CHAPTER 11

Offshore wind turbine design

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Offshore wind plants have become a real option in the EU countries when onshore wind plants quickly occupy the prime land for wind energy generation. This chapter reviews the state of the art and some of the technical challenges anticipated during the development of U.S. offshore wind power plants in the U.S. It highlights challenges that are unique to the coastal U.S., e.g. hurricanes, in addition to the general challenges for the offshore wind industry, irrespective of geographical location. It will be shown that experience from the oil and gas industry is not completely applicable to the wind industry, although it certainly should be leveraged and modified to fit the unique needs of offshore wind. Finally, some of the research needed to further address these challenges are outlined.

1 Introduction

Offshore wind presents a tremendous opportunity for the United States and Europe. Onshore wind plants often face land use disputes, noise, and visual impact obstacles. Moving wind plants offshore not only mitigates these problems, but provides other important advantages including:

- Availability of large continuous areas suitable for major wind plants
- Higher wind speeds, which generally increase with distance from the shore
- Less turbulence, which allows turbines to harvest energy more effectively
- Reduced fatigue loads on the turbine
- Lower wind shear allowing shorter towers
The United States enjoys significant onshore and offshore resources. While onshore plants are more cost effective to develop than offshore ones, some of the onshore sites in the U.S. have the following disadvantages:

- They are away from the population centers in the U.S. More than half of the United States population lives at or near shore.
- Similarly (and perhaps as a consequence of 1 above), these onshore resources are away from the grid connections.
- They are mostly in areas which do not have significant electricity demand thus depressing electricity prices in those areas and upsetting the economical structure for wind developers.

On the other hand, some regions of New England and the Mid-Atlantic states have some of the highest electricity prices, thus making wind and other (generally more expensive) renewable energy sources more cost effective. East coast states also have high land usage preventing the development of onshore wind plants or even the development of fossil-based onshore power generation stations. These states also have readily available grid connectivity close to the shore where most of the population is located.

While onshore wind plants are well understood, offshore installations present unique challenges to the wind industry, particularly as coastal communities demand them to be placed further off shore. These challenges are discussed in the following sections.

2 Offshore resource potential

Significant offshore wind energy resources are available in the United States. Figure 1 shows the U.S. wind power resource with superb wind power availability around the coastal areas. Table 1 shows the offshore wind resources along U.S. coast. Looking at Fig. 1 and Table 1, one could argue the United States enjoys significant wind resources inland, and much of these resources are in mid-western states with limited land use or visibility issues. However, while development of these inland areas is more cost effective than offshore plants, they are unlikely to be fully developed for several reasons:

- Distance from population centers – more than half of the U.S. population lives at or near a coastline. Developing midwestern sites results in significant energy transportation costs.
- Distance from grid – similarly, available inland resources are not near grid connections.
- Low local demand – available midwestern sites primarily fall in areas which do not have significant electricity demand, thus depressing electricity prices in those areas.

On the other hand, it is clear that both New England and the mid-Atlantic regions have significantly more offshore wind resource than is available on land. In addition, New England and the mid-Atlantic states have the highest electricity prices, thus making wind and other renewable energy sources more cost effective. East coast states also have higher land usage, which tends to prevent development of inland
wind power plants, or even development of other types of power generation stations. Finally, these states have readily available grid connectivity close to shore and the major population centers.

### 3 Current technology trends

Trends in the global wind industry are pushing toward larger, multi-megawatt turbines. Currently, Vestas has produced more than 740 MW of offshore turbines consists mostly of the V90 3 MW turbines. A new V120 4.5 MW turbine from
the NEG MICON merger is in the works. GE holds a 3.6 MW turbine specifically for the offshore market and just acquired a 3.5 MW direct-drive product through merger with SCANWIND. REpower, Multibrid, and Enercon are known to be testing designs in the 5–7 MW and >100 m rotor diameter range. Nordex has a 2.5 MW N90 offshore product. On the more advanced pace, Siemens is demonstrating their 2.3 MW 93 m rotor turbine on a floating foundation suitable for deep water and has a 3.6 MW 120 m rotor turbine in the pocket. Gamesa recently introduced an advanced compact G10X 128 m rotor 4.5 MW turbine with a 120 m concrete tower that might serve as a low cost offshore wind turbine in the future.

The current industry trend to increase turbine power and blade sizes is based on two fundamental assumptions. First, the trend assumes that the cost of foundations and other balance-of-plant items do not increase linearly with the turbine’s power. Second, the assumption is made that the cost of operating and maintaining a smaller number of bigger turbines is lower than operating and maintaining large number of smaller turbines.

In reality, offshore plants break both assumptions almost completely. With existing technology, foundation costs increases significantly as the plant is placed at deeper sites. Similarly, operations and maintenance costs also increase as plants are placed further offshore. Therefore, when considering offshore plants, it is no longer true that industry should blindly head toward larger turbines. With offshore plants, turbine size is not the only factor of importance unless the push toward increasing turbine sizes is coupled with significant reductions in foundation, operation and maintenance costs, as well as improvements in reliability and availability, to achieve the potential and viability of offshore wind power plants.

4 Offshore-specific design challenges

Significant wind turbine design innovations are required for offshore environment. Characterizing the potential development barriers and identifying the technologies to overcome them will be the important aspects of these innovations. Offshore wind plants present challenges that can be broadly grouped into three categories:

- Economic challenges
- 25-m barrier challenge
- Design envelope challenge

4.1 Economic challenges

The capital cost of offshore wind plant foundations increases as sea depth increases. While the current onshore wind plant foundations represent around 10% or less of the total overall capital cost, the foundation cost jumps to 20% simply by placing the turbine offshore. As shown in Fig. 2, the foundation contribution to the overall capital cost steadily increases as the sea depth increases. As foundations do not directly contribute to any increase in generating power, the increased cost of foundations directly increases the cost of electricity.
Due to the cost increase along with increasing depth, the often-encountered local public demands to place the offshore plants further from the coastline results in increased sea depth due to the reduction of available shallow seabed. For example, the area with depth less than 20 m off Dutch North Sea coast, which is well fit for offshore development, reduces about 2/3 from 8 km to 12 miles away from the coast (Table 2). Hence moving wind plant further into the sea will in general increase the cost of foundation and eventually the cost of electricity.

### 4.2 25-m barrier challenge

The U.S. wind energy industry currently faces what is termed the “25-meter barrier” challenge. Simply put, this means that wind plants placed deeper than 25 m are essentially outside of the existing technical capabilities for manufacturing and construction limitations as well as design limitations.

- Manufacturing and construction limitations:
  - Even in benign soil conditions, monopile foundation, which is the most popular offshore wind turbine foundation currently, needs a diameter that reaches 5.5 m

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**Figure 2:** The foundation contribution to the overall capital cost steadily increases as the sea depth increases [3].

**Table 2:** Dutch North Sea offshore wind available area vs. distance to coast [4].

<table>
<thead>
<tr>
<th>Distance to coast</th>
<th>Depth &lt; 20 m</th>
<th>Depth &lt; 40 m</th>
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<tbody>
<tr>
<td>&gt;8 km</td>
<td>1,700</td>
<td>22,000</td>
</tr>
<tr>
<td>&gt;12 miles</td>
<td>680</td>
<td>20,000</td>
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with a thickness extending to 90 mm at 25 m water depth from around 5 m and 50 mm accordingly at 10–12 m depth. The resulted weight could be 250 metric tons. This level of dimensions and weights stretch the maximum capability of the fabrication factories and installation vessels to their limits. In fact, only a few vessels in the world can even handle the hammering requirements of such a large pile.

- **Design limits:**
  - At 25 m depth, and for a hub-height of approximately 75 m above sea level, a monopile foundation’s natural frequency becomes dangerously close to the turbine’s natural frequency. The engineering solution is to increase either pile diameter or thickness, which is either at the manufacturing limit or at the construction limit already.

### 4.3 Overcoming the 25-m barrier

Due to these manufacturing and design limitations, the 25-m barrier is quite real, especially as coastal communities demand wind power plants to be placed even farther offshore. However, overcoming the 25-m depth is not without precedent and this gives strong hope for the wind industry to cross the barrier.

Before 1996, the gravity foundation was the industry’s standard offshore foundation. However, in 1996, the industry reached the gravity foundation potential, approximately 7.5 m deep. Danish research performed in 1996–1997 recommended Danish wind industry to use monopile foundation for the deeper sites. Since then, the monopile has become the primary foundation choice for the offshore wind industry.

As an additional benefit from the 1997 monopile development, overcoming the gravity foundation depth limit gave Danish companies a significant lead in the offshore wind development race. While the offshore challenges are more significant for the United States as compared with European sites for reasons such as higher waves, susceptibility to hurricanes, and increased wave breaking energy, the 25-m barrier presents the United States with a significant opportunity for technology breakthrough and leadership in the offshore wind industry.

The opportunity exists for the United States to spearhead a development effort similar to the European effort to break the 7.5-m barrier. Because of the coastal community demands for farther offshore deployment location, overcoming the 25-m barrier will be the enabler for the growth of the offshore wind power plants market in the United States.

The offshore wind challenges are not without parallel in other U.S. industries, particularly oil and gas. Given its offshore oil and gas experience, the United States is ideally suited to assume the lead on attacking the 25-m barrier challenge. However, it would be a mistake to assume that the solution amounts to the direct translation of the oil and gas experience to the wind industry.

The magnitudes of loads affecting oil and gas structures are much higher than those affecting wind energy structures. However, force magnitudes are neither the sole factor nor the most important one affecting foundation design. The ratio between over-turning moment and vertical load is known as “eccentricity” and is
by far the most important factor governing foundation geometry and shape. This ratio is several orders of magnitude higher in wind energy structures than in the oil and gas structures.

Hence the foundation design to break the 25-m barrier needs significant research and development efforts pertinent to the wind industry-specific situations on top of leveraging the oil and gas experience.

4.4 Design envelope challenge

Wind turbines operate in uncertain environments. There is currently an insufficient understanding of the design envelope that accurately and probabilistically characterizes the extreme conditions off the United States northeast and mid-Atlantic coasts. Because of this, several challenges must be considered when developing new wind turbines.

4.4.1 Wind speed assumptions

The currently accepted wind turbine and foundation design envelope, such as the one used for the GE 3.6 platform, was developed by the IEC and adopted by Germanischer Lloyd AG in Hamburg, Germany. This design envelope specifies Class I wind turbine plants be designed for 50-year recurring, 10-min average wind speeds of 50 m/s and 5-s wind gusts of 70 m/s. However, it is not clear how closely these extreme design assumptions, developed based on European onshore experiences, will apply to U.S. regions that host offshore plants.

4.4.2 Turbulence ratio

A common wind industry practice calls for utilizing a 12% turbulence intensity for offshore sites [5]. This is based, again, on European experiences and it is not yet clear whether this is truly representative of potential U.S. sites.

4.4.3 Hurricanes

U.S. east coast is susceptible to hurricanes. The presence of hurricanes or typhoon is unique to the U.S. and Asian-Pacific areas because there is no similar scale storm hazard in Western Europe where the offshore wind technologies were pioneered. Although U.S. offshore construction and foundation design codes of practice have acquired significant expertise in understanding the impact of hurricanes in the Gulf of Mexico, this expertise may not be all transferable to the wind industry along the upper east coast.

In the northern hemisphere and because of their counter-clockwise rotation, hurricanes generally have lower wind speed at their western or left side compared with their eastern or right side as shown in Fig. 3. In the Gulf of Mexico where landmass largely extends east to west, oil and gas installation must be designed for the maximum wind speed of the hurricanes on its eastern side. For the wind industry, which focuses mainly on the east coast of the United States currently, landmass extends roughly south to north. It is less likely that the eastern side of a hurricane will affect a wind power plant unless the hurricane makes prior landfall and hence losing half or more of its energy (Fig. 4).
Nevertheless, the probability of encountering the sustaining maximum hurricane wind speeds on its eastern side increases as wind power plants move further offshore, i.e. further east. An internal study at GE showed that although the eastern tip of Long Island is unlikely to sustain hurricanes above level 2, moving 150 miles westward increases that probability significantly (Fig. 4). The effect of hurricanes on the low cycle fatigue and design wind gust speed is not known and represents one of the risks in developing offshore wind projects in the northeast and mid-Atlantic U.S. Technologies and methods need to be developed to accurately characterize the impact of hurricanes on the design envelope for both the turbine and the foundations in the target offshore locations.

4.4.4 Geotechnical conditions
While designing wind power plants, the geotechnical conditions account for most of the rest of uncertainties encountered other than Hurricane. Engineers normally
demand to collect borehole soil samples at each turbine locations. However, this increased the plant development costs significantly. Moreover, it is not clear if a geotechnical program comprising boreholes at every turbine site, which is referred to as “full coverage”, would significantly reduce the overall geotechnical risk. Studies performed by the oil and gas industry show the full coverage might be unnecessary as long as adequate information exists regarding the overall geological structure in the area, which can be synthesized utilizing non-intrusive geophysical measurement techniques. There exists a need in the wind industry to quantify the increased risk associated with less than full coverage of all turbine sites based on the synthesized geological and geophysical knowledge on the general plant area. Subsequently the marginal risk reduction from each additional borehole can be traded-off with the increasing investigation costs. Some boreholes will always be needed to get an idea about the real soil conditions across the site. However, there may not be a need for a borehole under each turbine.

4.4.5 Mud-line evaluation
At the end of foundation design life or immediately after severe storms, no techniques exist to evaluate foundation conditions below the mud-line. Effective above-the-mud-line evaluation techniques do exist to identify cracks using eddy circuits or visual observations. However, these techniques cannot be easily transferred to foundation sections below the mud-line. Moreover, there are no techniques to assess soil condition, which is an important element of the overall system condition. Technologies such as digitally extract soil density images with high-frequency ultrasound techniques before and after severe storms need to be developed to answer the critical questions over wind power plant residual life.

The above challenges are barriers to synthesize accurate design envelope that can be used to design the wind power plant system including the turbine and the foundation. These challenges stem from the uncertainty associated with the offshore wind environment. In developing that design envelope along with the uncertainty associated with the above challenges, it is the key to work within a probabilistic framework that provides feedback on the changing risks and costs. This will aid wind power plant developers, owners and design engineers to trade-off effectively based on cost and risk for decisions.

4.4.6 Sediment transportation
At the offshore wind power plant seabed level, the wave and current constantly transport the sediments around to morph the landscape. This effect could expose the embedded portion of the turbine foundation and produce problem later on during the plant life along with scoring. Anti-scoring typically involves expensive operations to lay stone layer around the foundation. New innovations utilizing plastic/rubber mat material has been tested to mitigate this problem. Its long-term effectiveness need to be checked. More global sediment transportation effects need to be evaluated additionally during the site survey period.
4.4.7 Unique U.S. challenges and oil and gas experiences

There are other challenges that are more significant in the U.S. compared with potential European sites:

1. Because of the longer fetch length, wave heights are significantly higher in the open Atlantic Ocean than in the most challenging European sites in North Sea. The most utilized extreme wave power spectral density function is modified Pierson-Moskowitz (PM) spectrum [6]. It assumes a fully developed sea, i.e. all the wind energy has been imparted to the sea over an infinite fetch length. However, in many coastal situations, that may not be the case and much smaller fetch lengths may exist. The Joint North Sea Wave Project (JONSWAP) proposed the JONSWAP spectrum [7, 8] that includes scale parameters for the fetch length. The marked difference between PM and the JONSWAP spectrums is that JONSWAP is significantly more peaked. The shorter the fetch length, the more peaked JONSWAP becomes. Over long fetch lengths, the sea receives more energy from wind shear and has more opportunity to develop random waves with more variable spectrum of wave heights and lengths. So the JONSWAP spectrum experience may need amendments when it is applied to the U.S. coastal wave evaluation.

For offshore structures, Germanisher Lloyd has certification requirements for applying both wind and wave loads on offshore wind turbine without being too conservative. For fatigue analysis, load spectra are to be determined which include the influences to be considered for the wind turbine plus those from wave, currents, and sea-ice [9]. These load cases are also common with the oil and gas industry and are largely borrowed from that industry. However, it has to be carefully reconsidered and studied for the U.S. market. The first reason is that wave heights in the Atlantic are on the average higher than those in the North Sea since North Sea and Baltic Sea coasts have shorter fetch lengths and lower wind speeds compared with the U.S. North Atlantic coasts. Figure 5 shows the 95% confidence intervals for the long-term Weibull distribution of the probability of the extreme significant wave heights. Figure 5 shows that the

![Figure 5: Wave heights in the U.S. east coast and Europe [3].](image-url)
North Atlantic has 30% higher wave heights on the average compared with North Sea. It is worth noting that the 30% difference can be accounted for almost exactly using the JONSWAP spectrum [8]. The higher significant wave heights in U.S. pose many challenges for the structural modeling and design.

2. Back to the hurricane problem at the turbine design level, the current wind turbines are typically designed for up to IEC class 1 wind load, which can be roughly translated to a maximum wind speed between the Hurricane category 1 and category 2 conditions. However, many population centers along the U.S. east coast are hit by higher than category 2 hurricanes in a frequency higher than once per 50 years. So the safety of the offshore wind turbine erected near these regions could be a challenge to the system and structure design.

3. Wave breaking occurs when the ratio between the wave height and the sea depth exceeds a certain limit. Furthermore, in certain circumstances wave breaks as plunging wave instead of surging wave, which can cause significantly more fatigue load force on any structural element present at the breaking point. At a UK experimental offshore wind power plant in Blyth Harbour, one of the towers was erected at a wave breaking point and sustained significantly increased fatigue load. A study of wave breaking probability in U.S. sites vs. European sites shows that the probability of plunging wave breaking is about the same. However, because the U.S. sites have higher wave heights and are deeper in depth, the plunging wave could break with as much as four times the energy of its European counterparts.

There are many breaking wave theories available in the literature. The simplest and oldest model is:

\[ H_b = 0.78h \]  

where \( H_b \) is the wave breaking height and \( h \) is the sea depth. A little more sophisticated equation that considers the sloping seabed effect is termed the Goda expression:

\[ H_b = 0.071\tanh(kh) \]  

Many other theories exist in the literature with varying degree of complexity. Anastasiou and Bokaris [10] evaluated 19 of the hypothetical expressions available in the literature against their own data and found the two simplest equations above to be the most accurate ones. On the contrary, Kriebel [11] found that other equations to be better using different sets of data. So there is a high degree of disagreement that may never be resolved because of the complex and uncertain nature of the wave breaking phenomenon. However, it is possible to devise a methodology to generate a site-specific wave breaking prediction by fusing the site-specific short-term observations, the 3D bathymetry measurements, and the known wave breaking models. This task is not easy given the fact that the local current has impact to the wave breaking condition because increased current velocity increases the probability of wave breaking. The final prediction should be based on site-specific measurements to calibrate known physics and models. It should also be included as part of the wind turbine certification process for the site.
Above-mentioned challenges are certainly not new if we consider the significant oil and gas installations around the world. However, it is erroneous to make the assumption that overcoming these challenges amounts to direct translation of the oil and gas experience to the wind industry. Table 3 illustrates key differences between the two industries in terms of technical requirements.

Table 3 shows that magnitudes of loads affecting oil and gas structures are much higher than those affecting wind energy structures. However, the ratio between the over-turning moment and the vertical load, i.e. “eccentricity” which governs the foundation geometry and shape, is several orders of magnitude higher in wind energy structures than it is in the oil and gas structures. This problem is compounded by (1) the fact that non-dimensional ratio between eccentricity and the structure’s width in the wind turbine structures will be even higher than in the oil and gas structures, and (2) the heavily dynamic nature of the loads. Therefore, a straightforward translation of foundation shapes and designs from offshore oil and gas structures to offshore wind structures is simply not feasible.

In addition to the design limitations, there are other factors that differentiate the oil and gas experience from the wind energy structures needs:

1. In contrary to one giant oil and gas offshore platform installation, a wind power plant normally consists of tens to hundreds of identical turbine installations. Therefore, experience with assembly-line techniques and the associated compartmentalization, modularization, and quality control with six-sigma methods become more relevant.

2. It is certainly economical to have $100 million worth of platform foundations to produce crude oil equivalent to hundreds of megawatts worth of electricity from one oil and gas platform. If the same foundations are translated to the wind industry, its cost must be in the neighborhood of one million dollar for the overall economics to work.

On the other hand, ruling out direct translation of foundation designs from the oil and gas industry to the wind industry does not mean that wind turbine foundation designs should or need to start from a clean sheet of paper. The new research
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and development for offshore wind industry need to be based on the oil and gas experience that can be leveraged. This requires collaboration between the wind turbine manufacturers, who command the necessary understanding of loads, mass production issues, and the overall system design and economics trade-off issues, and the world-class institutions with specific expertise in developing oil platforms foundation technologies.

4.5 Corrosion, installation and O&M challenges

Corrosion, installation and operation and maintenance challenges are also essential to the success of the offshore wind power plant.

Most offshore wind turbines components have been coated, cathode protected and/or sealed per the typical naval military standards (MIL) to protect them from the excessive corrosive environment offshore. However, severe corrosion problem has still been observed on a major EU OEM’s electrical system and resulted in very expensive large-scale replacement of the electrical components in the field. Hence identifying the difference in the corrosion root cause between the naval vessel and the offshore wind turbine is something that needs further exploration.

On top of the corrosion issue, the installation of the offshore wind turbines, foundations and electrical infrastructures has been a major cost and schedule challenge due to

- The uncertainty in the weather, wave, current and soil conditions.
- The involvement of specialized large installation service equipments such as large hammers for pile driving and jack-up vessels for crane and general handling of the turbine.

To make large offshore wind project feasible, new installation concepts, technologies and equipments are needed to reduce the overall installation cost and extend the installation window period.

Furthermore, the operation and maintenance of the offshore wind plant requires special access capability to and survivability on the wind turbine in a variety of wind and wave combined conditions. Boat access is slow and the landing to the turbine can be dangerous even in the normal wave conditions. Helicopter-based access has been developed and preferred for its flexibility and speed. It requires special landing pad design for the turbine though. Many efforts have been invested in the condition-based monitoring (CBM) systems to minimize the need for human access.

4.6 Environmental footprint

There is a need to have independent and scientifically based studies on the true environmental footprint of offshore wind power plants. Expertises exist with regards to assessing environmental footprint, particularly on naval mammals and fish schools, in the north-eastern U.S. with institutions such as the joint marine biology program between MIT and Woods Hole Oceanographic Institution. These
unique expertise need to be leveraged in order to gain better understanding of the environmental footprint of offshore wind power plants.

5 Subcomponent design

The two key technology drivers for any offshore wind project design are:

- Achieving maximum turbine reliability to minimize the total cost of ownership;
- Designing cost-effective foundations.

These technology drivers stem from the offshore wind power plant environment with offshore site location, extreme weather conditions and limited accessibility throughout the year. Given these drivers, the total cost of ownership per kWh of electricity produced is a top-level critical figure-of-merit. It is also constrained by the popular demand for the placement of plants farther offshore. Significant effort on design trade-off is needed to identify the most promising configurations of the following subsystems:

- Low cost foundations
- Advanced rotor design
- Advanced control, monitoring, diagnostic and repair system
- Reliable drive-train and power electric system

The critical challenges for each subsystem and component are discussed below.

5.1 Low cost foundation concepts

Controlling the cost of the offshore wind turbine foundations present unique challenges for the wind industry as coastal communities demand wind power plants placement further offshore.

The current state of the art in the wind industry utilizes two types of foundations depending on the site conditions and in particular the water depth:

1. Gravity base structure (GBS) type foundation is built onshore in a dry dock and requires the transportation of a concrete caisson to the plant location either by flotation or by a barge. The concrete caisson is then filled with concrete or other ballast materials and placed on the sea floor. The turbine tower is then erected on top and the nacelle and rotor are placed on top of the tower. This foundation type has two disadvantages: (1) it requires extensive seabed preparation and (2) the caisson top height must exceed the sea depth so that its top surface facilitates the cheaper dry installation of the tower. This limits its application to the wind industry rough definition of “shallow” as below 7.5 m water depth. Some of the largest wind plant in the world are near-shore plants in shallow depths and therefore utilized gravity base foundations.

2. Monopile: Under the supported of the Danish government a group of two Danish power companies and three foundation engineering firms studied the
most suitable foundation types for approximately 15 m sea depth in 1996–1997. This was viewed at that time as the next offshore foundation challenge. The study identified the steel monopile as the most suitable for this depth. The monopile installation requires hammering a steel pile into the soil. Then a so-called “transition piece” is grouted on top to correct for any lack of pile verticality. Tower and turbine top components are erected on top of the transition piece. Since its introduction in Europe, the monopile has become standard for sea depth ranging from 10 m up to approximately 20 m. Figure 6 shows the pile hammering operation at the Arklow Bay, Ireland offshore power plant that features seven GE 3.6 MW wind turbines.

As water depths increases, the capability of monopile is stretched to the limit primarily because of the manufacturability and constructability limitations. For sites deeper than 25 m, the monopile diameter reaches 5.5 m with thickness up to 90 mm, which could weigh upward of 250 metric tons. This level of dimensions and weights are near or exceeding the maximum capability of the fabrication factories, hammers and the installation vessels across the world.

To take advantage of the offshore wind energy in U.S., the wind industry must break the 25-m barrier in a profound way with technology development.

One recent trend practiced by some EU OEMs is to use tripod, quadpod and in general jacket type foundation structure to extend the service water depth to 50 m. These structures utilize O&G platform and shipbuilding welding technologies and tend to be very expensive in fabrication, transportation, and installation. We still need to wait and see if the new effort such as the REpower 5M jacket foundation in Beatrice as shown in Fig. 7 [12] and the new innovations such as the REpower 5M casted steel multiple-direction joints depicted in Fig. 8 will help to reduce the cost drastically and make this type of foundations economical.

Figure 6: Pile hammering at Arklow [3].
Figure 7: Repower 5M quadpod offshore foundation installed in 2006 [12].

Figure 8: Prototype of a REpower 5M offshore wind turbine in Bremerhaven, Germany with casted joints [12, 13].
5.1.1 Level-controlled suction caisson foundations

Suction caisson foundations are currently utilized in the oil and gas industry for sea depths up to 50 m. Their installation involves transporting the suction caisson and placing it on the seabed. Water is then pumped out of the hollow dome in the caisson resulting in the caisson sinking into the soil and being anchored in place as shown in Fig. 9. Large hammers are not needed and the installation process takes hours in contrary to days with monopile. As such, this is very conducive to assembly-line operations.

There are risks to utilize the suction caisson foundation in wind power plants. They include:

- Performance under lateral dynamic wind loads – Two experimental wind turbines were constructed, in Denmark and England, using suction caisson foundations. Results indicate that performance under long-term lateral dynamic loads remains a key issue preventing large-scale utilization of suction caissons in deeper sites.
- Proper tower installation – Caisson verticality tolerance is not necessary in the oil and gas industry. However, wind turbine tower installation requires controlling the foundation top surface verticality within 1°. One degree off on verticality could result in several meters of eccentricity at the hub height. It not only results in increased over-turning moment, which is a key design criterion, but also affects turbine performance. One EU OEM suffered an installation failure for a near-shore test turbine because of the verticality problem from a hard spot under one side of the caisson bottom edge during the suction process.

5.1.2 Jetting and grouting in deep sea piling

With conventional monopile foundation, heavy vessels needed for pile driving account for 20% of the total foundation costs. Jetting and grouting eliminate the
need of hammering and hence the heavy vessel. It is not only limited to monopiles but also can be easily extended to tethered foundations. Thus the costs could be reduced for both very deep sea wind power plants and the close to shore monopole-based wind power plant developments.

5.1.3 Tethered foundations

Tethered foundations are often used in oil and gas installations for water depth exceeding 100 m. Tethered foundations are quite scalable with water depth. However, their usage in wind power plants does present challenges particularly in the severe lateral loads, which is common in wind turbines and could affect overall system stability. Using ballasts and damping methods counters the lateral load with the risk of increasing the total cost to a level higher than the seabed-mounted foundations. This is particularly true at the lower water depths.

There are two types of tethered foundations for potential offshore wind applications.

1. **Tension leg platforms (TLP)**: With the TLPs, the hull and the tendon design is highly coupled since their natural frequencies are not significantly distinct. TLP stability comes from the buoyancy of the hull, which provides extra tension in the tendons and consequently provides adequate horizontal stiffness. TLPs as

![Tension leg platform](image)
shown in Fig. 10 have an edge over the other tethered or moored systems because of the minimum need for submersible hull depth. Therefore, they could be deployed in the shallower sites which could be just a bit too deep for the seabed-mounted foundation concepts.

As offshore wind foundation, the TLP could achieve extra hull buoyancy by increasing hull breadth instead of volume. It in turn enhances the lateral load carrying capacity for the overall system. There are two challenges for the TLP in offshore wind applications. Firstly, the overall hull-tendons-turbine system must be designed as one integrated unit because of the coupling of the dynamics. This makes the design process more complex. Secondly, the current wind turbine designs require maximum angular deformation at the sea level to be less than 1° to avoid imbalances in rotor loads. This deformation level may be difficult to achieve without using more advanced high-tension-high-buoyancy TLP, which could very well be the answer to the offshore wind developments in deeper sites. Oscillation damper technology and advanced high-strength tendon materials need to be evaluated to reduce the overall costs for this type of TLP.

2. Spars: As shown in Fig. 11, spars rely on ballast weight at the spar keel for stability. The ballast is much stiffer than the tendons. Therefore their designs are decoupled. Using spars in offshore wind may be problematic because their stability under lateral loads increases as the submersible length increases. There-

Figure 11: SWAY concept with 640 ft tall spar floating buoy [16].
fore, spars may not be suitable for sites less than 200 m, which could be way off limit for future wind power plants over the next 10 years. Spars also face other challenges similar to TLPs [16].

5.1.4 Hybrid tethered system

It is conceivable that the ultimate tethered concept may be a hybrid between the high-tension-high-buoyancy TLP and the spars in which lateral stiffness is provided by both ballast at the foundation keel and tension in widely separated tendons as seen in Fig. 12. The hybrid system will have the following features:

- Blasts at the keel ends, which is well assisted by the high-tension tendons, to provide lateral stability. The high tendon tension comes from the high buoyancy in the hull design.
- A hull with a liquid column oscillation damper, which consists of channels utilizing the differential inertia of water across different hull compartments to reduce lateral wave load. Liquid column dampers could either be actively tuneable or passively set at fixed frequency. Preference might be given to the passive system so as to reduce the reliance on the control system for the overall stability.

It is still likely that the turbine’s tolerance for lateral sea level angular rotation will have to be widened even after all the efforts. The appropriate implications to the control system design and the drive-train component design need to be addressed accordingly in turbine design.

Recently there have been efforts from several offshore engineering groups and wind turbine OEMs to put prototypes floating foundations with wind turbines on
5.2 Rotor design for offshore wind turbines

Rotor design for the offshore wind turbines requires new rotor structural concepts and aerodynamic models for blade geometry optimization.

5.2.1 Structural concept

Structural design for large offshore wind turbine blades calls for development of the hybrid carbon fiber/fiberglass blades at system ratings in the multi-megawatt to 5–7 MW range. Structural performance needs to be evaluated for various arrangements of the carbon blade spar. Critical performance aspects of the carbon material and blade structure need to be addressed. This type of rotor blade design will use carbon strategically. The goal is not just to reduce the weight and cost of such large blades, but to maximize the benefits of the introduction of aeroelastic tailoring, i.e. twist-bend coupling. These features combined will allow the blades to shed peak transient loads.

Earlier studies conducted by GE Wind Energy showed significant potential for relieving fatigue and extreme loads using aeroelastic tailoring. Research at TU Delft [17] in the Netherlands has further shown potential to use carbon to substantially reduce blade cost. The gains are particularly significant for large rotors with reductions of up to 10% in blade cost and 30% in weight when it is compared to the current practices.

As wind turbine technology evolving, the industry’s optimal turbine size has been steadily increasing. For turbines to grow into the 5–7 MW range and beyond economically, rotor blades longer than 60 m will be needed. Longer blades will help make lower wind speed locations close to shore more economically attractive since rotor diameter is the single biggest design parameter affecting the amount of energy capture for a given wind speed. In such conditions, it may be possible to put an ultra-long blade on a conventional turbine without exceeding its design load capability offshore. Few fundamental barriers have been identified to cost-effectively scale the current commercial blade designs and manufacturing methods over the size range of 100–140 m diameter. Turbine designs with low specific rating need to be studied for the lower wind speed sites. As specific rating is decreased, i.e. blade lengths increase at a given rating, blade stiffness and the associated tip deflections becomes increasingly critical for cost-effective blade design. The WindPACT rotor study [18] predicted added costs of transportation and assembly adversely affect the cost of energy (COE) for machines rated above 1.5 MW. Constraints for transportation cost should be considered in all projects. An option for offshore may be to place the blade fabrication plant at a harbor, which is advantageous with cheaper blade shipment using barge only.

5.2.2 Aerodynamics and blade geometry optimization

A lower importance of noise emission, expected for offshore wind turbines, offers new opportunities in rotor aerodynamics and blade geometry optimization.
Specifically, blade geometry can be optimized for a higher maximum tip speed as compared with wind turbine rotors designed for land-based deployment. So the tip of the blades can be designed for maximum aerodynamic efficiency. A higher maximum tip speed allows for a higher design tip speed ratio for the blades, which will reduce rotor solidity and facilitating transportation as well as reduce drive-train size and cost. Using high-lift airfoils can be considered to further reduce rotor solidity while giving due attention to the impact of reduced solidity on the blade structure strengths and cost. Overall, blade geometry can be optimized to minimize COE using tools that simulate and evaluate detailed aerodynamic blade design with considerations to blade structures and cost of all main turbine components.

A blade design tip-speed ratio between 9 and 10 is expected to be optimum for minimizing the COE of the offshore wind turbine system and the optimization process can be used to survey the design space.

Traditionally, the tip of a wind turbine blade has been designed to provide a smooth unloading because of the noise considerations. In particular, the chord lengths over the tip region are tapered below the optimal point for maximum aerodynamic efficiency. This approach results in a loss in power output. Tailoring the tip geometry towards that goal could make a gain in aerodynamic efficiency. Tip losses due to the tip vortex amounts to roughly 3% in annual energy capture. The optimization of a tip for maximum energy capture is expected to cut this loss to 1.5–2%, which is a significant improvement given the value of 1% more energy at the current multi-megawatt size of utility-scale wind turbines.

5.3 Offshore control, monitoring, diagnostics and repair systems

Offshore wind turbine control system will consist of three highly integrated sub-systems:

- Diagnostic system
- Regulatory system
- Supervisory system

The offshore wind turbine system size will allow for a sophisticated control system at a smaller fraction of the total turbine cost than is possible for a smaller onshore turbine. The advanced diagnostic/CBM system will monitor sensor data from major components such as blades, drive-train bearings, gearbox and generator to detect faults and rapid degradations which could negatively impact the power capture or lead to premature critical component failure.

The advanced regulatory system can use feedback from deflection and load sensors as well as local wind conditions to increase power capture and reduce fatigue and extreme loads well beyond current industry practice. Including the improved regulatory control in the design phase will mean that these advantages could be conferred in the initial design envelope.

The more advanced supervisory system can reduce unnecessary hard stops, thus significantly increasing the life of drive-train subsystems. This can be achieved
using redundant sensors and back-up systems, also to be incorporated in the design phase. This will ensure high availability and increased energy capture. It will offer component cost benefits through reduced fatigue load and the ability to mitigate or avoid some current design driving loads.

5.4 Drivetrain and electrical system

Improving overall system efficiency is a key goal of any offshore development effort. To obtain the lowest COE, losses must be reduced wherever possible. Large diameter, gearless generator technologies such as so-called “direct-drive” which uses permanent magnets generator are investigated by many companies as one solution for reducing losses and maintenance cost related to the traditional planetary gearbox-based system. Design trade-offs could be carried out for optimizing the cost and efficiency of drive train and the converter based on the generator side and grid-side converters location in the tower. Factors such as weight and cable loss should be considered.

The electrical system is the critical interface between the drive train and the utility network. It enables both the optimized drive-train design and the harvesting and transfer of power to the utility in accordance with grid regulations. An optimized electrical system design will result in higher system efficiency and lower system cost. Both of which affect the COE in a positive manner.

The following issues related to optimizing the design of a multi-megawatt to 5–7 MW offshore wind turbine need to be addressed:

- Design trade-offs for optimizing cost and efficiency of the drive train and converter: The power converter enables the electro-mechanical drive train to operate at the optimum power factor and deliver maximum output power through peak-power-point tracking. New circuit topologies and control, converter packaging and thermal management need to be explored to reduce cost and losses of the power converter as well as the generator. The power converter’s physical location and associated electromagnetics that may include transformers in the tower will be considered as a design factor to minimize cost and losses in the cables as well as reduction of weight in the nacelle.
- Electrical interconnection of wind turbines in a wind power plant: Studies need to focus on optimizing the electrical interface between turbines in an offshore wind power plant. The feasibility of the medium voltage (MV) DC interconnect system, based on cost and dynamic stability, need to be studied.
- Transmission of power from offshore to onshore: Voltage level and frequency are factors which impact cost of cabling and converter interface at the sending and receiving ends of electricity. MV or high voltage DC transmission is an enabling technology for such bulk power transfers. Optimum voltage levels as well as converter topologies need to be achieved to minimize the overall systems cost.
- Protection of electrical system: Electrical system protection from grid-faults and component failures is critical to system design from availability and reliability.
point of view, which directly affects the COE of an offshore plant. Advanced means of control for handling grid-faults and low/zero-voltage ride through as well as modular converter topologies that enable part-load/full-load operation and optimization of ratings of the protection equipments such as circuit-breakers along converter system need to be studied.

6 Other noteworthy innovations and improvements in technology

This section describes other key improvements that need to be achieved by the offshore wind industry.

6.1 Assembly-line procedures

Unlike today’s construction method, i.e. building unique one-of structures, the future offshore projects will utilize assembly-line procedures to maximize cost control in a mass production manner.

6.2 System design of rotor with drivetrain

Current commercial wind turbines utilize a three-blade configuration. However, two-blade designs which incorporate alternative hub structures may see a rise in popularity because they allow turbines to reach higher rotor speed without visual or noise constraints. Upwind configuration might be preferred as it allows less dynamic loads and has less rhythmic noise effects. Detailed investigations need to be carried out on the blade deflections and resonant modes under turbulent wind loading.

The WindPACT rotor study [18] was designed to explore many of these configurations and attempt to determine their impact on overall turbine operation and COE. The study has found that several loads in the final two-bladed downwind machine were higher than the corresponding loads in the baseline design. The downwind two-bladed rotors also experience strong harmonic loading from the tower shadow, which may excite natural frequencies. In the future offshore wind projects detailed investigations need to be carried out on the relative advantages and disadvantages of a two-bladed upwind with the corresponding three-bladed version. The real benefit of two-bladed design with unconstrained tip speed is simplified gearbox and more optimal direct-drive drive train. Preliminary studies conducted by GE Global Research Center indicate that the rated speed of the wind turbine has a large impact on the direct-drive cost. Considering aerodynamic power only, the rated speed for a two-bladed turbine could be up to 30% higher than a three-bladed turbine. In which case a direct-drive drive train for a two-bladed turbine rated at 19.1 rpm would cost substantially less than one for a three-bladed turbine rated at 11.7 rpm for a 5 MW system. However, energy capture will likely to be less than an equivalent three-bladed wind turbine of the same diameter and hub loading needs to be investigated as both tower and hub will require reinforcement due to the two per rev loads. The suggestion in the WindPACT study to
combine the rotor design with drive-train configuration studies needs to be implemented, which could ultimately contribute to reduce the COE.

6.3 Service model

A solid and viable offshore service model is extremely important for any successful offshore wind project. The basic philosophy will evolve around a global performance and product data warehouse specifically aimed for autonomous offshore operations.

The performance data from offshore wind power plants can be processed in the global data warehouse, which will feed information to different areas. The operating information could be used by future product development teams or for existing product improvements. The service information will be used for making contractual service agreements, remote monitoring and diagnostics and knowledge-based maintenance. Customers can use the availability information to understand the capacity factor and overall plant health.

Contractual services has a major emphasis on developing new technology tools to support the offshore wind business. The new technology tools are aimed at improving reliability and availability, extending parts lives and enhancing plant performance.

7 Conclusion

Offshore wind turbines need to achieve high reliability and availability at low COE, which is competitive to other energy sources. The chapter identifies innovative options for new foundation concepts, construction techniques, rotor design, drive train and electrical system while optimizing the total life cycle cost of offshore wind power plants. Turbine design will need to incorporate best technologies and practices from the land-based turbines while incorporating lessons learned from first generation offshore pilot projects to develop a new robust turbine concept optimized for offshore operations. Optimum turbine size will be determined for locations and is expected to be in the multi-megawatt to 5–7 MW range suitable for more than 25 m water depths.

References


