Chapter 2
Offshore Wind Energy System Components

2.1 Meteorological Systems

A meteorological mast (or met tower) is the first structure installed during the planning stages. The purpose of a met tower is to evaluate the meteorological environment and resource data within the project area. A mast consists of a foundation, platform with boat loading, meteorological and other instrumentation, navigational lights and marking, and related equipment (Fig. 2.1). A buoy may also be used.

A mast collects wind data at multiple heights by intersecting the wind with an anemometer to characterize the project area's meteorology. Sensors collect data on vertical profiles of wind speed and direction, air temperature and barometric pressure, ocean current velocity and direction profiles, and sea water temperature. The data from the meteorological mast serve to test power performance, perform due diligence evaluation, and facilitate estimates of operation maintenance management.

Permit authorizations for the installation of monitoring systems are obtained through the U.S. Army Corps of Engineers (Nationwide permits 5 and 6), the U.S. Coast Guard (private aids to navigation), and the BOEMRE (limited lease) or state leasing agencies.

2.2 Support System

The support system refers to the foundation, transition piece, and scour protection. The primary purpose of the foundation is to support the turbine. A transition piece is attached to the foundation to absorb tolerances on inclination and simplify tower attachment. Scour protection helps to ensure that ocean conditions do not degrade the mechanical integrity of the support system.

M. J. Kaiser and B. F. Snyder, *Offshore Wind Energy Cost Modeling*,
Green Energy and Technology, DOI: 10.1007/978-1-4471-2488-7_2,

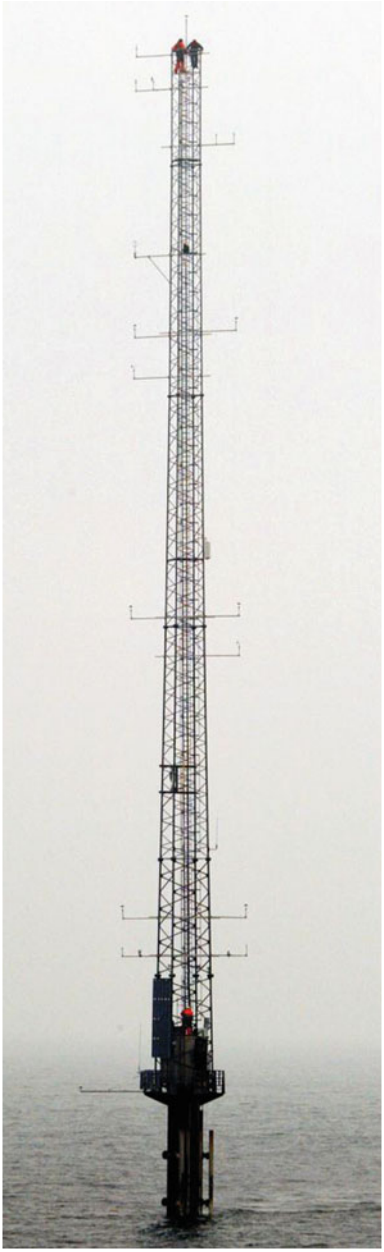

Fig. 2.1 Met tower at Horns Rev wind farm. *Source* DONG Energy

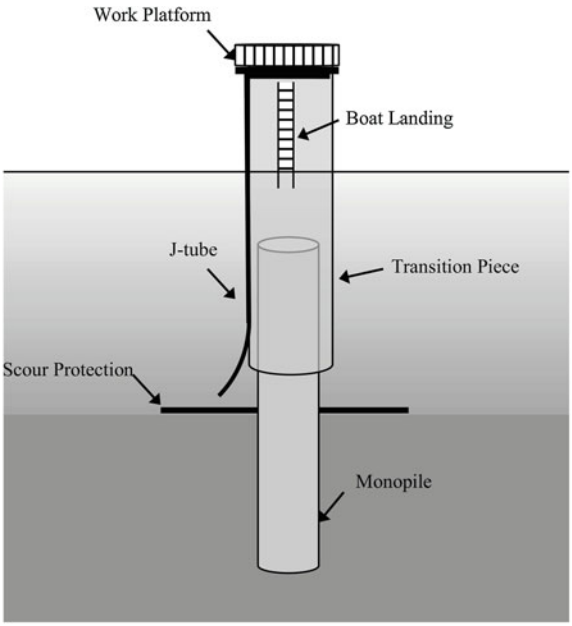

Fig. 2.2 Components of a monopile foundation

2.2.1 Foundation

Foundation technology is designed according to site conditions. Maximum wind speed, water depth, wave heights currents, and surf properties affect the foundation type and design. The size and weight of the turbine and tower are also key components. Within a wind farm, each foundation is customized to the water depth at its particular location.

Four basic types of foundations have been used in offshore wind farms: monopiles, jackets, tripods, and gravity foundation. Additionally, a single 2.3 MW demonstration turbine has been installed on a floating foundation. Foundations are prefabricated onshore in one piece, carried offshore by barge or other vessel, launched at sea, and set on bottom by a crane or derrick barge.

Monopiles
Monopiles are large diameter, thick walled, steel tubulars that are driven (hammered) or drilled (or both) into the seabed (Fig. 2.2). Outer diameters usually range from 4 to 6 m and typically 40–50% of the pile is inserted into the seabed. The thickness and the depth the piling is driven depend on the design load, soil conditions,[1] water depth, environmental conditions, and design codes. Pile driving is more efficient and less expensive than drilling. Monopiles are currently the most common foundation in shallow water (<20 m) development (Table 2.1) due to its

1 In soft soil regions, deeper piles and thicker steel are required.

Table 2.1 Estimated distribution of foundation types of offshore wind farms

Foundation type	Installed by end of 2008 (%)	Planned for 2009–2011 (%)	Projected for 2011–2020 (%)
Monopile	75	80	50–60
Concrete base	24	15	5
Jacket/tripod	1	5	35–40

Source Bluewater Wind 2010

lower cost and simplicity, but because they are limited by depth and subsurface conditions, they are likely to decline in popularity in deeper water. However, in nascent markets such as the U.S., and for the near term future, monopiles are expected to be heavily employed.

Tripods
Tripods consist of a central steel shaft connected to three cylindrical steel tubes through which piles are driven into the seabed (Fig. 2.3). Tripods are heavier and more expensive to manufacture than monopiles, but are more useful in deep water. The Alpha Ventus project is the only operating wind farm that employs tripod foundations (Fig. 2.4).

Jackets
Jacket foundations are an open lattice steel truss template consisting of a welded frame of tubular members extending from the mudline to above the water surface (Fig. 2.5). Piling[2] is driven through each leg of the jacket and into the seabed or through skirt piles at the bottom of the foundation to secure the structure against lateral forces. Jackets are robust and heavy structures and require expensive equipment to transport and lift. To date, jacket foundations have not been used extensively due to the preference for shallow, near-shore environments. At around 50 m, jacket structures are required. Jackets have been used for two of the deepest developments, Beatrice (45 m) and Alpha Ventus (30 m), supporting large 5 MW turbines. Jackets are also commonly used to support offshore substations (Fig. 2.6). Jackets can be used in deep water (100s of meters), although economic considerations are likely to limit their deployment to water under 100 m.

Concrete Structures
Gravity foundations are concrete structures that use their weight to resist wind and wave loading (Fig. 2.7). Gravity foundations require unique fabrication facilities capable of accommodating their weight (either drydocks, reinforced quays, or dedicated barges). Gravity foundations have been used at several offshore wind

[2] Monopiles, jackets, and tripods are attached to the subsurface using piles. However, designs could be modified to use suction caissons in which a cylindrical steel caisson (resembling an overturned bucket) is allowed to sink into the seabed under its own weight [1]. Suction is applied to the inside of the caisson and water is pumped out. The resulting pressure differential causes the caisson to be driven into the seabed.

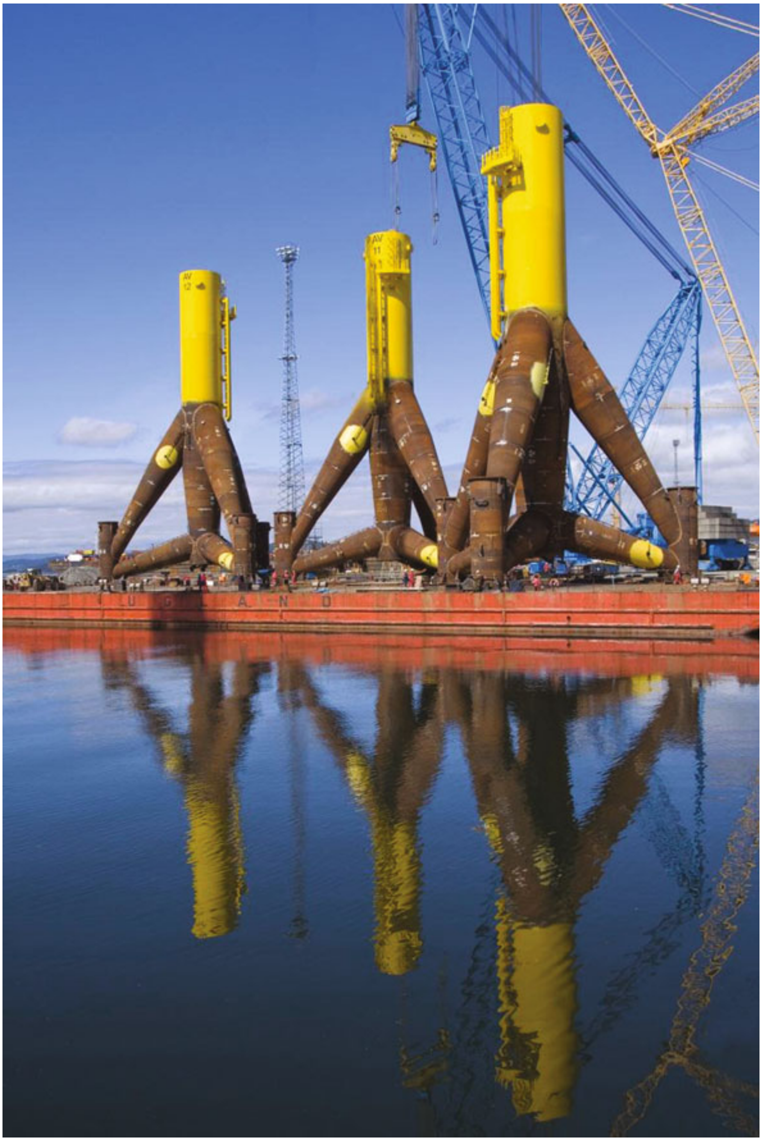

Fig. 2.3 Tripod foundations. *Source* Alpha Ventus

farms, including Middelgrunden, Nysted, Thornton Bank, and Lillgrund. Gravity foundations are less expensive to build than monopiles, but the installation costs are higher, largely due to the need for dredging and subsurface preparation and the use of specialized heavy-lift vessels (Figs. 2.8 and 2.9). The deepest gravity foundations in operation are in Thornton Bank (27 m). Gravity foundations are most likely to be used where piles cannot be driven and the region has dry-dock

Fig. 2.4 The Taklift 4 placing a tripod foundation at Alpha Ventus. *Source* Alpha Ventus

facilities for concrete construction [2]. Gravity foundations may also have an advantage in ice-prone regions [3].

In the North Sea, gravity foundations have been used in the offshore oil and gas industry, but in the U.S. there has been no use of concrete structures for offshore oil and gas operations and no plan to use them in offshore wind development. In Europe, gravity foundations will likely continue to fill an important niche for shallow to moderate water depth regions where drivability is a concern. However, they are unlikely to be used in U.S. waters.

Floating Structures
As water depth increases, the use of a steel platform will be limited by economic considerations. In the offshore oil and gas industry, the water depth limit for fixed platforms is about 450 m (1,500 ft), but in the offshore wind industry, the limit is likely to be less than 100 m because of economic conditions. Floating structures consist of a floating platform and an anchoring system. There are several alternative designs for floating turbine foundations all of which are variations on the spar and tension-leg concepts in the oil and gas industry (Fig. 2.10).

The Hywind concept is being developed by StatoilHydro. A pilot turbine was placed in waters off Norway in 2009 (Fig. 2.11). The foundation consists of an 8.3 m diameter, 100 m long submerged cylinder secured to the seabed by three mooring cables. Hywind was towed horizontally to a fjord and partially flooded and righted. Additional ballast was then added and the turbine installed on top. The assembled turbine was towed out to sea and the anchors were placed.

Fig. 2.5 A jacket foundation. *Source* Alpha Ventus

Blue H has developed a deep water concept based on the tension-leg platform. A prototype has been deployed off the coast of Italy and another is planned off the southern coast of Massachusetts. The Blue H concept consists of a two blade turbine placed on top of a buoyant, semi-submerged steel structure attached to a counterweight on the seabed. Plans are to assemble the turbine and foundation onshore and tow it to the offshore site.

Fig. 2.6 A jacket structure supports the substation at Alpha Ventus. *Source* Alpha Ventus

Fig. 2.7 Gravity foundations under construction for Thornton Bank. *Source* Luc van Braekel

Fig. 2.8 A gravity foundation being installed at Thornton Bank by the heavy-lift vessel *Rambiz*. *Source* Luc van Braekel

Fig. 2.9 The *Eide Barge* 5 lifting a gravity foundation from a barge at Nysted. *Source* DONG Energy

Fig. 2.10 The Hywind turbine and support structure. *Source* Statoil

2.2.2 Transition Piece

After the foundation is installed, a transition piece is placed on top of the foundation to create a level platform (Fig. 2.12). Transition pieces pass through most of the water column but do not rest on the seabed; boat fenders, access ladders, access deck, and handrails are attached on the outside. For monopile foundations, the gap between the pile and transition piece is normally filled with cement grout. For jackets and gravity foundations, transition pieces are installed in port and would not require a separate offshore lift, and do not contain boat landings, electrical conduits, or other accessory components as these are installed elsewhere on the foundation.

2.2.3 Scour Protection

When a structure is placed in a current and the seabed is erodible, scour may lead to structural instability. Scour refers to the removal of sediment from the area

Fig. 2.11 The Hywind turbine being towed offshore. *Source* Oyvind Hagen/Statoil

Fig. 2.12 Transition piece ready to be lowered on the monopile at Horns Rev II. *Source* DONG Energy

around the base of a support structure. Scour protection requirements depend on the current and wave regime at the site, substrate, and foundation type. Low tech and relatively inexpensive methods are usually adequate to address the problem. Commonly employed measures of scour protection include dumping rock of different grade and placing concrete mattresses around the foundation. For monopile foundations, a layer of small rocks may be installed prior to or following pile driving; later, after cabling is installed, large cover stones may be placed around the foundation [4]. Monopiles, gravity foundations, and tripods require significant scour protection, while piled jackets require little or no scour protection [5–7].

2.3 Wind Turbine

The wind turbine is composed of a tower, nacelle, hub, and blades. The blade/hub assembly is called the rotor. The tower is attached to the transition piece, and the nacelle is attached to the tower; the rotor is attached to the nacelle (Fig. 2.13). There are several different options for installation which will be discussed in Chap. 5.

Offshore turbines range from 2 to 5 MW and typical weights are shown in Table 2.2. Component size and weight varies with the electrical capacity of the turbine, the rotor dimensions, and the selection of blade, hub, and nacelle material and equipment. Turbines are an established commodity but offshore technology is in the early stages of evolution and will continue to develop. In 2011, Vestas released plans for a 7 MW offshore turbine and Siemens installed a prototype 6 MW gearless model. Sway plans on installing a prototype 10 MW turbine in late 2012.

Tower

Towers are tubular structures consisting of steel plate cut, rolled, and welded[3] together into large sections. The tower provides support to the turbine assembly and the balance of plant components, including a transformer located in the base,[4] a yaw motor located at the top, and communication and power cables. The tower also provides a ladder and/or an elevating mechanism to provide access to the nacelle. In installation, tower sections are bolted to each other during assembly, or are preassembled at port. Tower height is determined by the diameter of the rotor and the clearance above the water level. Typical tower heights are 60–80 m giving a total hub height of 70–90 m when added to the foundation height above the water line. Tower diameter and strength depend on the weight of the nacelle and expected wind loads.

[3] Manufacturers purchase steel as hot-rolled plates which are cold rolled and welded using standard machinery.

[4] The turbine transformer is either located up tower in the nacelle or at the base of the turbine (down tower). Turbine transformers take the energy generated by the turbine and convert it to approximately 34.5 kV for connection with the collection system.

Fig. 2.13 An assembled rotor being lifted onto a nacelle at Nysted. *Source* DONG Energy

Table 2.2 Weights of commonly used offshore turbines

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

Source Company data

Nacelle

The nacelle houses the generator and gearbox and monitors communications, control, and environmental maintenance of the equipment (Fig. 2.14). The nacelle is principally composed of a main frame and cover. The main frame is the element to which the gearbox, generator, and brake are attached, and must transmit all the loads from the rotor and reaction loads from the generator and break to the tower [8]. Nacelles are large units and typically the heaviest and highest lift and play an important role in determining installation vessel suitability. The relative size of a nacelle is depicted in Figs. 2.15 and 2.16.

Hub

The hub is a cast steel structure which transmits horizontal wind loads from the blades to the nacelle and rotational energy to the gearbox via a low speed shaft.

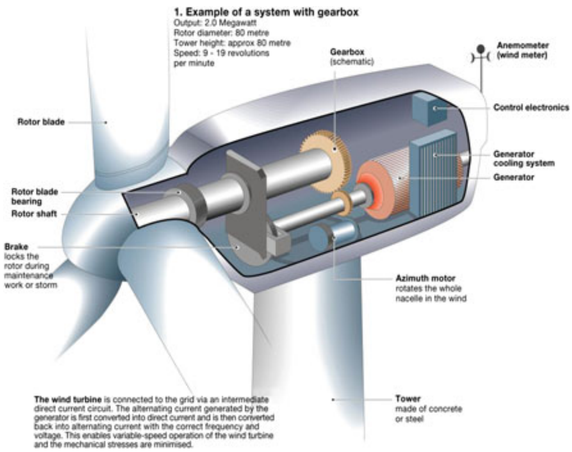

Fig. 2.14 Diagram of a nacelle. *Source* German Renewable Energies Agency

The hub is one of the most highly stressed components of the turbine [9] and may contain motors for controlling blade pitch.

Blades
Blades are airfoils made of composite or reinforced plastics. The blades are bolted to the hub either onshore or offshore. Due to the construction materials low weight and long length (50–60 m), blades are sensitive to high winds during lifting operations. The size and shape of assembled configurations complicate onshore and offshore transport.

2.4 Electricity Collection and Transmission

Cables connect the turbines and the wind farm to the electrical grid. Collection cables connect the output of strings (rows) of turbines depending on the configuration and layout of the wind farm. The output of multiple collection cables is combined at a common collection point or substation for transmission to shore (Fig. 2.17).

Inner-Array Cable
The inner-array cables connect the wind turbines within the array to each other and to an offshore substation if present. The turbine generator is low voltage (usually, less than 1 kV, often 500–600 V) which is not high enough for direct interconnection to other turbines. A turbine transformer steps up the voltage to 10–36 kV for cable connection. Inner-array cables are connected to the turbine transformer and exit the foundation near the mudline. Cables are buried 1–2 m below the mudline and connected to the transformer of the next turbine in the string. The power carried by cables increases as more turbines are connected and the cable size or voltage may increase to handle the increased load. Installation of

Fig. 2.15 Relative size of a nacelle. *Source* Siemens

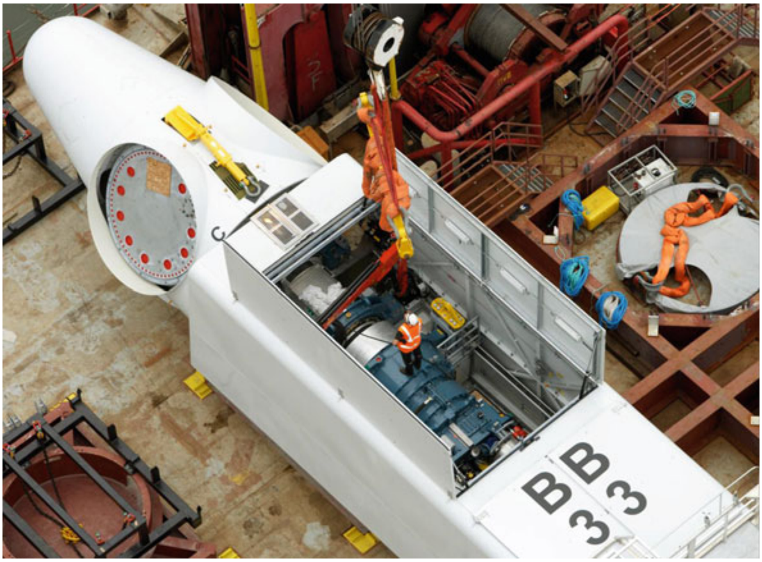

Fig. 2.16 Relative size of a nacelle. *Source* Siemens

connection cable is performed in discrete steps from turbine to turbine. The amount of cabling required depends on the layout of the farm, the distance between turbines, and the number of turbines.

Export Cable

Export cables connect the wind farm to the onshore transmission system and is typically installed in one continuous operation. Export cables are buried to prevent exposure, and in some places, may require scour protection. At the beach, cables

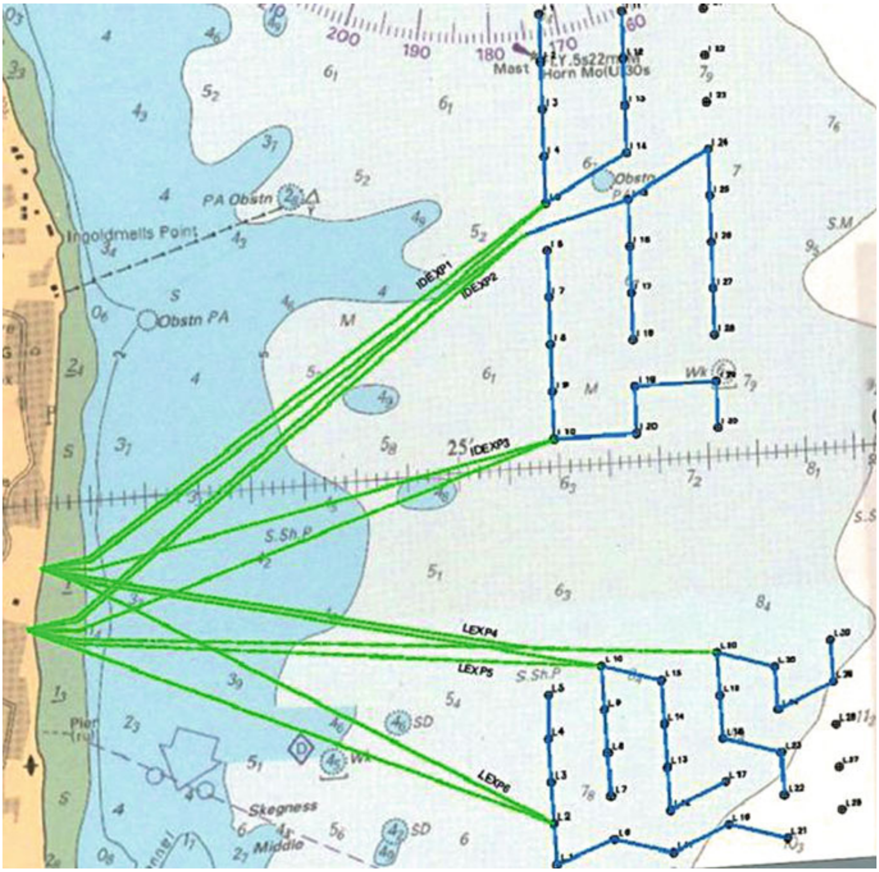

Fig. 2.17 Inner-array and export cable layout at Lynn and Inner Dowsing. *Source* Siemens

come onshore and may be spliced to a similar cable and/or connected to an onshore substation. Water depths along the cable route, soil type, coastline types, and many other factors determine the cable route, time, and cost. At the onshore substation or switchyard, energy from the offshore wind farm is delivered to the power grid. If the point of interconnection (POI) voltage is different from the submarine transmission, transformers are used to match the POI voltage; otherwise, a switchyard is used to directly interconnect the wind farm. At this point, power generated is metered and purchased via a PPA with a local utility or by entering the Independent System Operator's merchant market.

Export cables are composed of three insulated conductors protected by galvanized steel wire. Medium voltage cables are used when no offshore substation is installed and usually range between 24 and 36 kV. High voltage cables are typically 110–150 kV and are used with offshore substations. High voltage cables have the capacity to carry more power than a medium voltage cable but are heavier and

Fig. 2.18 Substation being lifted onto monopile at Gunfleet Sands. *Source* Offshore Wind Power Marine Services

wider in diameter. High voltage cable may weigh 50–100 kg/m while medium voltage cable may weigh 20–40 kg/m.

2.5 Offshore Substation

The purpose of an offshore substation is to increase the voltage of the electricity generated at the wind turbine to minimize transmission losses. The substation is sized with the appropriate power rating (MVA) for the project capacity, and steps up the line voltage from the collection system voltage to a higher voltage level, usually that of the POI.

All offshore wind farms require substations but not all substations are located offshore. The need for offshore substations depends upon the power generated and the distance to shore which determines the tradeoffs between capital expenditures and transmission losses [10]. The components of offshore substations include voltage transformers, switchgear, back up diesel generator and tank, accommodation facilities, j-tubes, and medium- and high-voltage cables. Substations are positioned within the wind farm at a location that minimizes export and inner-array cable distance. Substations are typically 500 tons or more and are placed on foundations similar to those used for turbines (Fig. 2.18). Onshore substations also include equipment to monitor power quality, such as voltage stability and harmonic disturbances, and SCADA systems allow the behavior of the entire system to be monitored and controlled.

2.6 Commissioning

Commissioning refers to the activities after all components are installed but before commercial operations begin. This includes electrical testing, turbine and cable inspection, and related quality control activities. The communication and control systems are tested to enable the turbine controllers to be accessed remotely from the control room.

References

1. Byrne B, Houlsby G, Martin C, Fish P (2002) Suction caisson foundations for offshore wind turbines. Wind Eng 26(3):145–155
2. Volund P (2005) Concrete is the future for offshore foundations. In: Proceedings of Copenhagen Offshore Wind, Copenhagen, 26–28 Oct 2005
3. Volund P, Jorgensen LB, Gravesen H, Sorensen SL, Pedersen B, Lorenz RS, Miller R, Ostergaard S, Riber HJ, Pedersen J, Gjerding JB (2003) Ice loads on offshore wind turbine foundations. Energi E2 #15822
4. Gerwick BC (2007) Construction of marine and offshore structures, 3rd edn. Taylor and Francis, Boca Raton
5. Den Boon JH, Sutherland J, Whitehouse R, Soulsby R, Stam CJM, Verhoeven K, Høgedal M, Hald T (2004) Scour behaviour and scour protection for monopile foundations of offshore wind turbines. European Wind Energy Conference, London, 22–25 Nov 2004
6. Seidel M (2007) Jacket substructures for the REpower 5 M wind turbine. European Offshore Wind Conference, Berlin, 4–6 Dec 2007
7. Larsen JHM, Soerensen HC, Christiansen E, Naef S, Vølund P (2005) Experiences from Middelgrunden 40 MW offshore wind farm. Copenhagen Offshore Wind Conference. 26–28 Oct 2005
8. Manwell JF, McGowan JG, Rogers AL (2002) Wind energy explained-theory design and applications. Wiley, New York
9. Hau E (2006) Wind turbines: fundamentals, technologies application economics. Springer, Berlin
10. Wright SD, Rogers AL, Manwell JF, Ellis A (2002) Transmission options for offshore wind farms in the United States. In: Proceedings of the American Wind Energy Association Annual Conference, 1–12 2002