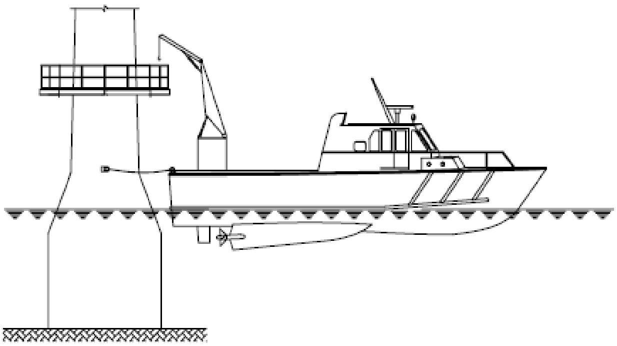

Figure 52: Crane on supply vessel (Source: Offshore Centre Denmark, 2004)

Helicopter

Helicopters can, in addition to transporting crew, also transport equipment. The usual approach is to winch down the equipment onto an installed platform on the top of the nacelle. However, the weight of the equipment which can be transported using current helicopters is quite limited. However, in theory, larger helicopters with more space and higher carrying capacity could be used in the future.

2.3.4.3 Maintenance and service operations

In the ‘Strategic Research Agenda’ (TPWind, 2008) it is stated that operation and maintenance (O&M) strategies, which maximise the energy yield from turbines while minimising O&M costs, are essential for the commercialisation of offshore wind power. These strategies must take advantage of risk-based maintenance philosophies and condition monitoring in order to improve operational efficiency and reduce costs.

A typical offshore wind farm requires approximately four to six visits per wind turbine per year. Of these, there are one or two planned visits for regular service/maintenance and two to four unplanned visits for corrective repairs to components. It is also common practice to perform major overhauls at 5-yearly intervals. During overhauls all major components are inspected together with the underwater parts of the wind turbine. The above figures are averages; there is a wide variety in the number of visits for different wind farms. The maintenance regime applied offshore is in many instances adopted from land-based applications, and the long-term component effects of a saline atmosphere may not be covered by these established maintenance regimes. For floating structures the movement element needs to be taken into account, as it may contribute to different failure patterns.

Maintenance and service operations involve the transport of crew and equipment to the location. Due to weather window restrictions and the travelling distance from shore, it can be worthwhile for remote wind farms to reduce travelling times by installing an accommodation platform as part of the wind farm. Until now, this concept is only applied at Horns Rev 2, where an accommodation platform was installed alongside the offshore substation (Figure 53).

Figure 53: Offshore substation with accommodation platform alongside (Source: www.dong-energy.com)

Scheduled maintenance tasks include typically inspection of the turbines and servicing. For these tasks, no large equipment is needed. Scheduled maintenance is typically carried in the summer months when access is easier due to better weather conditions and revenue losses from stopping the turbine are lower due to lower average wind speed. A turbine is always stopped by remote control before personnel are allowed to enter it. Unscheduled maintenance is necessary when unexpected faults occur in turbines. In general, maintenance actions can be divided into four categories depending on the operation and the equipment required. The following table gives an overview of the different maintenance actions and their average occurrence.

Table 4: Maintenance actions at an offshore wind farm and their occurrence (Source: Salzmann 2009)

Maintenance action	Required equipment	Occurrence
Replacement of small part (man carried) or inspection/repair	Vessel or Helicopter	69%
Replacement of small part (<1 ton)	Vessel, Permanent internal crane	23%
Replacement of large part	Vessel, Build up internal crane or Crane vessel	7%
Replacement of heavy component	Vessel, Jack-up with crane	1%

Replacements of small parts or normal inspections are responsible for the majority of maintenance operations. These tasks can also involve small repairs without exchanging components. Typically, only the personnel and some tools (which can be carried by the personnel) have to be transported to the turbine. It can also be necessary to work outside the turbine, for example for inspection or cleaning of the blades. Other typical tasks are visual inspections, refilling of lubricants, replacement of consumables and cleaning. Replacement of small parts (for example the pitch motor) involves transport of the part with a vessel and an outside hoisting operation using the internal crane on the wind turbine. This maintenance operation is even more weather dependent due to the outside hoisting operation. If larger parts have to be replaced a minimum of a build-up internal crane has to be used. Another alternative is a crane vessel. Replacement of heavy components (such as gearboxes or blades) is a more demanding operation and usually involves transport vessels and jack-up barges. These operations are quite time consuming and can be compared to the operations undertaken when installing a wind turbine.

Condition monitoring (CM) techniques are being developed for wind farms. Areas where CM can detect failure progression are:

- Rotor - Blade surface roughness, rotor mass imbalance (icing, losing material), aerodynamic asymmetries
- Drive train - Shaft, bearing and gear failures
- Generator - Winding, squirrel cage, slip ring and brushes failures
- Transformer - Wiring and contacting faults
- Contacting and switching gear - Reduced conductivity, corrosion and burning mark failures

While use of condition monitoring techniques may contribute to a better understanding of the failure progression of the components in wind farms, the implementation of CM regimes should reduce the amount of visits needed to the wind turbines.

2.4 Actors and participants

A large number of Norwegian actors are active in offshore wind power, even though no offshore wind farm has yet been constructed in Norway. The Hywind pilot is the only offshore wind turbine constructed so far. However, concessions have been awarded for several projects and there are even more farms in the concept stage. Several actors are involved in foreign offshore wind farm projects, for example in the UK and Germany. Actors and subcontractors in offshore wind power can be categorised using the different phases of the life-cycle of an offshore wind farm. Figure 54 shows the various actors and subcontractors involved in the different phases of the project.

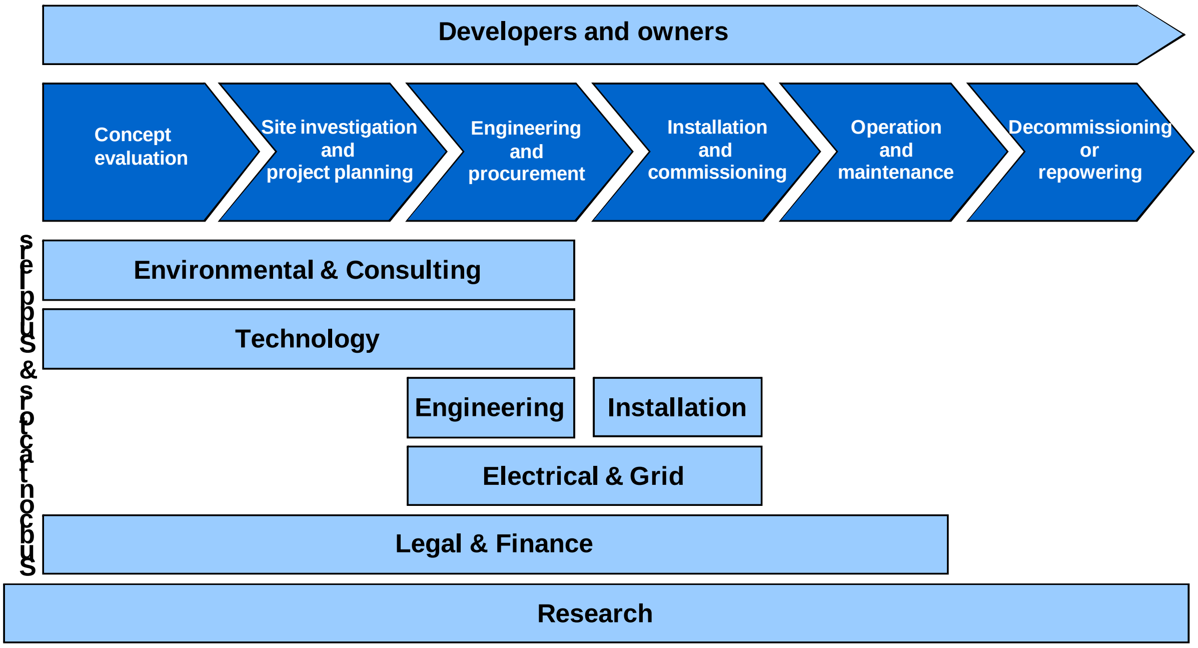

Figure 54: The supply chain of an offshore wind farm project (Based on Volden et al., 2009)

Developers and owners plan and operate the farm. They are involved throughout the life-cycle. In Norway, developers are mainly electricity companies such as Statkraft and BKK. Statoil is another active developer. Various subcontractors and suppliers are needed in an offshore wind farm project and typically, the tender process is divided into: manufacturing of substructures, manufacturing of wind turbines, construction of the offshore substation, and the production and laying of the subsea cables. The installation of the substructures, wind turbines and offshore substation can be part of the manufacturing tender, but is also often contracted in additional tenders. Environmental and consulting companies include companies that offer services for environmental surveys, those that support concept evaluation and project planning, and engineering consultants. In the early phases technology companies contribute their knowledge on different technological concepts. They cover the whole range, from the substructure, to components for the wind turbine, to complete wind turbines. Engineering companies are needed for engineering the main parts of the wind farm and have to assure that the farm is designed to last for the planned lifetime. Electrical and grid contractors include companies who produce subsea cables and offshore substations. The laying of the subsea cables is usually also done by these companies. Substructures, wind turbines and offshore substation have to be installed offshore by specialised installation companies (the installation category). The whole project is supported by legal and finance companies who assure that the project is properly financed. They support the developer in contract preparation and negotiation with other subcontractors. All these types of companies exist in Norway and the following tables give an overview of them.

Table 5: Norwegian companies in the offshore wind energy supply chain (Source: INTPOW)

Developers & Owners	Environmental & Consulting	Technology	Engineering
Agder Energi AS	Ask Rådgivning AS	Aker Solutions AS	Acergy ASA
BKK AS	Det Norske Veritas AS	AngleWind AS	Aibel AS
Fred. Olsen Renewables AS	EC Group AS	Baze Technology AS	Aker Solutions ASA
HavGul AS	ECON Pöyry AS	Chapdrive AS	Bergen Group Rosenberg AS
Havvind AS	Ernst & Young	Devold AMT AS	CTC Marine
Lyse Kraft AS	Falck Nutec AS	Flochem AS	Dr.Techn Olav Olsen AS
Statkraft AS	Fugro Oceanor AS	Highcomp AS	Fabricom AS
Statoil ASA	Inwind AS	HyWind AS	Force Technology AS
Vestavind Kraft AS	Kjeller Wind Technology AS	Innowind DA	Inwind AS
	Marintek	Jotun AS	Linjebygg Offshore AS
	Meteorologisk Institutt	Kongsberg Maritime AS	Marine Offshore AS
	Reef Systems AS/Seacult	Norsafe AS	Maritime Projects AS
	Safetec Nordic AS	Owec Tower AS	MIKA AS
	Scandpower ASA	Powel ASA	Multiconsult AS
	Sedicon AS	Rolls-Royce Marine Foundry AS	NLI AS
	StormGeo AS	Ruuki Profiler AS	Norconsult AS
	Windsim AS	Scana Industrier ASA	Sweco Norway AS
		Scanwind AS (GE)	Technip Norge AS
		Seaproof Solutions AS	Tristein AS
		Seatower AS	Aak Group AS
		NLI Innovation AS	MTI Engineering AS
		Smartmotor AS	
		SWAY AS	
		Trelleborg Offshore Norway AS	
		Troll Windpower AS	
		Umoe Rywing AS	
		Vestas Casting Kristiansand	
		Vici Ventus Technology AS	

Table 6: Norwegian companies in the offshore wind energy supply chain (Source: INTPOW)

Electrical & Grid	Installation	Legal & Finance	Research
ABB AS	Norwind AS	Bull & Co.	Sintef
AREVA T&D AS	Buksér og Berging AS	DnB Nor ASA	CMR
Cecon AS	Fred Olsen Windcarrier AS	Eiger Corporate AS	IFE
Draka Norsk Kabel AS	GDV Maritime AS	Eksportfinans ASA	Iris
Eltek Valere AS	Grieg Logistics AS	Energy Capital Management	NCE Halden
Møre Trafo AS	Inwind AS	Energy Ventures	NTNU
Nexans Norway AS	Master Marine ASA	GIEK	UiS
Statnett AS	Oceanteam ASA	Nordea ASA	
Teksal Hineco AS	Odfjell Drilling Technology AS	SEB Bank	
Øglænd System AS	Parker Scanrope AS	Wiersholm, Melby & Beck	
	Technip Norge AS	Wikborg Rein AS	
	Ulstein Group		
	Vestkran AS		

2.5 Norwegian offshore wind farm locations

There are several possible locations for Norwegian offshore wind farms. Information about probable locations is available from two sources. The developers of Norwegian farms that still are in the concept stage have planned locations. In addition, the Norwegian Water Resources and Energy Directorate (NVE) published the *Havvind* report with proposals for areas that could be used (NVE 2010). Locations for the planned offshore farms and the proposed development areas largely overlap. The following table (Table 7) gives an overview of planned Norwegian offshore wind farms and whether they are intended to be bottom fixed or floating structures. It is also worthwhile noting that farms are planned along the whole coast of Norway (see also Figure 55).

Table 7: Planned Norwegian offshore wind farms (Source: www.vindkraft.no)

Project	Location	MW	GWh	Depth	Foundation	Status
Hywind	Rogaland	2,3	7,9	210 m	Floating	In operation
Havsul I	Møre and Romsdal	350	1000	4 - 30 m	Bottom fixed	Concession received
Sway	Rogaland	10	15	120 - 400 m	Floating	Concession received
Siragrunnen	Vest-Agder	200	700	10 - 40 m	Bottom fixed	Concession requested
Ægir	Continental shelf	1000	4500	50 - 63 m	Bottom fixed	Reported
Utsira	Continental shelf	300	1200	270 m	Floating	Reported
Sørlige Nordsjøen	Continental shelf	1000	4500	45 - 60 m	Bottom fixed	Reported
Utsira pilot	Rogaland	25	100	150 m	Floating	Reported
Selvær	Nordland	450	1600	5 - 30 m	Bottom fixed	Reported
Stadtvind	Continental shelf	1080	4500	160 210 m	Floating	Reported
Mørevind	Møre and Romsdal	1200	5400	30 - 60 m	Bottom fixed	Reported
Gimsøy	Nordland	250	800	0 - 15 m	Bottom fixed	Reported
Lofoten havkraft	Nordland	750	2400	25 - 30 m	Bottom fixed	Reported
Idunn	Continental shelf	1100	4800	60 - 70 m	Bottom fixed	Reported
Vannøya	Trøms	775	2500	up to 60 m	Bottom fixed	Reported
Fosen	Sør-Trøndelag	600	1500	2 - 20 m	Bottom fixed	Reported

The *Havvind* report proposed several areas that could be used for offshore wind farms in Norway (Figure 55). The distances from shore of the proposed areas vary from 1-60 km for areas all along the Norwegian coast. The Southern North Sea area is around 150 km offshore. This has implications for the use of an accommodation platform at the site. It is likely that (at least) for wind farms that are a long way offshore, permanent accommodation platforms will be used for maintenance and to reduce travel times.

Figure 55: Possible areas for Norwegian offshore wind farms, bottom fixed (blue) and floating (red) (Source: NVE, 2010)

2.6 Surrounding conditions for offshore wind farms in Norway

As stated in section 2.5, future offshore wind farms in Norway will be located in deeper water and further from shore than most existing farms. Only some of the areas currently identified are as close to the coast and at water depths that resemble current international installations. Wind turbines operate in wind speeds of between 4-25 metres/second. Production will stop at 25 m/s and not start again until the wind drops to 20 m/s. The areas outside Stadt are most exposed to storms above 25 m/s, though average wind speed ranges from about 8-12 m/s in the areas identified for development. The water depth in the identified areas ranges from 5-350/400 metres. 70 metres is considered the maximum allowable depth for fixed installations. The average wave height ranges from 0.6 metres (for fixed installations) to 2.75-3.0 metres. For most of the areas identified, the average wave height is above 2 metres. The highest waves are found in the Norwegian Sea (NVE, 2010).

2.7 Access windows for possible offshore wind farms in Norway

Table 8 shows percentage of time of beneath significant wave heights[6] (2.5 m and 1.5 m) for Ekofisk and Gullfaks. The numbers, provided by the Norwegian Meteorological Institute, are based on hindcast data each third hour for the period 1958-2009. For Ekofisk, the significant wave height is lower than 2.5 m 71% of the time on a yearly basis and lower than 1.5 m 40% of the time. There are high season variations. In January the significant wave height is lower than 2.5 m 49% of the time, while it is 93% in July. The wave heights are higher further north, e.g. Gullfaks, as shown in the table.

Table 8: Percentages of time beneath two levels of significant wave heights at Ekofisk and Gullfaks on yearly basis, for January and for July.

Significant wave height:	Ekofisk			Gullfaks		
	Yearly	January	July	Yearly	January	July
2.5 m	71%	49%	93%	54%	24%	89%
1.5 m	40%	18%	70%	23%	4%	54%

Table 3 in section 2.3.4 provides an overview of significant wave heights different boats used for landing personnel at wind farms can operate under. As a result of data in Table 8 above, boats that can operate at a significant wave height of 2.5 meters can in average land personnel on wind farms in the Ekofisk area 71% of the time on a yearly basis. However, there are high seasonal variations as can be seen in the table. Going further north, to the Gullfaks area, the access time is reduced even more to 54% on a yearly basis.

3 Regulations, standards and guidelines

In this chapter we present some of the regulations, laws and specifications that are relevant for offshore wind energy farms. SINTEF's evaluation of regulations is presented in chapter 6.

The Energy Act

The Energy Act (LOV 1990-06-29 nr 50: Act on the generation, transmission, trading, distribution and use of energy etc.) is applicable to the generation, transmission, trading, distribution and use of electrical energy and district heating facilities on land. The Act aims to ensure that these activities take place in a socially efficient manner; including consideration of the public and private interests that are affected. The Act is fairly comprehensive (18 pages of A4). Much of it is devoted to rules for the application and issue

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[6] the average wave height of the one-third highest waves

of licenses for development of electrical systems and various obligations and conditions for the sale of electric energy, clearing etc. In other words, matters of little interest in the HSE context. The Act also does not apply in Norwegian territorial waters.

The Ocean Energy Act

The Ocean Energy Act (LOV 2010-06-04 nr 21: Act on renewable energy production at sea) is relatively new; it came into force in June 2010. The Act applies to the utilization of renewable energy resources - such as wind, waves and tides - and the conversion and transmission of electric energy at sea, i.e. in Norwegian territorial waters outside the baseline and the continental shelf. However, it has the power to issue regulations, such as expanding the scope of certain provisions in internal waters. The purpose of this Act is to facilitate the exploitation of the said resources in accordance with social objectives, and to ensure that energy facilities are planned, constructed and disposed of so that the interests of energy, environment, security, business, etc. are safeguarded. It requires that the construction, operation and decommissioning of energy installations covered by this Act shall be such that "a high level of safety" can be maintained and developed in line with technological developments (§ 5-1).

The Act is less extensive than the Energy Act (10 pages of A4), and much more relevant. It contains provisions regarding planning, impact assessments, licenses, safety and emergency preparedness, and more. It includes a provision (of particular interest in the safety context) that before a license can be granted, the Ministry will have received and approved a detailed plan for development and operation. The plan must explain the technical, safety and environmental conditions. Detailed regulations can also be given for nine specified conditions, including emergency and safety measures to avoid or minimise damage to the environment etc.

IEC 88/379/NP: Standard for Floating Offshore Wind Turbines

The original New Proposal (NP) for this item is dated 8th October 2010. The title of the proposal includes the word "Standard", but was later changed to "Technical Specification". A comprehensive draft (98 pages of A4) has been worked out and sent for comment.

The draft specification contains detailed implementation guidelines for floating offshore wind turbines using the concept of spar buoys, tension leg platforms, barges, and mooring systems. The specification includes "all properties for wind turbine, floating platform, structure, hydrodynamic, and mooring-control systems". Thus, it defines "principles, technical requirements and assessment procedures for the design, installation and maintenance of Floating Offshore Wind Turbines (FOWT)". Its purpose is "to provide an appropriate level of protection against damage from all hazards during the planned lifetime".

The document should be read in conjunction with IEC61400-1:2005, Wind turbines – Part 1: Design requirements and IEC61400-3, Wind turbines – Part 3: Design requirements for offshore wind turbines.

Other legislation

Other legislation relevant to offshore wind turbines probably includes the Employment Protection Act, the Petroleum Activity Act and the Pollution Act in addition to a large number of other applicable regulations.

There is also the question of whether the EU Directive 2006/42/EC on machinery (FOR 2009-05-20 nr 544: Forskrift om maskiner (in Norwegian)) will be valid for offshore wind turbines. SINTEF has not had the opportunity to go deeper into the potential challenges that this would generate for Norwegian producers and/or regulatory authorities. With appropriate reservations, we believe, however, that the following questions will require clarification:

1. Will offshore wind turbines be considered a machine according to the definitions in the Directive 2006/42/EC on machinery and thus be subject to all relevant provisions of the Directive?
The Norwegian Petroleum Safety Authority (PSA) has discussed the matter with the British and Danish governments. They have stated that there is a consensus in the EU that towers, nacelles and rotors in wind turbines will be seen as a machine and should be declared in compliance with the Directive, and CE marked accordingly. Whether the foundation should be included, seems to have not been determined[7].

2. If the provisions of the Directive apply, will this create problems for manufacturers and/or operators of offshore wind turbines?
Norwegian specialists in the wind turbine industry have stated that they already use the Directive as their basis and that this works well. If, in the offshore context it would prove that there are problems with respect to which regulations and design standards should apply (to the foundation, for example), this must of course be clarified with the relevant authorities. Thus, we cannot immediately see that there will be significant differences between offshore wind turbines and other offshore installations.

3. Which or what services can/should be 'Notified Bodies' ('*teknisk kontrollorgan*' in Norwegian)?
We assume that this will not create special problems. This is because the question has been relevant in a number of other contexts for many years, and the Norwegian authorities have found satisfactory solutions. Of course, the question could be asked who should have the authority to issue a Declaration of Compliance for the installation as a whole. Even if all components or subsystems are CE marked there is no guarantee that there will be no interface problems.

4. What or which agencies should have supervisory responsibility for offshore wind turbines?
We do not feel qualified to answer this question, but it may be tempting to draw a parallel with the question of who should have supervisory responsibility for helicopter decks on offshore installations. During work on NOU 2001: 21 and NOU 2002: 17 (Helicopter safety on the Norwegian continental shelf), the issue of which agency should be responsible for the supervision of the helicopter deck on offshore installations on the Norwegian Continental Shelf was discussed. The conclusion then was that the Norwegian Petroleum Safety Authority (PSA) had the main responsibility and should make use of the Civil Aviation Authority (CAA-N) as a professional body. People working in the offshore industry are sceptical of this division of responsibility, which they say, performs poorly. This, they claim, is because the CAA-N lacks sufficient qualified inspectors (following the move to Bodø in northern Norway), and has to go through the PSA in order to carry out inspections. The result has been that current practice is for oil companies and helicopter operators to perform inspections themselves. It is desirable to avoid a similar situation for the supervision of helicopter use for wind turbines at sea.

One of the major Norwegian labour unions (LO Industri Energi, 2010) states that in their view the PSA is the most suitable agency to coordinate safety aspects of offshore wind turbines. The PSA has long and extensive experience in coordinating a number of regulations and supervisions in the offshore petroleum industry and is, they claim, probably the only Norwegian authority with relevant experience in this regard. However, according to the same source, international experience suggests that in the future, the offshore wind turbine industry will be subject to effective international regulation and HSE will have a very strong

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[7] Reference is made to the e-mail from Svein Anders Eriksson, PSA, of December 5th 2010.

focus. They suggest that the existing North Sea Offshore Authorities Forum (NSOAF) could be instrumental in this respect.

4 HSE issues experienced at offshore wind farms

The publicly available information on accidents and incidents on offshore wind farms is scattered and lacks detail. We identified two main sources of incident information: the Caithness Windfarm Information Forum (CWIF) database on wind farm incidents, and an American report by Sharples and Sharples (2010). Both these sources provide a brief overview of what has gone wrong on offshore wind farms. However, incident descriptions lack detail, mainly because they are based on online news articles. It must also be assumed that there are more incidents than those covered by the mass media. Sharples and Sharples state that neither the industry nor authorities gather information about offshore wind farm incidents. However, Renewable UK (www.bwea.com) does have a reporting system for health and safety incidents for onshore and offshore wind farms, but access to the database is subject to confidentiality agreements between participants and Renewable UK. Offshore wind farms are a relatively novel industry, which means that "regulators and those working in offshore wind have to learn lessons as they go, build a body of experience and then develop a regulatory framework" (Atkinson, 2010:35).

We have been in contact with the Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Labour Inspection Authority to get information about HSE incidents reported in Norwegian onshore wind farms. NVE does not have a system for collecting information about these incidents. Since 1989 the Norwegian Labour Inspection Authority has registered six accidents with minor injuries (strains, fractures etc.) in 'production of electricity by wind', four of these being falls. According to the authorities, a high degree of underreporting must be assumed.

This overview of HSE issues experienced is therefore based on little data, which must be assumed to be the tip of the iceberg. The material must thus be treated accordingly. Nevertheless, the material gives some indication of the most critical and frequent HSE incident scenarios: lifting operations; personnel accessing and leaving turbines; maritime operations; and emergency handling.

4.1 Mass media descriptions of wind farm incidents

The Caithness Windfarm Information Forum (CWIF) (www.caithnesswindfarms.co.uk), which is "run by a group of people concerned about the proliferation of windfarms in Scotland", has created a huge database showing all kinds of incidents (from fatalities to technical failures) for wind farms all over the world from 1975 until the present day. In October 2010 there were 936 events registered in their database. There are some double registrations and some of the incidents have limited descriptions and no references. For some of the events it could also be questioned whether the incident should be registered in the database as unwanted. Nevertheless, the database provides an overview of unwanted incidents. CWIF's database was searched for incidents related to offshore wind farms. The data set retrieved was further analysed, and relevant incidents with thorough descriptions and proper references were selected and are presented in the table below. Most of the incident descriptions are based on online news articles, and consequently lack transparency and descriptions of root causes.

A qualitative interpretation of the overview in Table 9 reveals the following information:

- There are several reports of incidents related to lifting operations during the installation of offshore wind farms.
- Severe sea conditions are a safety threat during installation.
- Due to the distance travelled, repairing essential equipment such as installation vessels can lead to delays of several months (there is an example of several months of stopped production

at Nysted, Denmark due to a transformer failure). The accident at Ijmuiden indicates that such delays puts pressure on workers to work more efficiently to meet installation deadlines within the summer time window.

- Corrosion is a possible challenge for the technical integrity of offshore wind farms.
- There could be structural safety issues related to the seabed connection.

Table 9: Selected offshore wind farm incidents from Caithness Windfarms Information Forum's database (2010). Incidents in chronologic order

Hazards involved	Time, place	Phase	Incident description	Consequence			Reference
				Personnel	Environment	Material	
Lifting operation, falling object	13 October 2006 Barrow, UK	Lifting	Whilst lifting hoses for a generator gearbox oil change from the vessel Amstelestroom up to the nacelle on WTG D5, the deck winch blocked. The chain failed and dropped, 80% landed in the sea and 20% landed on the deck of the vessel.	-	-	-	Barrow Annual Report 2006/7
Lifting operation, falling object	24 January 2007 Barrow, UK		Whilst using the davit on the transition piece the shackle pin (50g) on the lifting gear came loose and fell approximately10m on to the vessel	-	-	-	Barrow Annual Report 2006/7
Environmental conditions (lightening)	30 April 2007 Scorby Sands, UK	Operation	A blade was destroyed due to a lighting strike	-	-	Blade destroyed	Scorby Sands annual report 07
Technical failure: transformer	June 2007, Nysted offshore wind farm, Denmark	Operation	Major transformer failure. The reason for the failure is not yet known, but a short circuit is probably to blame.	-	-	Several months of no production as the 140 ton transformer was brought ashore for repair	Reference

Hazards involved	Time, place	Phase	Incident description	Consequence			Reference
				Personnel	Environment	Material	
Lifting operation, falling object	29 July 2007, Ijmuiden port, Netherlands	Installation	The operator of a 60-metre high crane aboard the jack-up barge Sea Jack ran out of wire rope. The crane's huge steel boom crashed down onto the quayside. The incident happened at the supply port for the Q7 project	Near accident	-	The delay due to the lack of a crane pushed the project closer to the storms of winter, when offshore work becomes difficult. [8]	Reference
Loss of vessel	16 Sep 2007 Robin Rigg offshore wind farm, Scotland	Installation	Thirty-eight wind farm workers were rescued from a jack-up barge, in the Solway Firth last night after it began to capsize. The spokesman said the legs of the jack-up barge appeared to have punctured the sea bed, causing them to bend and the vessel to list badly	Evacuated	-	-	Reference
Technical failure, gearboxes	September 2007		"Danish wind turbine manufacturer Vestas Wind Systems AS is developing a new offshore wind turbine model following recent gear box problems at several of its currently operating turbines, the Swedish magazine Ny Teknik said. Peter Wenzel Kruse said gear boxes are a problem for the entire wind power industry, because strains on the boxes increase as ever bigger windmills are built".	-	-	Gearbox failures	Reference
Lifting operation, falling object	2007, two incidents at Kentish Flats, UK	Lifting	During the mounting of a ballast block there was a misunderstanding between the operator and signalman (no radio was in use). The block was dropped some five metres away from three Vestas engineers working on the gangway. Radios are now to be used for all lifting operations and no	Near accident	-	-	Kentish Flats offshore wind farm – second Annual

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[8] Related to delay, the importance of good weather conditions for installations is noted: "The weather last autumn was worse than anyone – or any weather statistics – predicted," says Albert Winnemuller. "Much of the wind was from the north, which creates long waves that make it hard for even a big vessel to hold its position."

Hazards involved	Time, place	Phase	Incident description	Consequence			Reference
				Personnel	Environment	Material	
			personnel are allowed on deck or near the working area when lifts are underway. Another severe incident occurred during a gearbox change. Crane operations were being undertaken on the deck of the 'Sea Energy' when the boom out-rigger cylinder hit and damaged a blade on the WTG.				report
Lifting operation, falling object	21 February 2008, Barrow, UK	Operation Lifting	When a technician was descending the ladder from the transition piece, the platform hatch dropped down and hit him on the head. The procedure is to be changed so that the hatch is left open when you leave the transition piece.	1 minor injury	-	-	Barrow Annual Report 2007-8
Environmental conditions (weather)	Robin Rig, UK. January 2009	Installation	Severe sea conditions made an installation vessel lose three anchor lines. All personnel were evacuated. There were 48 knot winds and sea swell of between 4 and 5 m (13 – 16 ft) in the area at the time.	Evacuation	-	-	Reference
Lifting operation, falling object	13 Nov 2009 Gabbard, UK	Installation Lifting	During construction of a wind farm, an accident occurred when a chain snapped and struck two workers on board the tugboat 'Typhoon'.	1 fatality 1 minor injury	-	-	Reference
Structural failure, seabed	Reported April 2010, Horns rev	Operation/ Maintenance	After examining 20 turbines at Horns Rev 1 and another five at Kentish Flats, Vattenfall concluded that it was necessary to repair the transition pieces connecting the towers to the monopile foundations sunk into the seabed. The same problem was experienced at a Dutch offshore wind farm in 2009.	-	-	Seabed foundation	Reference
Lifting operation, falling object	May 2010 Bard Offshore 1, Germany	Installation/ Transportation Lifting	A 90-metre foundation tube fell back onto the deck of an installation vessel while installing the sixth of 80 tri-pile foundations to be sunk into the seabed.	No human impact	-	Minor repairs on vessel	Reference
Lifting operation, falling object	21 May 2010	Transportation of goods	While loading cargo a cradle collapsed from a crane at a port in Harwich, Essex. A 45-ton crane turbine blade hit two workers.	1 fatality 1 serious injury	-	-	Reference
Environmental effect – internal:	Reported August	Operation/ Maintenance	Siemens are repairing corroded turbine bearings offshore. Routine maintenance discovered that the	-	-	Corroded turbine	Reference

Hazards involved	**Time, place**	**Phase**	**Incident description**	**Consequence**			**Reference**
				Personnel	Environment	Material	
corrosion	2010. 4 UK offshore wind farms		"protection" (gaskets?) had failed for the hub bearings.			bearings	
Environmental effect – internal:	Reported August 2010. Scotland	Operation	Grout injected during the construction of offshore wind farms is breaking up, leading to concerns over their structural integrity. The problem arises with current offshore wind farm designs that use a monopile construction. Grout is injected into the gap between the T-piece and the monopile. The grout transfers axial loads from the T-piece to the monopile, and is critical to prevent movement of the T-piece either downwards or out of alignment	-	-	Structural failure	Reference

During our work, we came across other online mass media descriptions of some offshore wind farm incidents, which are not mentioned in the CWIF database described in Table 9. These are described in Table 10.

Table 10: Selected offshore wind farm incidents retrieved from online mass media descriptions

Hazards involved	Time, place	Phase	Incident description	Consequence			
				Personnel	Environment	Material	Reference
Moving object	25 August 2006 Beatrice offshore wind farm, UK	Installation, lifting	A worker was injured during installation when a 15-ton structure swung into and crushed his leg. The accident has been investigated by the UK HSE. The HSE state that the companies involved should have foreseen the potential for the load to swing and should have taken measures to prevent such incidents. The HSE brought the case to court; the two companies were fined for the accident.	Permanent injury, amputated leg	-	-	Reference
	27 July 2010, Bard Offshore 1, Germany	Operation/ maintenance - diving	During work on the fundament of a transformer station, a diving accident happened at 40 m deep. The diver had trouble with the oxygen supply. It is now being investigated why the diver did not use his oxygen cylinder. According to Bard, the company he was diving for, there is no relation between the accident and the work he performed at the wind farm.	1 fatality	-	-	Reference
Falling object	27 November 2010, Alpha Ventus, Germany	Emergency	A worker was working at a height of 15 metres when a fuse box fell onto him, leading to an occupational accident. Due to high waves (up to 3 metres) it was not possible to rescue him by boat. A naval helicopter rescued the man by dropping a wire from 50 metres, in what was characterised as “a spectacular manoeuvre”.	Minor injury	-	-	Reference

4.2 The Health and Safety Executive on safety risks related to energy developments.

HSE (2006) identifies two principal occupational accidents related to offshore wind farms:

- Construction and major repair, in particular lifting operations and operation of jack-up construction vessels. It is also pointed out that this safety issue will become more challenging in the future as the new generation of wind turbines become even larger and taller.

- Maintenance and minor repair operations, in particular access and egress, working at height and emergency response.

4.3 Analysis of accidents to assist accident prevention on offshore wind farms on the US outer continental shelf

The Caithness Windfarms Information Forum's (CWIF) database is also the main basis for an American report by Sharples and Sharples (2010) prepared for the Mineral Management Service of the United States Department of the Interior. The report describes accidents resulting in human injuries; additionally it describes reliability data for wind farms. In addition to CWIF's database, the report is partly based on information from other similar NGOs. Although Sharples and Sharples (2010) tried to comprehensively map information on offshore wind farm incidents by requesting data from different sources, they were unable to gather any extensive information. They conclude that neither the industry nor regulators have a system for wind farm accident reporting. In addition to this accident analysis report, the project has developed a framework for a safety management system for offshore wind farms (available at www.boemre.gov/tarprojects/633.htm)

The report by Sharples and Sharples (2010) makes the following HSE-relevant observations:

- Worldwide, there have been 14 accidents with jack-up construction vessels in the period 1999-2008, which has led to two fatalities and several wrecked vessels.
- The report pays particular attention to the fatal accident with the vessel 'Russell W Petersen' at Delaware, USA, which happened during a storm. The vessel was wrecked. It was a converted service ship for oil installations in the Gulf of Mexico. There is an ongoing investigation by the US Coast Guard into the accident.
- Service crafts colliding with offshore turbine towers are a potential threat that has not been given much attention by designers and operators.
- The report presents some statistics on accident causes from different sources.

Table 11: Breakdown of accident causes for on/offshore wind farms (Sharples and Sharples, 2010)

	Paper by Nitschke et al. (2006)	Japanese report	www.windmonitor.de, last updated 2006
Lightning	24%	31%	4%
Storm	20%		5%
Icing	-	8%	3%
Design/material/defect of parts	27%	-	37%
Failure elec.sys./ short circuit	8%	13%	-
Failure control system	-	21%	23%
Fire	7%	-	-
Failure-drive system	-	13%	-
Software	-	11%	-
Loosing of parts		-	3%
Grid failure	-	-	7%
Others	14%	-	11%
Unknown causes	-	-	7%

Table 12: Breakdown of component failures for on/offshore wind farms (Nitschke et al., 2006)

Component damages	
Tower	18%
Blades	17%
Gearbox	16%
Generator	13%
Transformer	10%
Nacelle	8%
Control eq.	5%
Others	13%

Based on their overview of threats and hazards, Sharples and Sharples (2010) make recommendations for safety management systems for offshore wind farms. The following recommendations are relevant when assessing HSE challenges for offshore wind farms on the Norwegian continental shelf:

- In case of fire: fire-fighters must not open the door to the turbine and thereby create a chimney effect.
- There have been a number of issues with the subsea cable. Burying the subsea cable at an appropriate depth to avoid anchor issues is probably one of the most important factors in preventing major downtime and the grid loss that can put wind turbines at risk should a storm occur during the outage.
- Oil leaks from wind turbines.
- Lightning is a frequent hazard for offshore wind turbines.
- Equipment which is certified to last 20 years often has to be replaced in 2-3 years and with a guarantee of no longer than a further 5 years. The report questions the certification process.
- While no-one has been hurt from loose blades it is important to note that the practice of turning the turbine off when it is under maintenance should be adhered to.
- Technical integrity. Ensuring the integrity of transformers is important.
- Extreme weather conditions. Hurricanes, typhoons, and/or cyclones can produce multiple failures.
- Lifting operations. Whenever lifting is going on it is very important to stay a considerable distance away.

4.4 Case Study of European offshore wind farms

Gerdes et al. (2006) made a case study of European offshore wind farms in order to gather and evaluate experiences and lessons learnt from planning and development procedures from eight offshore wind farms: Nysted, Denmark; Scroby Sands, UK; Greater Gabbard, UK; Egmond aan Zee, the Netherlands; Horns Rev, Denmark; Borkum West, Germany: Butendiek, Germany and Thornton Bank, Belgium. Nysted, Horns Rev and Scroby Sands were the only ones in operation, the rest were planned at the time the report was written. The study consists of a literature review and interviews with experts. The report mainly focuses on planning, design and operation without paying particular attention to HSE challenges. However, the following safety challenges are identified:

- The only potential accident mentioned in the report is ships colliding with wind farm installations. Planned farms must be sufficiently far from shipping routes. Preventative measures such as land radar, signal lights and navigation marks are proposed.
- At Greater Gabbard, UK, the following safety challenges related to ship collision have been identified:
    - A vessel on a planned passage through the Inner Gabbard/the Galloper gap is forced to leave its planned track, enters the wind farm and collides with a tower or rotor
    - A vessel becomes disabled, drifts into the wind farm and collides with a tower
    - A vessel runs aground on the Inner Gabbard or the Galloper gap and either swings with the tide and strikes a tower or one of her salvage tugs strikes a tower
    - A construction vessel drops or drags its anchor over an unburied cable and damages it
    - A member of the maintenance crew slips between the boat and the boat landing ladder (on a turbine) and is injured
- During installation at Horns Rev (2002) a construction vessel destroyed one of the interconnection cables in the wind farm: the anchor hit the cable, which lay unprotected on the seabed.

- The following factors for safe and efficient installation at Nysted have been identified: safe anchoring of transport barges; safe sea fastening of foundation; short installation time to fit within weather windows; suitable equipment; management of risks caused by waves, tides and currents.

With regard to environmental impact, the three farms in operation (Nysted, Horns Rev and Scroby Sands) show that they have made environmental impact assessments and carry out monitoring. However, they do not show the results. For example, Nysted show that they made a baseline measurement before installation, a measurement during installation and a measurement in the operational phase. Horns Rev has assessed the environmental impact on the sea floor flora and fauna, fishes, porpoises, seals, and birds.

4.5 Environmental impact assessments

According to companies operating offshore wind farms in Europe, much effort is put into environmental surveys on birds, fishes and other marine flora and fauna. Most of these companies provide the results of their environmental surveys online. In this subsection we look at a few of these reports, to assess the environmental effects of offshore wind farms. It must be noted that these reports are based on installations that are not operating in the North Sea.

4.5.1 Bird monitoring

A post-construction report on environmental monitoring for the Barrow offshore wind farm (Barrow, 2009), shows neither any indication of decrease in the bird population in the area nor of disturbance to migration paths. The study is based on observations from boats and by plane. Similarly Kentish Flats' annual report for 2007 shows that boat-based and aerial bird surveys performed in 2005 show natural changes but also concludes that in most cases these cannot be attributed to the wind farm construction, although some localised temporary disturbance to some seabirds was noted during the construction period.

The results of an environmental impact assessment of birds at Horns Rev and Nysted (Vattenfall, 2008) show the same tendency. Based on 165 observation days in 2005 and 2006 the main migration periods during spring and autumn were studied. The study shows that only a fraction of migrating birds come close to the wind farms. Most water birds (pelagic species, sea ducks, swans, geese and others) seem to avoid the farms by a wide margin. Birds which migrate closer to the farms during daytime, such as large numbers of Common Scoter (*'sjørorre'*), Common Eider (*'ærfugl'*), Great Cormorants (*'storskarv'*), terns and others also avoid the farms, however the effect is not as clear as for the water birds. The report concludes that the species mentioned above effectively avoid the wind farms. However, they are affected by a habitat loss. There are no available statistics on collisions, however the observation study shows that resident species such as gulls, non-migrating cormorants and a small number of raptors regularly enter the wind farms; likely due to food sources, which also expose them to collision risk. Large numbers of songbirds cross the area of Horns Rev and Nysted, mainly at a flying altitude of more than 300 metres. Nevertheless a considerable proportion migrates through the area at wind turbine height, in particular at night. The report mentions that onshore studies show that migrating songbirds apparently cross wind farm areas without colliding. Furthermore, the study concludes that both offshore and onshore studies show that unforeseen poor weather conditions can lead to a considerable number of collisions.

4.5.2 Fish

In 2006, a program of seasonal fish monitoring at Kentish Flats was completed. The survey shows a natural variation in fish populations across the survey area and throughout the observation period. The report concludes that there is no evidence of any harmful effects on fish populations. The post-construction environmental monitoring performed at Barrow (2009) shows the same tendency, i.e. no notable differences in diversity and abundance of fish and echinoderms (e.g. starfish).

Hydro-acoustic surveys performed at Horns Rev show no general effects on fish due to the presence of the wind farm (Vattenfall, 2005). The survey does not provide evidence that the installations worked as an artificial reef, attracting reef fish. Several of the fish observed within the wind farm are typically found around shipwrecks in the North Sea, indicating that turbine noise and vibrations have no major impact on these fish.

Other environmental effects studied are:

- Studies at Barrow and Horns Rev indicate an increased number of species and biomass of hard bottom flora and fauna (e.g. barnacles, mussels and anemones) have been found on the turbines (Vattenfall, 2005; Barrow, 2009)
- At Barrow, scour (1-5 metres deep) have been detected around fixed installations (Barrow, 2009)
- At Horns Rev no effect is shown on fauna (e.g. worms and crabs) and sediment around fixed installations (Vattenfall, 2005)
- Observations at Horns Rev, indicate no local effects on seals in terms of avoidance, when they swim or dive inside the wind farm (Vattenfall, 2005)
- At Horns Rev a weak negative effect has been identified on porpoises. During construction there was a partial displacement, but it returned to baseline during normal operations (Vattenfall, 2005)

4.6 Hazards related to load-carrying structural components

4.6.1 Brief review of some past structural failure modes for offshore wind farms

Table 8 (selected incidents for offshore wind farms taken from the Caithness database), shows that incidents related to structural failure are listed as (i) blade damage due to lightning, (ii) collapse of legs of jack-up barge, (iii) loss of three anchor lines of installation vessel, (iv) transition piece of monopile foundation sinking into the seabed, (v) corrosion and (vi) grout damage related to the pile-head.

Some of these failures are intrinsic to the marine environment as they occur to structural components that are not present in onshore wind turbines. Other categories of failure (such as damage due to lightning and corrosion) are also relevant for onshore wind turbines, but the probability of failure will increase due to being located in the offshore environment.

The same considerations regarding the probability of failure are likely to apply to structural damage (with the associated possibility of serious consequences in relation to human injury and fatalities) which is due to human error. Such errors may occur during all phases of the life cycle of a wind farm: installation, commissioning, operation, inspection and maintenance. It can be seen that more hostile working conditions and narrower time-windows related to man-assisted operations may easily lead to a higher frequency of human error, which may in turn affect loading on the structural components in a critical way.

In this respect, it is very interesting to consider the most likely cause of failure, related to collapse of the column structure of an onshore wind turbine, which is illustrated in Figure 56 below.

(Source: Teknisk Ukeblad, 29.08.2007)

Figure 56: Example of collapse of a wind turbine column structure

For this structure, there seems to have been an operational error following inspection and maintenance of the wind turbine. The consequence of this was that the turbine was left in the wrong condition leading to rotor overspeed and column overloading during a subsequent storm. This clearly demonstrates the vulnerability of these types of structures to human mistakes and omissions. It also clearly illustrates the potential for high loads on the structural load-carrying elements due to mal-operation of the propeller system.

4.6.2 Challenges related to the design of structural wind farm components in the offshore environment

4.6.2.1 General

Compared to similar onshore structures, wave loading represents an additional source of dynamic excitation. Similarly, currents add an additional static loading. The presence of dynamic loads with a different frequency range to that of the wind load implies that dynamic amplification effects need to be carefully assessed. This applies to all project phases, from design through installation, operation, inspection, maintenance and decommissioning.

For offshore wind farms there are also additional challenges which are intrinsic to this type of structure. These features are discussed below.

4.6.2.2 Specific concerns for some categories of structural components

In this section, some particular design considerations relevant to the various structural components of offshore wind farms are discussed. This comprises the bottom foundation, the substructure, the column structure and the propeller blades.

One of the intrinsic components of bottom-supported offshore wind farms is the bottom foundation, which is largely different from that of an onshore counterpart. The design of appropriate structures for mounting the foundation of wind turbines is a challenge for the engineering community, particularly when applied to offshore locations. The base of the foundation may be affected by scour; erosion of bottom material in the vicinity of the foundation caused by a local increase of the flow velocity induced by waves and currents. A scour hole may have a big impact on the dynamic behaviour and the stability of the wind turbine. After some time in operation, a range of seabed conditions can develop. These are caused by complicated flows generated by the interaction of water movements, the pile and the seabed. The result will depend on the incoming flow velocity (e.g. the relative magnitude of waves and current), the geometry of the bed, the bed material, as well as the ratio between the near-bed oscillatory fluid particle excursion amplitude and the pile diameter.

The effect of pile stiffness on increasing levels of scour need to be considered. Then the resulting variation of the natural frequency and the dynamic response of the wind turbine can be computed. Specific design criteria related to the 'Ultimate and Fatigue Limit States' for the turbine tower structure then need to be looked at, in order to define critical scour depths. The corresponding critical conditions relating to the wave and current environment (i.e. in a long-term statistical sense) can then also be established.

The presence of a bottom-fixed substructure (e.g. support structures of the tripod or jacket type) may clearly introduce additional structural failure modes compared to onshore wind turbines. Operational limits, as well as fatigue-induced damage caused by the combined action of waves and wind needs to be carefully considered. This applies to the structural response that occurs during all phases of the project, ranging from transport and installation to decommissioning.

Compared to traditional bottom-fixed offshore structures, a higher level of load variability (and uncertainty) will result due to the presence of the propeller and turbine. Furthermore, the properties and algorithms of the control system implemented for the propeller will influence the static and dynamic loading of the support structure (as well as the other load-carrying components). When combined with additional uncertainty related to the stiffness of the bottom foundation and the corresponding natural frequencies, prediction of the static and dynamic response levels becomes more challenging. This requires significant modifications to design procedures compared to existing structures of similar type.

The response of the column structure is influenced directly by wind load, wave loading (for extreme waves), and possible wave run-up. There is also an indirect response component caused by static and dynamic loading on other parts of the structure. These will create additional fatigue and possibly an extreme response. Spray from seawater will accelerate corrosion unless a protective coating is applied.

The propeller blades are subject to more extreme static wind loads (up to a certain asymptotic level when the distance from the shore becomes large enough) than for onshore conditions. Assuming that the extreme wind speed can be predicted with sufficient accuracy, adequate structural capacity can be implemented using proper design procedures. Turbulence levels (which depend on the dynamic component of wind velocity), do not seem to increase for offshore, compared to onshore structures. On the contrary, turbulence may decrease in offshore conditions. This will reduce the wind-induced part of fatigue damage. However, higher static loading means there could be a more critical interaction between fatigue-induced damage and the possibility of subsequent failure due to extreme events.

For floating wind farms there will be additional, tensioned, structural components, such as tethers and mooring lines. For tether components, the potential for a dynamic response caused by higher-order harmonics, due to so-called 'springing' or 'ringing' needs to be considered. Experience from the design of TLP (tension leg platform)-type platforms will be valuable, but the higher percentage of total loading resulting from dynamic wind (as compared to TLPs) will require greater care in the design.

Mooring line failure is a frequent cause of accidents for traditional types of floating offshore structures. As is the case for the tethers there will be a higher percentage contribution to the static and dynamic tension in the mooring line from wind loading than for more traditional floating systems. Design procedures must reflect this feature.

4.6.3 Additional sources of accidental loading

For offshore wind farms, there are additional sources of accidental loading compared to similar onshore structures.

In the design of offshore structures in general, the so-called Accidental Limit State (ALS) or Progressive Limit State (PLS) are applied in order to prevent catastrophic structural failures. The requirement is that the structure should be able to survive the associated critical event without collapsing. At the same time, material can be pushed to greater limits than is allowed for in more likely scenarios. This implies that some degree of residual deformation (for example yielding, plasticisation or local buckling) is allowed.

These limit states take care of, for example, possible but very unlikely extreme weather conditions. They imply that the associated extreme loading caused by the combination of wind, waves and current are accounted for. The design of offshore wind farms must take into account such conditions. For extreme wind conditions the consequences of corresponding rotor overspeed and structural resonance also needs to be assessed.

For offshore wind farms, accidents can be caused by ship impact and collision. Smaller impacts can be expected to occur during local operations such as transfers between service vessels and the wind farm installations. Larger impacts can be caused for example by vessels that are drifting because of engine failure or manoeuvring errors. For the smallest impact levels, additional structural resistance or fendering systems may be adequate. However, for the largest impact levels other types of risk mitigation need to be assessed.

Historically, failure of rotor blades due to lightning has occurred at offshore wind turbines. It seems that rotor blades made of composite material are particularly vulnerable. As there is an increased probability of lightning in the North Sea, increased awareness of such events is required. It is difficult to achieve adequate mechanical resistance to avoid this type of failure. Hence, the design needs to take into account secondary structural loading due to blade impact, together with other types of risk mitigation (e.g. warning systems). In general, blade failure may also be due to other causes, which in principle can be designed against, such as overloading and fatigue failure. It has been observed that blades can fly through the air over distances of several hundred metres. Hence, particularly for wind farms with a large number of turbines, such events and the associated preventive actions need to be properly addressed.

The increased probability of falling objects found in marine lifting operations (compared to similar onshore lifting operations) represents an additional source of accidents. The corresponding accidental design loads can be estimated, e.g. using risk assessment methods.

The increased likelihood of human error in offshore operations has already been mentioned. Some of the consequences of such human errors (unforeseen loads on structural components) can be very difficult to design against. Hence, there may be a transitional boundary between failure events that are best prevented by means of proper work procedures rather than an increase in structural strength.

Similarly, failure of the brake or control system will in general imply unexpected structural loading. However, it is not necessarily the case that such failure will occur more frequently for offshore than for onshore turbines. This topic would need to be addressed as a separate study. It is also likely that there will be technical developments in these systems that will reduce the associated probability of failure.

For the load-carrying structural components, the highly corrosive environment at offshore sites represents an effect that can be designed against by adding a corrosion allowance to the required thickness of the material used. If there is a higher corrosion rate than anticipated and the damage is not detected, accidents may occur. However, since corrosion typically is a very slow process such consequences can be prevented by proper inspection and maintenance procedures.

4.7 Use of helicopters

How helicopters are currently used for transport and operations is described in sections 2.3.3 and 2.3.4.

The following is a quote from the PSA's Note 'F-Logistics and readiness', 18th November 2009, p. 41 (unofficial translation):

"The use of helicopters for access via a basket to the nacelle is found today in both the UK and Danish sectors on a relatively large scale. This solution is considered by many Norwegian players as an evacuation solution and not an acceptable solution for planned transfers to the wind turbine. Norwegian players believe it will be important to investigate the possibility of alternative helicopter access, as this is an established method of transportation in the area and there are opportunities for synergy with the oil and gas installations and permanently stationed helicopters".

Communication with one of the two largest Norwegian offshore helicopter operators and Statoil's own helicopter expert revealed that the concept of using helicopters for access to the nacelle via a basket, in the North Sea must be regarded as very risky. This, it was claimed, is for several reasons:

- To carry out the operation, the helicopter must hover over the top of the wind turbine without the pilot having adequate visual references. There are helicopters with advanced automation that can maintain the correct position, but this equipment is very expensive and not widely available in today's helicopters.

- The basket will have to hang from a rope several metres long. This will cause fluctuation and the stronger the wind, the more fluctuation. In addition, the installation will also swing. Certainly, such helicopter operations are permitted today, for example, when a pilot is set down on the deck of ocean going ships, but this is also regarded as risky. Recently, a pilot was fairly severely injured when he fell onto the deck during such an operation. The reason why such operations are nevertheless permitted is that in practice there is no alternative method. In addition, these flights are subject to strict operational limitations, which include night flights (not allowed except in emergencies), wind speed, wave height and deck movements.

- If the use of helicopters is allowed in Norwegian waters for transport of personnel to and from offshore wind turbines, it is argued that one must assume that smaller and more or less disreputable helicopter operators will offer their services more cheaply than others, and thus be able to win business. The price will be lower, it is claimed, because the operations will probably be conducted using smaller, single-engine machines with only one pilot. Furthermore, these companies have to base their operations on their experience of cargo missions etc. over land. Lack of experience of the more demanding conditions at sea, must be assumed to imply a significant increase in risk.

More recent information indicates that our aforementioned informants might have been somewhat more pessimistic than is warranted. A Google search carried out on 21st April 2010 found these two results http://www.industrytoday.co.uk/energy-and-environment/wind-of-change-for-bristow and http://www.oilport.net/news/art.aspx?Id=17723. Helicopters Ltd., UK (the parent company of Bristow Norway, formerly Norsk Helikopter) is in the process of developing "a safe, flexible and cost effective method of helicopter access" to offshore wind turbines. Their offer will include transportation and lowering of personnel from approximately three metres above the wind turbine, transport of cargo (up to three tons), observations from the air, rescue operations and training on the lowering of personnel ("winch to work"). For each turbine, it is assumed there is a need to land personnel 5-10 times per year. "Delivering the engineers directly onto the platform saves a slow and difficult climb from a vessel up the turbine tower, and there is no loss of man hours due to sea sickness", the company says.

Another factor mentioned in connection with wind farms, is the need for marking and lighting in accordance with the Norwegian Regulation on Labelling of Aviation Hazards (BSL E 2-2). Despite correct labelling there will, however, still be a risk of collision with low-flying helicopters, particularly during rescue missions. Such operations are also performed at night and in bad weather. Another risk factor is flying ice that dislodges from the wind turbine blades. This has already been observed, although so far without causing damage to aircraft.

5 Analysis: hazards and accident scenarios (for offshore wind farms)

A general listing of hazards has been developed by Rausand and Utne (2009). The list includes hazards categorised as Mechanical, Vibration, Electrical, Thermal/Smoke/Fire, Radiation, Noise, Poor ergonomics, Internal and External Environmental effects (including spills), Dangerous liquids, gases or materials, Organisation/Procedure and Terrorism/Sabotage. This list has been used as a basis for the analysis. In addition, we have added hazards (such as working at height, slippery surfaces, bird strike, unclear roles and responsibilities, insufficient procedures and insufficient means to detect deviations) which were not in the original list but that we identified as important for offshore wind energy production.

As there are no indications that floating wind turbines are significantly different in terms of HSE issues, the following analysis applies to both main categories of concepts. Where future floating installations may differ is discussed in section 6. The hazards identified for different phases of offshore wind energy production are listed in the following tables.

Table 13: Hazards identified for the installation and commissioning phase

Hazards identified for installation and commissioning	
Mechanical	Falling structure/ load/object (lifting operations) Potential energy (work at height, lifting operations) Kinetic energy (vessels, helicopters, moving parts) Marine operations (ship collisions, man overboard) Helicopter operations
Vibration	(During testing)
Electrical	Short circuit Overcharge Electrostatic phenomena (shock, spark/ignition)
Thermal/smoke/fire	Fire and/ or explosion - turbine, vessel
Radiation	NA
Noise	From machinery and tools/equipment
Poor ergonomics (construction and design)	Physiological effects due to heavy lifting and repeated movements, uncomfortable working positions etc. (manual work carried out during installation) Work at height Slippery surfaces Psychological effects due to poor working and living conditions
Environmental effects (internal)	Base/ground failure
Dangerous liquids, gases or materials	Flammable Poisonous Harmful Oxidizing/corrosive Battery acid(?)
Environmental effects, external	Wind Waves and currents Lightening Earthquake (?)
Organizational	Time pressure Insufficient/missing safety equipment

Hazards identified for installation and commissioning	
	Incorrect use of machinery and tools/equipment Lack of relevant expertise, due to new types of offshore operations Several different actors/companies involved in same operation
Terrorism/sabotage	Sabotage Terrorism

Table 14: Hazards identified for operation

Hazards identified for operation	
Mechanical	Falling structure/load/object (blade failure, structural failure) Potential energy (work at height, lifting operations) Kinetic energy (vessels, helicopters, moving parts, rotating parts, turbine overspeed)
Vibration	From machinery and tools/equipment In turbine
Electrical	Short circuit Overcharge Electrostatic phenomena (shock, spark/ignition)
Thermal/smoke/fire	Fire and explosion
Radiation	NA
Noise	From machinery and tools/equipment
Poor ergonomics (construction and design)	Human error Physiological effects (uncomfortable working positions etc.) Psychosocial effects (mental overload, mental underload, stress etc.) Impossible to see deviations in system operation (Human Machine Interface)
Environmental effects (internal)	Damp environment Corrosive environment Slippery surfaces Base/ground failure
Dangerous liquids, gases or materials	NA
Environmental effects, external	Wind Waves and currents Lightening Earthquake (?) Bird strike Changes in seabed conditions
Organizational	Time pressure Lack of relevant expertise Unclear roles and responsibility Inadequate procedures (if remotely controlled) Lack of communication between onshore control rooms and offshore installation
Terrorism/sabotage	Sabotage Terrorism

Table 15: Hazards identified for maintenance work

Hazards identified for maintenance work	
Mechanical	Falling structure/load/object (Work at height, lifting operations, blade failure, structural failure, falling tools/parts, crane failure) Potential energy (work at height, lifting operations) Kinetic energy (vessels, helicopters, moving parts, rotating parts, turbine overspeed) Sharp edges Tensile energy (springs etc.)
Vibration	From machinery and tools/equipment In turbine
Electrical	Short circuit Overcharge Electrostatic phenomena (shock, spark/ignition)
Thermal/smoke/fire	Fire and explosion Too hot or too cold surfaces
Radiation	From instruments?
Noise	Vibration and noise from equipment
Poor ergonomics (construction and design)	Human error Physiological effects due to heavy lifting and repeated movements, uncomfortable working positions etc. Work at height Slippery surfaces Working alone? Psycho-social effects (mental overload, mental underload, stress, etc.)
Environmental effects (internal)	High or low temperatures Damp environment inside tower Slippery surfaces Human access and egress
Dangerous liquids, gases or materials	Oxidising Flammable Poisonous (oil, paint) Harmful (asbestos, cyanides?) Corrosive Carcinogenic Harmful to genes
Environmental effects, external	Wind Waves and currents Lightening Earthquake Bird strike
Organizational	Time pressure Lack of relevant expertise Unclear roles and responsibility Inadequate procedures Insufficient safety equipment Wrong use of machinery and equipment Insufficient planning (e.g. use of spare parts) Unusual working hours Lack of communication between onshore control rooms and offshore installation
Terrorism/sabotage	Sabotage Terrorism

Furthermore, we have identified possible accident scenarios based on knowledge of existing accident scenarios in the offshore petroleum industry, in aviation and in work with electricity. The accident scenarios that have been identified, together with descriptions are listed in the following tables, as well as possible consequences for humans, the environment and materials/construction.

Table 16: Accident scenarios for the installation and commissioning phase

Accident scenarios – INSTALLATION AND COMMISSIONING PHASE	Description	Catchwords related to offshore wind turbines in particular	Consequences		
			Human	Environmental	Material
Vessel or drifting installation on collision course	Possible collision with turbine, transformer, living quarters, substations	Several ships are involved in lifting operations when installing turbines	Fatality Injury	Pollution to sea	Total loss or partial damage to vessel Structural damage or loss of turbine
Capsizing of vessel	Jack-up, barge	-	Fatality Injury	Pollution to sea	Total loss or partial damage to vessel Structural damage or loss of turbine
Human overboard	When accessing turbine or other installation from vessel. When climbing outside the tower. Fall from nacelle Fall from vessel	Many transfers for offshore wind energy workers during installation	Fatality Injury	-	-
Anchoring failure, (dynamic) positioning failure	-	-	Fatality Injury	-	Total loss Damage
Occupational accident	Electrocution Falling from height Squeezing Cutting etc.	Manual work in difficult working environments (narrow rooms, at height, slippery surfaces etc.)	Fatality Injury	-	-
Diving incident	-	Diving operations are used internationally	Fatality Injury	-	-
Falling object	The object may hit humans on the installation vessel or fall into the sea	Lifting operations of large objects are relevant in all installation work on offshore turbines (except floating turbines towed offshore)	Fatality Injury	Pollution to sea	Loss of or damage to equipment Structural damage

Accident scenarios – INSTALLATION AND COMMISSIONING PHASE	Description	Catchwords related to offshore wind turbines in particular	Consequences		
			Human	Environmental	Material
Vessel or drifting installation on collision course	Possible collision with turbine, transformer, living quarters, substations	Several ships are involved in lifting operations when installing turbines	Fatality Injury	Pollution to sea	Total loss or partial damage to vessel Structural damage or loss of turbine
Capsizing of vessel	Jack-up, barge	-	Fatality Injury	Pollution to sea	Total loss or partial damage to vessel Structural damage or loss of turbine
Fire	In turbine On vessel	-	Fatality Injury	Possible secondary effect: Pollution	Total loss Damage
Structural failure	Loads from wind, waves and current	Mooring problems Yielding seabed	Fatality Injury	-	Total loss Damage
Helicopter crash	Helicopter crashes during lifting operation, transport etc.	-	Fatality Injury	Minor pollution to sea	Total loss or partial damage to aircraft Structural damage to turbine
Pollution to sea	Hydraulic oil, gear oil, transformer oil, etc.	Only small quantities	-	Birds, fish etc.	-

Table 17: Accident scenarios for operation and maintenance

Accident scenarios – OPERATION AND MAINTENANCE PHASE	Description	Catchwords related to offshore wind turbines in particular	Consequences		
			Human	Environmental	Material
Vessel or drifting installation on collision course	Possible conflict with turbine, transformation station, living quarters, substations	The resistance power of the tower and mooring is uncertain	Fatality Injury	Pollution to sea	Total loss or partial damage to vessel Structural damage or loss of turbine
Mooring failure	Rupture Loosening	Wind, waves and current loads Drifting object or ice	-	-	Installation unstable or drifting
Human overboard	When accessing turbine or other installation from vessel When climbing outside the tower Fall from nacelle Fall from vessel	Wave height limits for current access methods from vessels are 2.5 to 3 m	Fatality Injury	-	-
Occupational accident	Electrocution Falling from height Squeezing Cutting etc.	Manual work in difficult working environment (narrow rooms, at height, slippery surfaces etc.)	Fatality Injury	-	-
Falling object	During lifting operations Inside tower during maintenance	Much work is done at height	Fatality Injury	-	Loss of or damage to equipment Structural damage
Fire	Burning oil, electrical equipment or inflammable liquids	Difficult access makes extinguishing problematic	Fatality Injury	Possible secondary effect: Pollution	Total loss Damage
Air collision	Between helicopters, military or civil aircraft, incl. unmanned aircraft. Collision with turbine	Transport to/from other installations (incl. petroleum) Military exercises Environmental surveys	Fatality Injury	Pollution	Total loss or partial damage to aircraft Structural damage or loss of turbine
Helicopter crash	Helicopter crashes during lifting operation, transport etc.	-	Fatality Injury	Minor pollution to sea	Total loss Damage
Bird strike	Bird hits rotor blade(s)	-	-	Dead bird(s)	Structural damage Loss of blade

Accident scenarios – OPERATION AND MAINTENANCE PHASE	Description	Catchwords related to offshore wind turbines in particular	Consequences		
			Human	Environmental	Material
Blade failure (falls off)	Material fatigue or design/ construction weakness	Rotor blades have been shown to fly up to 800m. They may hit ships, other installations or helicopters in flight	Fatality Injury	-	Loss of blade Structural damage Possible damage to hit objects within landing zone
Structural failure	Welds Concrete Composite material	Corrosive environment Wind, waves and current loads Icing at rotor blades or structure Drifting ice	Fatality Injury	Possible secondary effect: Pollution	Total loss Damage
Ice throw	-	Ice thrown from rotor blades can hit helicopters in flight, vessels etc.	Fatality Injury	-	Damage to helicopter or vessel
Environmental impact	On fauna/birds, fish etc.	Vibrations/noise Pollution to sea	-	Surveys show little or no impact on fish, bird migration etc.	-
Lightning	Rotor blades of composite material are particularly vulnerable	Considerable probability of lightning in the North Sea	Fatality Injury	-	Fire Structural damage Short-circuit
Extreme weather conditions	Rotor overspeed Structural resonance	-	If personnel are present: Fatality Injury	Possible secondary effect: Pollution	Water break-through Capsizing Structural damage Icing
Pollution to sea	Hydraulic oil, gear oil, transformer oil, etc.	Only small quantities	-	Birds, fish etc.	-
Loss of remote control	Onshore remote control systems	Breakdown of digital infrastructure	-	-	Structural breakdown due to uncontrolled installation

Most of the accident scenarios can be found in existing 'Defined Situations of Hazards and Accidents' (DSHAs) in the petroleum industry. The most frequent scenarios for offshore wind farms seem to be related to crane and lifting operations during installation and heavy maintenance work, transport of equipment and parts, and access (to the vessel, turbine etc.). Maritime operations are involved in most of the frequent scenarios. Major accident scenarios with the most severe outcomes in terms of fatalities and material loss are related to transport using maritime vessels and helicopters, as well as structural damage during operation. The DHSAs from the petroleum industry that seem to be relevant for offshore wind farms are listed in Table 18 below.

Table 18: Listing of Norwegian Continental Shelf (NCS) petroleum DSHAs and relevance for offshore wind energy production. DSHAs in italic are not in use in the petroleum industry as of 2009

No	Original DSHA description, petroleum	Relevance for offshore wind energy production
1	Non-ignited hydrocarbon leaks.	NA/little relevance
2	Ignited hydrocarbon leaks.	NA/little relevance
3	Well kicks/loss of well control.	NA
4	Fire/explosion in other areas, flammable liquids.	Relevant
5	Vessel on collision course.	Relevant
6	Drifting object.	Relevant
7	Collision with field-related vessel/installation/shuttle tanker.	Relevant
8	Structural damage to platform/stability/anchoring/positioning failure.	Relevant
9	Leaking from subsea production systems/pipelines/risers/flow lines/loading buoys/loading hoses.	NA
10	Damage to subsea production equipment/pipeline systems/diving equipment caused by fishing gear.	NA
11	Evacuation.	Relevant
12	Helicopter incident	Relevant
13	Man overboard.	Relevant
14	Serious injury to personnel.	Relevant
15	Occupational illness.	Relevant
16	Total power failure.	Relevant
17	*Control room out of service.*	Relevant
18	Diving accident	Relevant
19	H^2S emission	NA
20	*Lost control of radio-active source.*	NA?
21	Falling object.	Relevant
22	*Acute pollution.*	NA
23	*Production halt.*	Relevant
24	*Transport system halt.*	Relevant

There are some scenarios that are specific to offshore wind turbines. These include ice throw, blade failure (and the possible subsequent structural damage), as well as some aspects related to access to the turbine and tower. Ice throw is a known problem in wind farms. A report from Kjeller vindteknikk (2010) concludes that for an onshore wind farm close to shore, ice will form on the blades on average 4% of the time (range is from 2% to 9%) and that the probability of ice throw landing within a radius of 50 metres from the turbine is about 1/100 in a year.

Future decommissioning and repowering seems to resemble installation and commissioning to such a large extent that we have not found it necessary to analyse this phase in particular.

5.1 Hazards and scenarios for emergency handling

Emergency scenarios in the offshore wind energy industry include rescuing personnel, containment of possible environmental pollution and fire fighting. In addition, when few personnel are present during an operation, there is a risk that accidents and incidents are not detected in time and emergency handling become difficult to plan and activate. The following issues are found to be important for emergency operations in offshore wind farms.

In current offshore wind turbines, access to areas safe from fire is difficult. If personnel are present when fire starts, there are few alternative escape routes and few safe areas to wait for rescue. It has also been suggested that the tower may act as a chimney and this may make it difficult to open access doors etc. in the lower part of the tower.

Generally, use of helicopters close to an installation is risky. If helicopters are to be used for rescuing personnel in the sea or stranded at the turbine, the helicopter may not be able to get close enough. Use of a vessel may be the only solution, and there are currently limits on the conditions vessels can be used in (depending on wave height etc.).

Evacuating a sick or injured person from the nacelle may be challenging as ladders inside and outside the wind turbine tower are steep and may require the use of both hands when climbing.

Evacuating persons from wind turbines due to changed weather conditions may also be a challenge. Although the wind turbine may have a survival kit which can sustain stranded personnel for up to 48 hours, a wind turbine is not a good place to stay for long periods in bad weather conditions.

In the case of blade failure or other structural damage, it may be challenging to capture floating objects using boats, especially if the object is large.

Within the offshore petroleum industry, there are rules determining how an emergency response should be managed. For example, it is stated that a person who has fallen into the sea shall be rescued within two hours. How this is handled in the offshore renewable energy industry depends on how it is regulated. Differences in emergency handling for petroleum workers, fishermen and other maritime workers, and workers in the future offshore renewable energy industry should be examined.

As many actors are involved in the different phases of a farm for offshore wind energy production, it is important to identify who is responsible for emergency procedures and handling. Emergency procedures for different accident scenarios need to be set up and emergency handling for different scenarios must be planned for.

6 Discussion

Although there is little HSE data and underreporting must be assumed, the data presented in section 4 indicates that the most frequent incidents occur during the transport of material and people, including accessing wind farms and installations. Human injury and fatal accidents seem to occur most frequently during the installation of components and transportation of parts. Material damage and loss occur most frequently during installation and commissioning, but also during operation (if onshore accidents are included in the data). The data used here is mainly based on online mass-media descriptions, which lack detail and are non-transparent. Internationally, there is no public system for reporting offshore wind farm accidents either by the industry or authorities. Long-term statistics from the Norwegian Labour Inspection Authority indicate that (as for onshore accidents) there is a large degree of underreporting.

Maintenance and operations require personnel to be present. As the phases of an offshore wind farm (installation, operation, maintenance etc.) may be interwoven, especially in the early life of a farm, different personnel may be present for different reasons. They may be conducting very different operations, involving different risk scenarios at the same time. If personnel also are needed to conduct inspections and monitor production, even more people, vessels and/or helicopters may be present. This can mean that risk levels increase due to the complexity and confusion of situations involving many different actors, roles and authorities. Current research and technology development activities within the offshore wind energy industry (using floating installations), aims at developing systems that do not need such a large-scale human presence as the farms in use today. This is also a cost issue.

The most frequent scenarios seem to be due to crane and lifting operations. They are mostly related to installation, but they can also be associated with maintenance of larger parts like the nacelle and blades, access to the turbine from vessels or helicopters, and collision, either with vessels, a helicopter or drifting objects. In addition, emergency handling may be challenging, as access is difficult in high waves and strong wind. As weather changes quickly offshore, an accident that happens under normal conditions may become a challenging emergency scenario if the weather worsens.

Today’s HSE situation in the offshore wind energy industry is very different to the situation for other offshore operations. HSE procedures, use of protective equipment and safe working practices etc. seem to be lacking, or at least incomplete. Offshore wind power farms are a relatively novel industry, which means that “regulators and those working in offshore wind have to learn lessons as they go, build a body of experience and then develop a regulatory framework” (Atkinson, 2010:35). The actors involved are less familiar with offshore operations; authorities do not work together and do not have clear roles and responsibilities. There is no training for emergencies unless it is required by one of the companies involved.

There is also a general lack of regulation and coordination between authorities operating in the HSE area internationally. The general opinion seems to be that regulations and authorities need to be ‘put in order’ nationally and internationally. There is a need to adjust onshore wind power standards take to into account the demands of working offshore, as well as coordinating inspections and follow-up of maritime, aviation and energy regulations. Within the Norwegian industry, there is an opinion that the expertise built up in the offshore petroleum industry should be utilised in the offshore wind energy industry. Many Norwegian actors in the offshore wind industry use their offshore petroleum expertise (in installation, maritime operations, etc.) in the international arena.

Experience of maintenance and modifications is limited, due to the relative youth of the industry. There are indications that the design of today’s offshore wind turbines is unsatisfactory when it comes to access (for maintenance work or renewing parts). The installations are not suited to the usual ergonomic demands of work. Much of the work must be carried out in narrow rooms; access is limited and sometimes very risky. Thus, proper HSE considerations should be taken into account in the design phase of offshore wind turbines.

6.1 Suggested actions

As a result of the project, we suggest the following actions to be taken:

- Several measures should be taken to ensure the HSE for offshore wind energy operation in Norway and internationally. There is a need for regulations that respect Norwegian interests and traditions within HSE when working on the Norwegian Continental Shelf and internationally.
- The responsibility for HSE regulations, inspections and audits should be clear and coordinated.
- Appropriate inspections and audits should be conducted.

- The phases of offshore wind energy farms should be regulated to ensure that attention is given to HSE factors at an early stage. This includes the fact that responsibility for HSE should be clear and unambiguous at all times and in all phases.
- In order to minimise collisions and interference from vessels, there should be established safety zones around offshore wind farms, equivalent to the safety zones around offshore petroleum installations.
- There is a need in the design phase, for HSE requirements that ensure sufficient attention is given to ergonomic considerations in work areas. This may require an international standard or guidelines as most concepts come from international industry and are “off the shelf”.
- The wind energy industry is international. Thus, cooperation between the relevant authorities in different countries is necessary.
- An offshore wind farm for research, testing and learning should be established.
- All experience of operation, maintenance, reliability and HSE development in the offshore wind power industry in Norway should be collected from an early stage. Databases for this purpose should be established. Contribution to, and use of data from such databases should be open to all actors and authorities.
- Emergency preparedness plans and training sessions should be established.

7 Conclusion

The offshore wind industry is a relatively new industry, not least in Norway. Concepts, designs and plans for operation are still under development. The first part of this report has shown some of the developing trends, and includes important information for HSE management of offshore wind farms.

Although offshore wind energy is a new development in Norwegian waters, it has been around for some years in other countries. This should mean that there is data available on HSE experiences from these countries. However, a literature review has revealed only limited and scattered information. Accident descriptions found in a database created by the Caithness Windfarms Information Forum, an organization not obviously in favour of wind farms, provided a good basis for incident descriptions. However, the database is built on descriptions from mass-media sources, which lack detail and are not transparent. These descriptions, combined with conversations with the industry and other reports (Gerdes et al., 2006; HSE, 2006; Sharples and Sharples, 2010), indicate that the most expected frequent incidents are:

- Falling objects during lifting operations
- Ship collisions within the wind farm
- Man overboard related to access to, and egress from turbines
- Occupational accidents related to working at height
- Challenges related to emergency handling

These are known accident scenarios for the maritime and offshore petroleum industry, as well as for some onshore industries. Still, they may play out very differently in the offshore wind power industry. This is not generally acknowledged, as the industry is quite new. Other scenarios, like structural failure, blade failure and ice throw, are more unfamiliar and only sparse information from onshore wind farms is available. These accident scenarios may evolve differently in offshore conditions.

We have not found significant differences between floating and fixed installations in terms of HSE. Some HSE improvements have been reported for floating pilot installations (e.g. less vibration in the Hywind turbine), but knowledge of floating installations in deep sea, far from shore, is still in the future and further experience may give insight into other HSE issues. Technology developments are aimed at more automated remotely operated and monitored offshore wind farms. This may reduce the risk level for workers if HSE factors are taken into consideration at an early stage. On the other hand, new risks may arise.

7.1 Need for further work

In addition to the issues listed in section 6.1, we would like to point out that the offshore renewable energy industry is immature in Norway. This limits the ability of this report to provide a clear vision of future HSE challenges. Consequently, further research is important and a possible test/research wind farm needs to include study of HSE factors and risk assessment. In addition, a safety management system which includes risk assessment, collection and use of experiential data, and emergency preparedness plans should be developed.

References

Atkinson, P (2010) Securing the safety of offshore wind workers. *Renewable Energy Focus.* Vol 11. No.3, pp. 34-36

Barrow (2009) Construction Monitoring Report Full. Available at: http://www.bowind.co.uk/pdf/post%20cmr%202009/Construction_Monitoring_Report-_Full_012009.pdf

Caithness Windfarm Information Forum (CWIF) (2010) Summary of Wind Turbine Accident data to 30th September 2010. Available at www.caithnesswindfarms.co.uk/fullaccidents.pdf

Deutsche WindGuard GmbH; University of Groningen; Case study: European Offshore Wind Farms – A Survey for the Analysis of the Experiences and Lessons Learnt by Developers of Offshore Wind Farms. Available at: http://www.offshorecenter.dk/log/bibliotek/POWER-CaseStudy.pdf

Douglas Westwood (2010): Offshore wind assessment for Norway.

Eggen, A.O., Heggset, J., Gjerde, O., Valland, A. and Nona˚s, L.M. (2008), "Deep sea offshore windturbine technology. Operation and maintenance – state-of-the-art study", restricted report, SINTEF, Trondheim

European Wind Energy Technology Platform - TPWind (2008) Strategic Research Agenda - Market Deployment Strategy from 2008 to 2030. Available from http://www.windplatform.eu/92.0.html

EWEA (2009): Oceans of opportunity.

Fraunhofer IWES (2009); Windenergie-Report Deutschland 2009 – Offshore erschienen.

Gerdes, G, Tiedemannm A and Zeelenberg, S. (2006). Case Study: European Offshore Wind Farms - A Survey for the Analysis of the Experiences and Lessons Learnt by Developers of Offshore Wind Farms. Available at www.offshore-power.net/informationsub.asp?Page=96&menu=7&submenu=240&type=submenuen&print=print

Google searches on use of helicopter transport:

HSE (2006) The health and safety risks and regulatory strategy related to energy developments. An expert report by the Health and Safety Executive contributing to the Government's Energy Review. Available at http://www.hse.gov.uk/consult/condocs/energyreview/energyreport.pdf

http://www.industrytoday.co.uk/energy-and-environment/wind-of-change-for-bristow
http://www.oilport.net/news/art.aspx?Id=17723

Industri Energi (2010) Vindmøller offshore. Letter submitted to the Norwegian Confederation of Trade Unions (LO)'s committee for Oil & Gas

International Electrotechnical Commission (2005): Wind Turbines, Part 3: Design Requirements for Offshore Wind Turbines.

Kentish Flats (2007) Kentish Flats Offshore Wind Farm 2nd Annual Report. Available at http://www.decc.gov.uk/assets/decc/what%20we%20do/lc_uk/ic_business/env_trans_fund/wind_grants/file50164.pdf

Kjeller vindteknikk (2010) Gjeitfjellet, Snillfjord, Sør – Trønderlag. Konsekvenser av atmosfærisk ising på produksjon og ferdsel. Report number KVT/KH/2010/R010. Retrieved from http://www.saevind.no/saevind/prosjekter/article46669.ece on Nov. 24th 2010.

Nitschke, J.; Kragelund, N; Thiede, J.; Fusselbaugh, M.; Johst, M.; van de Velde, F..(2006) Engineering Insurance of Offshore Wind Turbines. Paper presented at the 39th IMIA Annual Conference on 12 September 2006 in Boston.

Norges vassdrags- og energidirektorat (2010) Havvind. Forslag til utredningsområder. Oslo (url: http://www.nve.no/no/Nyhetsarkiv-/Nyheter/Havvind---forslag-til-utredningsomrader-/, retrieved Nov. 26th 2010)

Offshore Center Danmark, Rambøll 2004: Access to offshore wind turbines

Rausand and Utne (2009).Risikoanalyse – teori og metoder. Trondheim, Tapir akademiske forlag.

Salzmann, David Cerda (2009): Amplemann – The development of an offshore access system. Presentation at We@Sea Conference 2.12.2009

Sharples, M and Sharples, B.J.M (2010). Damage and Critical Analysis of Accidents to Assist in Avoiding Accidents on Offshore Wind Farms on the OCS. Report prepared for Minerals Management Service, Department of the Interior, US. Project No. 633, Contract M09PC00015. Available at www.boemre.gov/tarprojects/633.htm

The Crown Estate (2009): A guide to an offshore wind farm.

Vattenfall (2005). Horns Rev Offshore Wind Farm Annual Status Report for the Environmental Monitoring Programme 2005. Available at: http://www.vattenfall.com/en/file/Status_report_2005_8458745.pdf

Vattenfall (2008) Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark. Available at: http://www.vattenfall.com/en/file/100858_Horns_Rev_and_Nysted_C_7842546.pdf

Volden, Gro Holst; Bull-Berg, Heidi; Skjeret, Frode; Finne, Håkon; Hofmann Matthias (2009): Vindkraft offshore og industrielle muligheter. SINTEF rapport A12652

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