International Journal of Sciences: Basic and Applied Research (IJSBAR)

ISSN 2307-4531
(Print & Online)

http://gssrr.org/index.php?journal=JournalOfBasicAndApplied

Introducing Wind Converters to New Designers Full Report

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Abstract

Engineering is lost somewhere between science and technology. Science, engineering, technology and innovation are very closely linked and interrelated. Wind energy, however as a part of engineering is no exception from this interrelated process. this paper highlighting the wind energy resources and explains different aspects of this green energy to both consumers, designers and policy makers in an attempt for rapid harvest through starting of conversion to this cheap everlasting and environmental friendly resources. The paper presents a state of the art report about broad horizons of electrical wind converting technology industry with emphasis being diverted to structural background.

Keywords: Wind energy; wind energy converter; design options of wind energy; renewable energy; green energy.

1 Introduction

Wind energy has two parts: the “know what” or ‘simply knowledge’ and the “know how” or ‘process’. The first part is the growing body of facts, experience and skills in this field of application, while, the second part is the creative process that applies knowledge and experience to find likely solutions, which uses experience and informed judgement to decide on the best solution.

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In fact, wind turbines are never installed so that conventional power stations can be closed prematurely; building wind farms, avoids the need to build new fossil fuel or nuclear power plants. Expanding the use of wind energy will increase energy diversity and improve the security of electricity supply, thereby reducing the international political risks and environmental damage (global warming due to greenhouse gases and acid rain due to sulphur and nitrogen emissions) associated with fossil fuels, the volatility of oil and gas prices, and hazards associated with nuclear power and depleting natural resources.

Despite its good reputation as renewable, green, sustainable, reliable and available energy, wind energy only recently has proven to be economically feasible and commercially competitive with other sources of energy, (a vital reason for consumers to convert to it). Wind energy coincides well with periods of peak electricity demand, which often peaks on cold, windy, winter days in the northern hemisphere just when wind turbines are at their most productive.

Due to the mentioned factors, and adding to that, less maintenance and operational requirements are needed; wind energy is perfect for farms, remote communities, islands and isolated locations that are not connected to utilities, (areas where wind mechanical energy was in use for pumping water for decades).

2. Where Does Wind Energy Come From?

In physics the word energy is defined, as the amount of work a physical system is capable of performing. According to the well-known principle of conservation of energy, energy cannot be consumed, destroyed or created. Energy however, may be converted or transformed into different forms: The kinetic energy of moving air molecules may be converted to rotational energy by the rotor of wind turbine, which in turn may be converted to electrical energy via an attached generator. Whenever energy is converted from one form to another, part of the energy from the source is converted to heat energy. Therefore, the use of the common expression of energy loss is absolutely wrong but rather, means that part of the energy from the source cannot be used directly in the next link of the energy conversion system, due to its conversion to heat. In fact most if not all mechanical systems, e.g. rotors, gearboxes and generators are never 100% efficient, because of heat losses due to friction in the bearings, or friction between air molecules. As fossil fuels burned, loosely speaking, the global potential for future energy conversion is reduced. Since the vast majority of wind turbines produce electricity, usually their performance is measured in terms of the amount of electrical energy they are able to convert from the kinetic energy of the wind. This energy is measured in kilowatt hours (kWh) or megawatt hours (MWh). Based on the reality, that energy cannot be created but only converted into different forms, wind turbines should be rather called wind converters, although the word turbine is widely used throughout the literature and is understood to have the same meaning as converter.

Power is energy transfer per unit of time; electrical power is measured in watt (W) or its multiplications. Power may be measured at any point in time, whereas energy has to be measured during a certain period of time, e.g. a second, an hour, or a year. The expression “horsepower” used in rating engines gives an intuitive idea that power defines how much “muscle” a motor or a generator has, whereas, energy tells how much “work” a generator or motor performs in a certain time.

Wind energy is an indirect form of solar energy. Between 1-2% of the solar radiation that reaches the Earth is converted into energy in the wind [1,2]. Winds result from an unequal heating of the earth's surface, causing cooler dense air to circulate to replace warmer, lighter air. While some of the Sun's energy is absorbed directly into the air, most of the energy in the wind is first absorbed by the surface of the Earth and then transferred to the air by convection.

Seasonal variations in the speed and direction of the wind result from the seasonal changes in the relative inclination of the Earth towards the Sun, which in turn changes the patterns of differential heating. Daily, or diurnal, variation is caused by differential heating of local regions, such as adjacent land and oceans.

This air movement is complicated by a number of global scale factors such as the Earth's rotation, continents, oceans and topology. Airflow is rarely smooth, with most places experiencing fairly rapid changes in wind speed and direction. The wind speed also increases with the height above the ground, due to the frictional drag of the ground, vegetation and buildings. It is clear that any plans to harness the wind must take into account these variables.

3. Energy of the Wind

The power in the wind is proportional to the cube of the wind speed or velocity ($\frac{1}{2}\ \rho\, A\, \mathrm{V}^3$) as will be discussed later. It is therefore essential to have a detailed knowledge of the wind and its characteristics if the performance of wind turbines is to be estimated accurately. As is well known, the highest wind velocities are generally found on hilltops, exposed coasts and out at sea. Various parameters need to be known of the wind, including the mean wind speed, directional data, and variations about the mean in the short (gusts), daily, seasonal and annual variations, and variations with height. They are used to assess the performance and economics of wind plant.

In order to create wind energy there is a process that must be completed to turn the wind into electricity. To start the process, the wind must pass over the air foil shaped blade. It passes more rapidly over the longer or upper side of the air foil, which creates a lower air pressure area above the air foil. The pressure difference between the top and bottom surfaces of the blade results in a force called an aerodynamic lift. This force causes the air foil to rise and this lift force causes rotation about the hub since the blades of the wind turbine are constrained to move in a plane with the hub at its centre. In addition to the lift force, another force called a drag force perpendicular to the lift force impedes rotor rotation. A relatively high lift-to-drag ratio is a prime objective in wind turbine design; this ratio can be varied along the length of the blade to optimize the turbine's energy output of various wind speeds, a subject of wide research activity and of concern to mechanical engineers and therefore outside the scope of this report.

The kinetic energy in a flow of air through a unit area perpendicular to the wind direction is $\frac{1}{2} \rho V^2$ per unit volume or $\frac{1}{2} V^2$ per unit mass.

For an air stream flowing through an area A the mass flow rate is ρAV, therefore:

$$\text{Power, } W = (\rho AV)\times \frac{1}{2}V^{2} = \frac{1}{2}\rho A V^{3} \qquad 1$$

Where ρ is the air density (kg/m^3), V is the wind speed (m/s) and W is the power in Watts or Joules per seconds.

The air density ρ is a function of the air pressure and air temperature:

$$\rho = \rho_o \left(\frac{288B}{760T}\right) \qquad 2$$

Where ρ_o is the density of dry air at standard temperature and pressure (1.226 kg/m^3 at 288 K, 760mm of mercury) and T is the air temperature (K) while B is the barometric pressure in mm of mercury.

Both the pressure and the temperature are functions of height above sea level. Taking a typical density of air at sea level as 1.2 kg/m^3, the power becomes

$$W = 0.6V^{3} \text{ per unit area} \qquad 3$$

At a wind speed V the energy is measured in watt-seconds passing through area A during time t is given by:

$$\text{Energy, } Wt = (1/2)\,\rho AV^{3}\,t \qquad 4$$

This is the total energy available for doing work on the wind turbine. Practically speaking, there is no change in the temperature of the air flowing through a wind turbine. This is also clearly the case in water turbines. In both cases the energy extracted using the change in fluid velocity, not through a change in temperature.

4. The World Wind Resources

To estimate the global potential for wind energy it is necessary to know the mean wind speed over the earth's surface. This has been measured and the results are published in the form of wind atlases for countries, regions, and continents, even for the whole Globe. In fact, these atlases are often depending on interpolation of wind data obtained from dispersed measuring stations, but still they can provide a useful estimate for the available wind resource for initial planning purposes [3,4,1]. Reference [6] reported 'The World Energy Council (1994)' as giving estimates of the global wind resource at about 27% of the earth's land surface experiences annual mean wind speeds higher than 5.1 m/s at 10 m above the surface. Only 4% of this area might be available for the electricity generating wind farm because of unsuitable terrain, urban areas, crop cultivation and other existing land use. Quoted from the last source assuming a generating capacity of 8 MW/km^2 and a capacity factor of 23%, it is estimated that the global potential for wind turbine power production is 20,000 TWh per year. For comparison (same source) in 1987 the total world electricity consumption was about 10,500 TWh (the prefix T stands for tetra or 10^{12}).

The mentioned estimate is for large scale grid-connected wind converters and it depends on a variety of assumptions. It does not include the potential for offshore wind energy developments or small-scale wind turbines used for water pumping or battery charging, feasible applications in wind speeds as low as 3 m/s. About 50% of the earth's land surface is exposed to mean annual wind speeds of between 4.4 m/s and 5.1 m/s quite suitable for small wind turbines (same source).

The outlook for future energy demand is that it is predicted to rise quite dramatically. It is supposed; Walker and his colleagues [6] that from 1998 to 2010 the world wide yearly electricity demand will rise by about 30% to about 20,825 TWh and by nearly 50% to about 27,326 TWh by 2020, with an annual growth of 2 per cent. The former source estimated that the entire electricity demand for the earth could have been covered by the use of only 0.04% of the kinetic energy extracted from wind resources in theory. Clearly, there is a serious energy problem associated with environmental catastrophe and the only viable solution is wind energy and solar energy. Based on the quoted estimation and given the renewable nature of wind, it is evident how much energy could be harvested from wind.

5. Vertical Wind Speed Gradients

The wind speed at the surface is zero due to the friction between the air and the surface of the ground. The wind speed increases with height about 2 km above the ground the change in the wind speed becomes zero, Walker and his colleagues [6]. The vertical variation of the wind speeds and the wind speed profile are expressed in different functions. Two of the more common functions which have been developed to describe the change in the mean wind speed with height are based on experimental evidence, these are power exponent function and logarithmic function [6,1,5].

The hub height of new generation wind energy converters is in the performance range around 1 megawatt lies over 60 metres above ground level for land based towers. The reliability of wind speed versus height must be treated with caution since they are based on extrapolation and very much dependent on the surroundings and terrain.

6. Wind Energy Trends

Since the beginning of the modern wind energy era, which followed the oil crisis of the 1970s, the installation of wind turbines has regularly been considered as different nations have formulated their wind energy programmes. The arguments were and still are, based on the notion that the potential of wind energy on land in densely populated countries is limited compared with total national energy demand, and that the countries with relatively long coastlines could increase their exploitable wind potential by installing wind turbines offshore. Yet, although wind speeds offshore are higher than those on land, integrating the converters electrical connections to the existing network will be more expensive to reduce energy loss. The challenge, therefore, is to balance those two counteracting parameters so that offshore wind energy is comparable in cost to electricity generated by land based wind turbines.

In order to sell the idea of offshore wind energy, cost reduction is the base line of all structural and technical activities; this necessitates a close consideration of:

- Determining wind resources, in terms of speed, duration and site based on detailed measurements of near-shore and offshore areas and mountains regions.
- Integrating wind, wave and current loading in the structural analysis and design which will eventually lead to avoidance of over designed or conservative structure, and hence reducing the cost of the energy outcome.
- Careful consideration should be given to relevant environmental issues, associated with this new energy, namely, oil and gas mining, noise, military use, ship traffic routes, fishery, effects on fish and birds breeding, sand mining, erosion, visual impacts and the natural environment.
- Development of dedicated offshore concepts. Use low maintenance, direct-drive generator systems, transport, installation, and maintenance ‘touch and go’ systems, power electronics for optimal electricity transport.

It has been recognised that the offshore waters of many countries are currently one of its principle energy sources, through its hydrocarbon deposits. Some of the gas accumulations in these fields are difficult to extract and utilize economically. Thus, combined use of this gas, with floating wind turbines could prove to be more economic. However, the cost of wind converters is falling and is expected to continue doing so over the coming decades and once more experience has been gained in building offshore projects, the offshore construction industry is likely to find similar cost-savings.

7. Offshore Wind Energy

Shortage of land sites in northern countries ‘biggest energy consumers’ is one reason for this move offshore other reasons include significantly higher wind speeds than on land, and thus higher energy production at sea where wind speeds are believed to be higher than what was previously anticipated. The marine environment gives more stable winds with less turbulence and less wind shear, facilitating the design of cheaper turbines with a longer life span.

To be economic and hence competitive offshore wind parks (as they normally called) have to be as large as economically feasible, and must therefore, use large turbines. New foundation technologies, using steel rather than concrete will probably improve the economics of the offshore wind power dramatically. Wind turbines at sea would have a longer design lifetime due to lower mechanical fatigue loads due to less turbulence.

Up to now, most offshore energy installations were built in shallow waters near shorelines, so if the mentioned economy factor is to dominate, which means larger systems, the feasible choice will very likely be a floating system. The total wind power resources offshore are vast and will certainly be able to supply a significant proportion of electricity needs in an economic manner.

Generally, there are six reasons for justification of the move towards offshore wind energy:

i) Land shortage:

One of the prime reasons for offshore wind farms is the lack of suitable wind turbine sites on land; this is evident, for Europe, India and China where most if not all countries are densely populated or relatively flat landscape.

ii) Higher wind speeds:

Equally important, however, is the fact that wind speeds are often significantly higher offshore than onshore, an increase of some 20% is common, Krohn [7]. With the fact that wind energy increases with the cube of the wind speed, the energy yield may be some 73% higher than on land, Krohn [7]. If turbines on land where to be located on good land sites, such as mountains or hill tops, where the wind speeds up significantly compared to flat terrain, in such situations, an onshore energy system is advisable.

iii) More stable winds:

In most wind turbine sites around the globe, the wind speed varies substantially, with high wind occurring rather infrequently, and low winds occurring most of the time. In most of the locations around the globe, as already mentioned, wind speeds happen to be positively correlated with peak electricity demand (more wind during the day than at night, more wind in winter than in summer). At sea, periods of complete calm are generally extremely rare, and quite short lived, thus the effective use of wind turbine generating capacity will be higher at sea than on land.

iv) More wind resources:

Offshore wind resources are enormous and everlasting and it is believed to be several times larger than the projected energy consumption, theoretically 15 times current energy consumption worldwide, Rehfeldt and Matthias [8], while for Europe for example, it is believed to be 8 times the current energy demand, Khün [9], another example, the UK’s offshore wind resource is equivalent to three times the current electricity usage and is some 33% of the total European potential [10,11].

v) Lower turbulence:

The temperature difference between the sea surface and the air above it is far smaller than the corresponding difference on land, particularly during the daytime. This means, that, the wind is less turbulent at sea than on land, which in turn, means lower fatigue load and thus longer serving time for turbines at sea than on land.

vi) Low surface roughness:

Another argument in favour of offshore wind power is; the generally smooth surface of water, which means that wind speeds do not increase as much with the height above sea level as they do on land. This implies that it may be economic to use lower (and thus cheaper) towers for offshore wind turbines.

In addition to the technical and engineering advantages of offshore energy, it is the environmental factor which is the most encouraging for the future. Once again, the reduction of greenhouse and acid rain responsible gases is a genuine reason, positive impact on marine wildlife is observed and still under surveillance, which will be another decisive factor for the choice of offshore wind energy. Nevertheless, there will be additional cost due to the more expensive marine foundations, due to weather conditions access will be restricted and installations will be more expensive. Furthermore, the limited access for operations and maintenance will result in an additional penalty of reduced converter usage and hence less output.

8. Components of Wind Energy Converter

Offshore wind energy system is usually made up of wind farms or parks, which vary in size according to the required energy outcome, however, due to the cost reasons; both the wind turbine and the wind farm have to be an optimum ‘large’ size compared to those onshore. The wind system (farm) in turn consists of a number of integrated wind turbines. Typical shallow water (bottom mounted) wind turbine is identical to land based turbine and comprises the following parts, Figure 2:

8.1 Rotor

Consisting of a hub, blades (one, two or three) and transmission, the blades are driven by the wind driving the turbine generator as shown in Figure 1: and Figure 2:. Sometimes gearing is used to increase the frequency of electricity generation, while in some designs the generator is directly shafted to the blades.

8.2 Nacelle

Of the size of a small van, the nacelle is elevated up in the air to capture more wind it is the house of most of the electricity generating equipment. Providing structural support for the included equipment and rotor, the main internal parts are: gear, drive, generator, and transformer. Sometimes gearing is eliminated due to cost reasons hence the generator is run directly. In many cases transformers are located either inside the tower or on the ground or submersed in offshore turbines. In fact, deployment of the transformer somewhere else other than the nacelle will serve reducing the nacelle weight, hence lowers the centre of gravity of the whole system which is of utmost benefit for stability of the floating structure. Electricity is transferred (either directly or in transformed form) to the next stage using cabling to be either stored or used by grid customers.

Horizontal axis machines working on the upwind principle (to be explained later) requires a mechanism to swing them into line with the wind. Also, small machines usually have a tail assembly, whereas large machines usually have a “servo mechanism” that orients them to the direction of the maximum power-yew mechanism.

Modern wind turbines are usually equipped with mechanisms to prevent damage in excessively high winds. Large machines may have complex arrangements to shut down generation at high wind speeds, whereas smaller systems change the blades’ orientation so that they present a smaller surface to the wind and thereby reduce the speed of rotation, or otherwise use mechanical brakes. A typical nacelle is shown in Figure 1 and Figure 2.

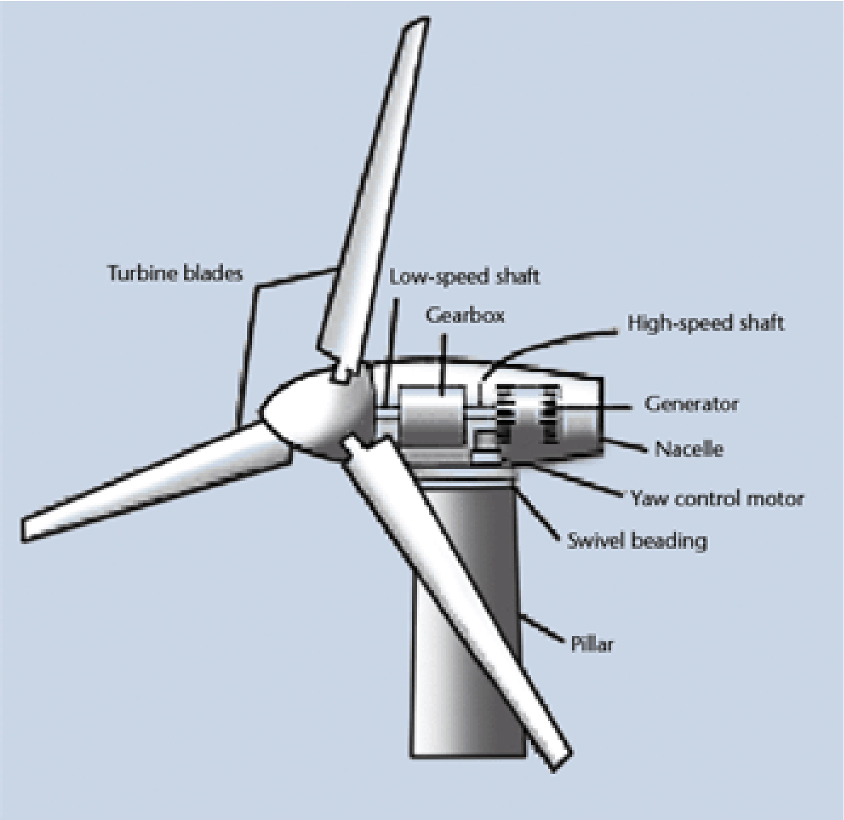


Figure 1 : Nacelle and rotor parts, Ref. [14]

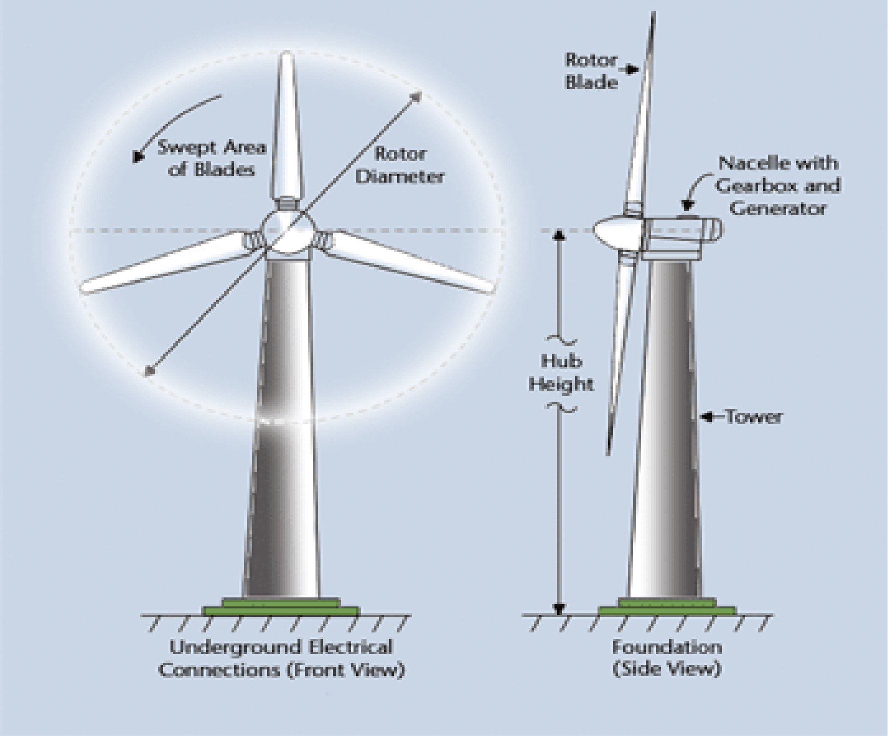


Figure 2: Wind converter (turbine) components, Ref. [14]

8.3 Tower

The tower Figure 2: supports the nacelle and the rotor (turbine assembly) well above the turbulent air currents close to the ground and captures high wind speed, (as already noted). Tower design is particularly critical, as it must be as tall as economically possible, robust, enabling access to the turbine for maintenance, and yet not add unnecessarily to the cost of the system. A particularly important aspect of tower design is elimination of resonance between the frequency range of rotating blades and the resonant frequency of the tower. Towers are made from tubular steel, concrete shaft or steel lattice, comprising the upper part of the supporting structure, which includes the foundation as well. Therefore, two types of towers are commonly used:

8.3.1 Tubular Tower

Most of the towers used for large wind turbines in shallow waters are shaped like a tube that is slightly wider at the bottom than at top, tubular steel towers are not only the strongest solution but are also believed to be the cheapest [8,11].

8.3.2 Lattice Steel Tower

A tower can be made out of general steel sections that are put together to form a lattice, a lattice tower is very strong and relatively inexpensive to manufacture. It does not take as much steel to manufacture a lattice than to make a tubular one, let alone, transportation and erection [8,11].

9. Foundations

When assembled together, the foundation and tower, comprise of what is known as the supporting structure, as has been noted before. The foundations are found to be one of the drivers in offshore wind energy development. They account for about (16-25) % of the total cost for a shallow water offshore wind farm [8,11,12]. Hence, a strong incentive is given to develop cost efficient support structures. In general, two major groups can be distinguished:

- Bottom- mounted support structures.
- Floating support structures.

It is obvious, the decision of which option to use will depend on water depth. For areas of relatively moderate water depths of up to say 40-50m, the focus is placed on bottom mounted structures, while floating support structures (drawn from offshore oil and gas industry) are intended for use of exploiting deep ocean wind energy.

Since wind energy farms deployment, they have been limited to near shore shallow waters, hence only bottom mounted support structures, namely, gravity and monopile foundations are widely used. This has led to complete domination of bottom mounted offshore turbines, and they have become synonymous with offshore wind farms. Most of the reported literature and drawbacks attributed to offshore wind energy are in fact typically for near shore bottom mounted wind farms. Various options for the foundations and some of their specifics are as follows:

9.1 Gravity foundations

Gravity based foundations, represent the traditional solution. As the name suggests, the gravity force of a concrete caisson is used to keep the complete structure (foundation, tower and turbine) in an upright position while being exposed to the overturning moment from wave and wind impact on the turbines' rotor and the support structure itself, as shown in Figure 3. They are structurally designed with the objective of avoiding tension between the foundation and seabed by providing sufficient dead loads to stabilise the whole structure against overturning moment resulted from horizontal forces. This foundation type is found to be sensitive to extreme hydrodynamic loading as substantial heave loads may occur during the passage of waves [8,12]. Wave heights in turn are dependent on water depths, and thus the weight of the foundation will have to be heavily increased with deeper water sites. It is assumed that this type of foundation is commercially unfavourable in water depths in excess of 10m, while physical constraint limits its use over some 20m [8,12].

Gravity based support structures provide rather stiff foundation properties, thus allowing little aerodynamic damping (damping of the fore-aft motion of the structure due to the adverse changes in the aerodynamic forces on the rotor in response to support structure motion). It also allows limited tuning of the support structure's dynamic characteristics. The fatigue life of the gravity based support structure (foundation and tower) is expected to be dominated by aerodynamic loading owing to stiffness of the concrete foundation. However, at extreme conditions at deep water sites the increased wave height hydrodynamic loading will gain in significance [8,11,12]. The gravity based foundation requires seabed preparations to be carried out contributing to a cost increase with water depth.

The seabed must be levelled and prepared with a layer of crushed stones, in sights prone to scour, hence some kind of protection against erosion will be needed. This is done by placing boulders around the foundation base [12]. In theory, the foundation may be easily removed after the service life, in practice however this may not be as easy as it might seem. The common technique is to build these caisson foundations in a dry dock and to float them out to the site of use after completion. To facilitate the transport, the caissons may be made hollow and ballasted on site with sand, gravel, concrete or olivine (a very dense mineral) to achieve the required weight.

Obviously, the large weight of gravity based foundations (typical weight 500-1000 tonnes) pose considerable demands on transport and installation procedures and in addition requires temporary site preparations. Also the effort for casting, formwork, and maintenance of the construction site are considerable for concrete foundations (typical diameter 12-15m). A new technology offers a similar method to that of the concrete gravity caisson. Instead of reinforced concrete it uses a cylindrical steel tube placed on a flat steel box on the seabed [12]. Because of its relatively low weight, it could be transported and installed rapidly with a fairly light crane. The steel tube once installed is filled with olivine, to give sufficient weight for stability. In this version as well, protection against erosion is required [8,11].

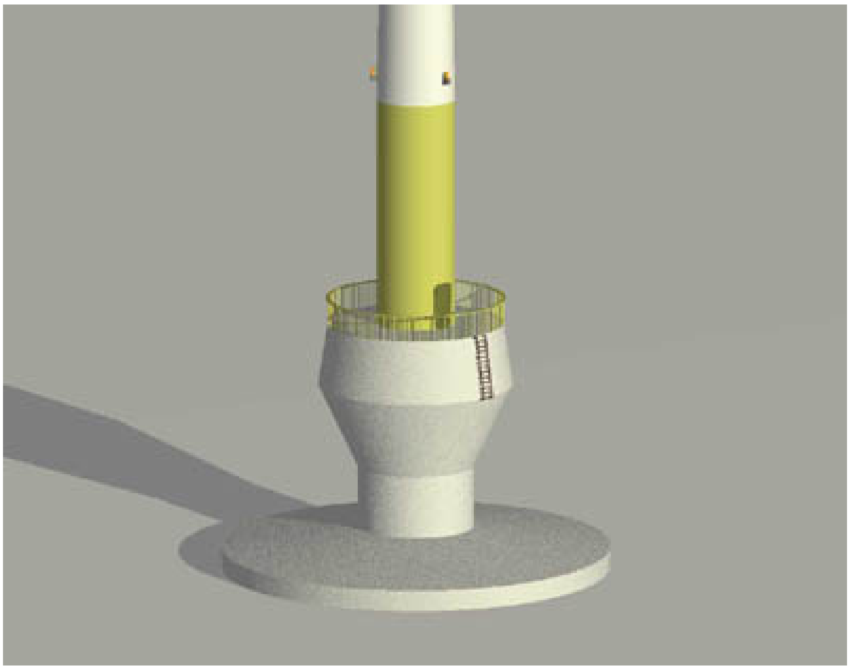


Figure 3: Gravity foundation, Ref. [14]

9.2 Monopile foundation

Piled foundations make up the most common form of offshore traditional foundations, shown in Figure 4. The pile, a simple steel tube, driven into the seabed by means of a vibrating or piling hammer and enables lateral and axial forces (tensile and compressive) to be transferred to the seabed. A monopile support structure would consist of the pile and the tower and possibly a connection between both. Pile diameter (typically 3-5m), weight (typically 175 tonnes), and penetration into the seabed are directly dependent on design philosophy, turbine size, and seabed soil conditions, typical values 10-25m. Maximum water depth for monopile support structures is identified to be around 25m [8,11]. The monopile foundation represents a rather soft design with respect to foundation stiffness. As such it offers significant advantages with respect to aerodynamic damping and reduced dynamic response, such characteristics offer the potential of considerably reduced fatigue from aerodynamic loading (rotor) if the support structure dynamic characteristics are properly tuned. In general, the design is expected to be fatigue driven, however, in ice invested waters, extreme loads from drifting ice may also require increased wall thickness.

The monopile does not require seabed preparation but is sensitive to scour. Hence, in regions prone to scour some form of protection such as artificial seaweed or shingles will be needed. Piling is restricted to seabed conditions with only a few boulders, as they might cause problems during piling. For very stiff seabed conditions drilling will be required. In such a case the monopile will be slotted into the drilled hole and grouted. With respect to corrosion it is worth noting that below the seabed line no coating will be used on the monopile, in order to provide adequate friction between pile and soil. For other foundation types, cathodic protection is most likely to be applied by either using passive sacrificial anodes or active impressed current. No anti-fouling will be used on the monopile. Removal of the monopile from the seabed may be accomplished by cutting it some metres below mud line or by extracting it from the seabed using a vibration hammer.

Piles are relatively easier to manufacture, to transport and to erect, with only moderate increase of cost in deep waters, and very stiff soils, monopiles are well researched and dominant for near shore wind energy.

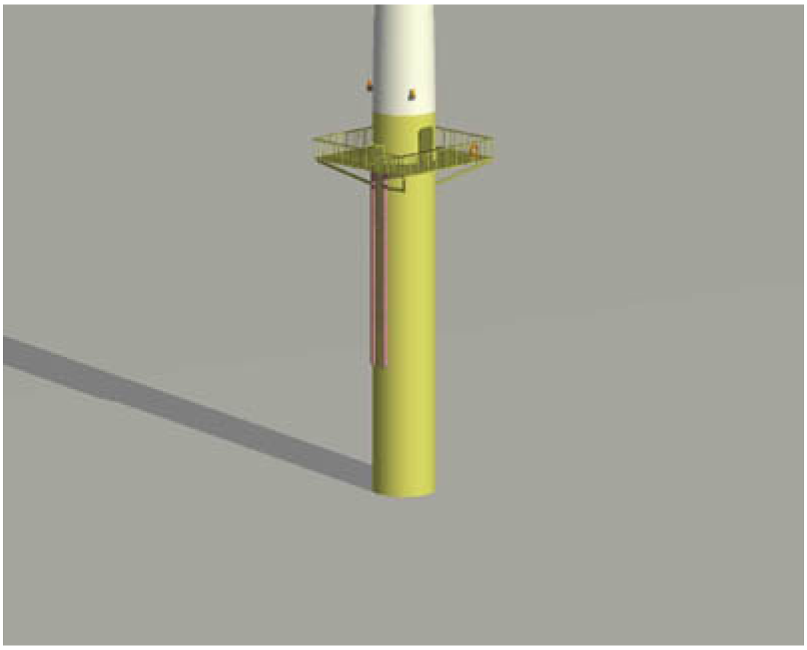


Figure 4: Monopile foundations, Ref. [14]

9.3 Tripod foundation

This type of foundation is drawn from experience with lightweight and cost efficient three-legged steel jackets for marginal offshore fields in the oil industry. The structure is made of a centre column that carries the tower and a steel space frame transferring the loads from the tower to mainly tension and compression loads in the three piles that are driven into the seabed and connected to the frame through sleeves at the three corners. The cylinder between piles and pile sleeves is filled with grout after piling to ensure a rigid connection, Figure 2 [8,11]. The centre column has a reduced diameter at the sea level to reduce wave and ice loads, while the penetration depth is dependent on seabed conditions.

As tripod foundations represent a lightweight structure, dynamic behaviour must be carefully examined. It is a rather stiff structure with small allowance for aerodynamic damping to reduce dynamic response when compared to the monopole[8,11]. Wave loading has been shown to be insignificant in water depths down to 11m some 10–25% contribution to the overall overturning moment [8]. Hence, as the tripod support structure is mainly governed by aerodynamic fatigue loading, the importance of wave loads becomes significant with deeper waters. Loading from ice crushing against the structure can also be the design driver in icy waters [8,11].

The tripod is well suited for greater water depths, however, in shallow water, a technical problem arises as service vessels cannot approach it without the risk of colliding into the structure.

It is relatively light to transport, but well-known and proven techniques should be applied during manufacture and erection. No seabed preparation is required, lifting and piling facilities are somewhat expensive. Below the seabed no coating will be used on piles to guard for corrosion, the reason, once again is to provide adequate friction with soil. As for the monopile, cathodic protection is most likely to be applied by either using passive sacrificial anodes or active impressed current, Hogler [12]. Once used it could be removed by cutting off piles, preferably below the mud line. As it most suited for deep water sites away from shore, it has the potential of being useful, although it is not being known to be used until now.

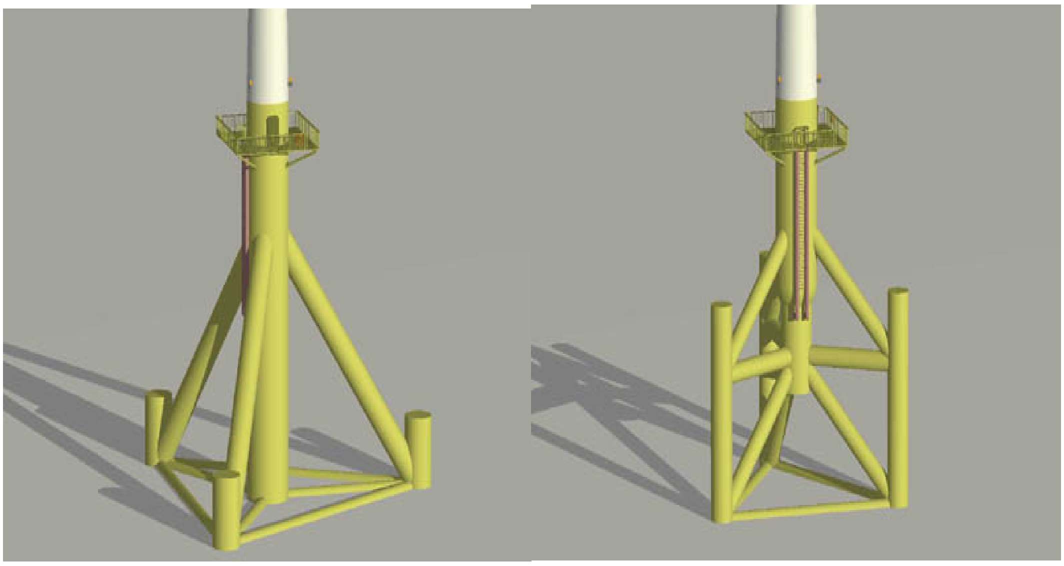


Figure 5: Tripod foundation, Ref. [14]

10. Floating Support Structure

An incentive to use floating support structures in offshore wind farm developments is the constraint to modest water depths necessary for any seabed mounted structure. This drawback can be overcome with floating support structures hence the development of offshore wind energy generating facilities could be extended to areas with water depths of up to several hundred metres. This approach has been mentioned by several references [8,12]. Accordingly, two feasible options for floating offshore wind farms emerged:

10.1 The Buoy Type

In the case of the buoy type system, the support structure comprises the tower, the hull and the moorings to the seabed. The tower, a tripod steel space frame, is bolted onto the deck of cylindrical buoy hull with a wider bottom disk, for improved dynamic behaviour the lattice tower could be replaced by steel tube tower, Figure 6. The mooring system is made up of units adaptable to water depths then the mooring lines are connected to mooring anchors piled at the seabed. A line tensioning system is to be mounted on the deck to allow tensioning of pairs of opposite facing lines during installation and during operation when needed. Once a pair of lines has been tensioned the lines will be locked off and the winches engage on the next pair of lines and tension them. The completed floating structure including the turbine would be floated to the site of development where, in a first phase, mooring lines and anchors are already installed. Mathematical models based on this concept will be the main subject of many future works.

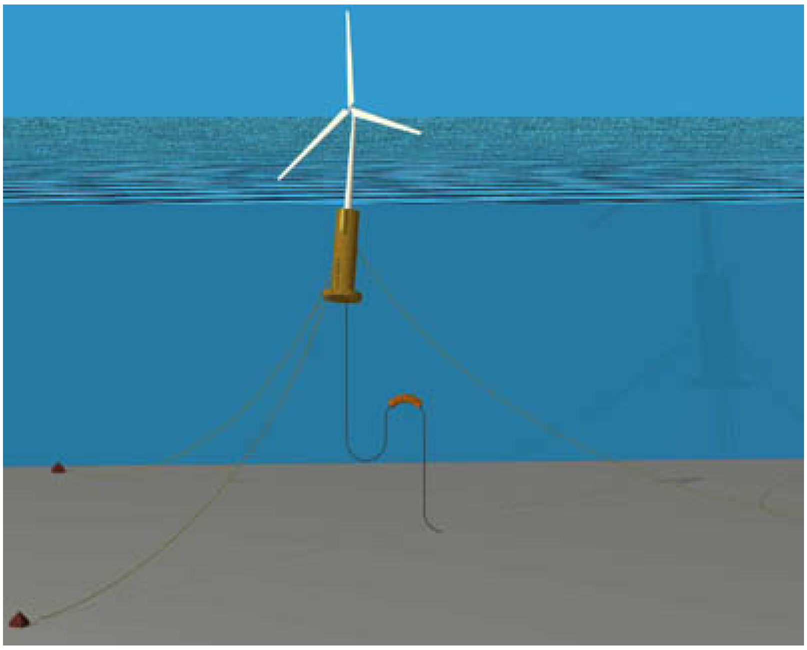


Figure 6: Buoy floating support structure, Ref. [14]

10.2 The semi-submersible type

As opposed to the afore-mentioned case the main semi-submersible support structure will be located below the water surface. This technique is well proven in the oil and gas industry, and the deep submergence of the individual hulls arranged in a larger structure lead to reduced response waves and with longer natural periods of motion. These characteristics are attributed to the wave kinematics to decay exponentially with depth. The hulls will be manufactured from reinforced concrete and braced to an overall structure capable of carrying a cluster of 3–6 multi megawatt turbines. These clusters can adopt various shapes to comply with different optimisation targets. The complete arrangement is to be moored by catenary chains to piled anchor points on the seabed. Investigating the loads on the turbine in comparison to those found for turbines on bottom-mounted support structures has provided evidence of a dramatic increase in fatigue damage for the floating case[8,11,12]. As already stated, floating offshore wind energy systems were directly drawn from oil and gas experience with the controversial increase in cost well justified, unlike the case for wind energy where cost reduction is the main driver. This leaves floating wind energy systems as an option that is considered to be technically feasible, but at present there is no incentive to take forward the cost for the exploration of these deep-water sites. This type of support is thoroughly investigated in the literature.

11. Floating Offshore Wind Farms

The principle of using a floating storage and or production towers as well as spar floating structures for many purposes was known and been in use throughout the second half of the past century. Over the final decades of the last century, a number of feasibility projects have examined the possibility of locating wind turbines on floating structures. Summary of the main advantages and disadvantages of the Multiple Unit Floating Offshore Wind farm (MUFOW) concept compared with single units as follows: lower installation costs (per unit), improved stability, better dynamic characteristics, easier maintenance, smaller turbine spacing, weather vamping required and limited range of water depth. Henderson [13], reported a detailed work at (UCL), includes the moorings, the motion response and economics of a floating wind energy concept consisting of multiple wind turbines mounted on a horizontal floating cylinder.

Henderson [13], reported work concentrated on overall concepts and investigated small unit multiple turbine devices. Various configurations were investigated with emphasis on the overall design, the conclusions were:

- Platform based turbines could be competitive with inland based schemes.
- Depth of water was a key parameter, when considering mooring performance and competitiveness with respect to fixed designs.

The float concept believed to be the future offshore wind turbine for deep ocean wind energy exploration, ‘Garrad-Hassan/Technomare/BMT’ developed this concept for the European Union and briefly reported by, Henderson [13], Group [11], and Hogler [12] and others, in the period between 1992 and 94. The selected concept was a single turbine located on a large floating cylinder, though other configuration such as barge platforms; four-column semi-submersible hulls and twin turbines were also reported.

The evaluation of using an explicit finite element analysis code .LS-DYNA3D for analysing this optimised design is the basis for the work reported in further detail by [14]. In summary, the concept consists of:

- Simple tubular concrete hull buoy,
- Water depth between 75m and 500m,
- Catenaries chain or taut wire synthetic fibre eight-line mooring,
- Shared piles anchors,
- Submerged or mounted 3.3/33kV transformer,
- Three bladed 60m diameter 1.4MW turbine,
- Free-yawing, downwind design at 45.6m above sea water level,
- High tip speed rotor.

The estimated cost of power was 9p/KWh, Rehfeldt and Matthias [8] and Group [11] for a site in the Northern Irish Sea.

Looking at the design in greater detail, the turbine hub is located at a height of 0.75 of rotor diameter, lower than might be practised for a land-based machine, to reduce the leverage of the wind thrust turning moment. As stability is critical for this offshore concept, using a tripod lattice steel tower (transparent) further reduces the turning moment.

Free yawing was selected due to the initially perceived inability of the floating structure to provide a sufficient reactive moment. This has implication in the design for the farm and physical size which will be used.

Henderson [13] reported all the above-mentioned floating concepts and added that a group from Milan investigated single turbine concepts under a title of ‘Eolomar’ including toroidal or lens shaped semi-submerged floating structures. The advantage of this novel shape is its good hydrodynamic performance, but it was subsequently discarded for a lattice design due to its likely expense. Both theoretical and model testing were claimed to be performed on the float concept, however none of the results of such tests were reported in the accessible literature.

12. Mechanical Characteristics of Wind Energy Converter

A wind energy system transforms the kinetic energy of the wind into mechanical then electrical energy that can be harnessed for practical use.

There are two basic designs of wind electric turbines:

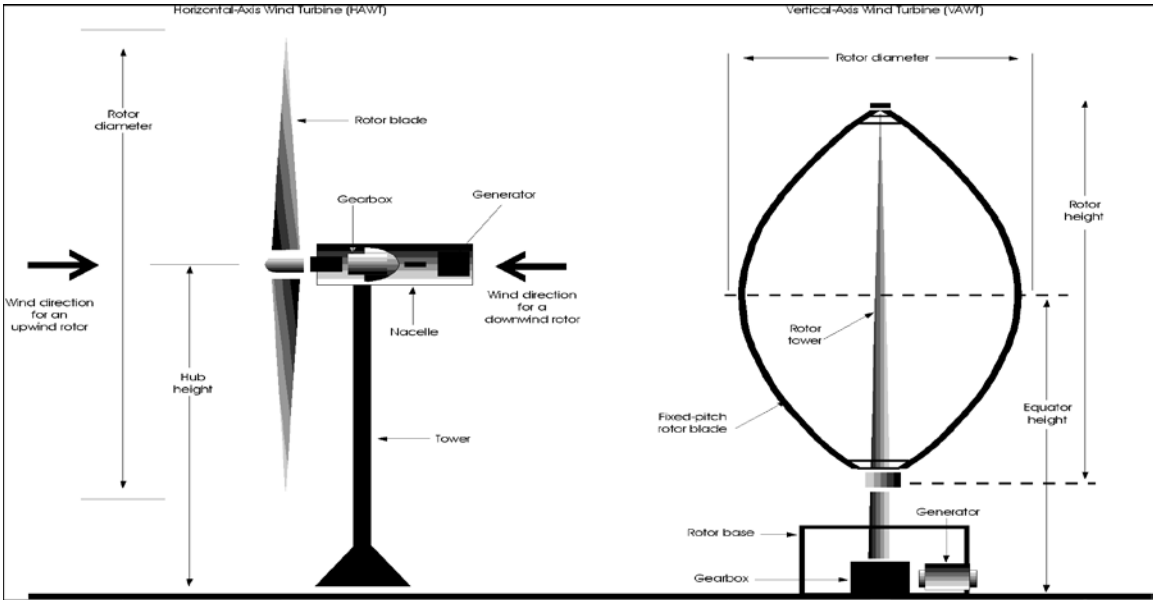
- Vertical-axis, or “egg–beater” style, Figure 7: (a) and
- Horizontal–axis machines, Figure 7: (b)

Simply refer to the axis about which rotation of blades is taking place. Horizontal axis turbines are the most common in commercial use. The wind turns the blades, which spin a shaft that connects to a generator and produces electricity.

Horizontal wind turbines could be operated by one, two or three blades, with the three blades option being mostly used as ‘upwind’ with blades facing the wind, while the two blades option is used as ‘downwind’ with the rotor placed on the lee side of the tower. The whole system (turbine) is mounted on the top of a tower (concrete or steel), with its foundations piled into or bearing on seabed for shallow waters or otherwise floating for deep waters as has been discussed in previous headings.

There are three basic physical laws governing the amount of energy available from the wind (The 3-law criterion). The first states that the power generated by the turbine is proportional to the wind speed cubed, i.e. if the wind speed doubles, the power available increases by a factor of eight. The second states that the power available is directly proportional to the swept area of the blade length, i.e. doubling the blade length will increase the power by four times. The third states that there is a maximum theoretical efficiency of wind generators of 59%. In practice, most wind turbines are much less efficient than this and different types are designed to have a maximum efficiency at different wind speeds, a matter of concern to mechanical engineers, and extensively researched.

Once electricity is produced, it has to be readily integrated into the utility grid or network by means of transformers, which could be installed inside the raising tower or somewhere near the surface.



(b) (a)

Figure 7: Vertical and horizontal axis wind converter (AWEA) website, 2001, Ref. [14]

13. Overall Design Considerations for Wind Energy Systems

There is a long experience in offshore technology with design of large and unique fixed structures for the petroleum industry, which are built “fit for purpose” with respect to their site and function.

Transportation and installation issues are often a main design driver since these costs can be even higher than those for the manufacturing of the structure onshore. Reduction and where possible elimination of underwater inspection and maintenance is essential due to the difficult access and the high costs associated with these operations offshore. Other important design aspects concern the safety of personnel working on or travelling to the structures, environmental impact and dismantling.

It is obvious, because of the diversity of the components, sites and materials involved in wind energy systems, that the engineering methodology of dealing with these different parts will be different. The design of the mounted components (nacelle and rotor) is a concern to mechanical engineering, with fatigue and heat control dominating as design criteria, however, discussion will be limited to their structural behaviour.

As for the design of the supporting structure (tower and foundation), in conventional design practice the environmental conditions are determined on the basis of independent estimates of extreme ice, extreme wave, extreme current and extreme wind conditions each having a return period of say 50 years or as required by the standard in use. These conditions are next assumed to occur at the same time and to act in the same direction. This result in environmental design conditions and a corresponding global load condition with a very long return period and unnecessarily conservative design. In fact, the probability of simultaneous occurrence of all these loads is very remote as will be discussed later.

For the supporting part of the mounted turbine (tower and foundation) it is primarily the stability due to the high moment resulting from lateral loads at the foundation seabed interface that govern the design, with sliding, compression, bearing, buckling and possibly shear.

In addition to the critical combination of wind, wave and current forces, affecting the support structure, fatigue due to hydrodynamic and aerodynamic damping loading is an important factor; fatigue due to aerodynamic loading is dominated by the rotor thrust and the fundamental frequency of the support structure relative to the rotor angular velocity. Fatigue due to hydrodynamic loading generally considered minor for shallow waters and will be significant for deep waters.

To insure structural integrity, safety factors must be applied to external loads, and partial material safety factors for fatigue analysis also must be applied the same arguments apply for bearing and sliding resistance of the foundation.

The primary objectives when choosing a concept for any energy generating project are: cost, safety and reliability. It is not clear which type of floating wind farm concepts will deliver these most efficiently. Floating wind farms will experience extremely hostile environments and will be subjected to a much more complicated mixture of static and dynamic effects, yet still its design is mainly preoccupied by cost reduction, unlike its rival, offshore oil and gas industry, where profit justifies innovation.

Broadly speaking, it is economic to invest a high amount of capital in order to achieve high and reliable energy output, for instance, a 30% increase in wind turbine costs results only in 10% extra energy cost, Hogler [12], others reported by Mohamed [14].

14. Different Design Methodologies for Offshore Wind Energy

Although the challenges of building large offshore wind farms will be considerable, with many of the problems relating to the converter (turbine) will have previously been faced on-land, and those relating to the support structure by the offshore industry. The key point will be to know how to integrate these two technologies. In fact, the combination is not always equal to the sum of the parts, both in a beneficial and a detrimental sense, hence a cost-saving opportunity may be missed and unexpected problems may be encountered during construction and operation. Once more, avoiding unnecessary costs is especially important now when offshore wind energy aims at becoming competitive on price with traditional energy sources.

Offshore wind energy is fairly new field; almost one may think of several different design approaches for an offshore wind park depending on the already gained experience, the project size, the design philosophy, applied standards, etc. Hogler [12] and others as well; reported four approaches, these are identified with their order of increased consideration of offshore wind energy conversion system (OWECS) design aspects and the required experience jointly integrated and used as a basis for European design approach. These approaches are:

14.1 Robust or traditional design approach

This approach makes use of the well-developed offshore oil and gas technology mixed with the relatively well known onshore wind energy technology. The main objectives of the approach are the demonstration, the investigation of environmental effects and the gathering of first experience rather than high economic performance. Therefore, more or less standard onshore wind turbine designs are applied. Wind turbines and towers out of the series production are installed in a similar manner to onshore.

Furthermore, reduction of operation and maintenance costs is aimed for by well proven onshore wind turbine designs marinized by features as for instance improved corrosion protection, air–tight nacelle, built–in lifting facilities, etc.

This approach was used by Danish designers in 1990s, and though it may be applicable for the site it was designed for, it may not be feasible for large scale wind energy systems due to its limitation to sheltered waters with minimum wave loading and poor economic performance, it is evident that this approach refers to bottom mounted turbines.

14.2 Parallel structural design approach

This approach was used by the Dutch and Swedish designers in 1990s and as a basis for Phase II of the (Opti–OWECS) project which is the European integrated design approach [14]. In this approach, one may think separately of the offshore design implications for the main sub-system as wind turbine, support structure, grid, etc.

In the Dutch version of this design, monopile foundation supports a standard onshore tower and a cable laying technique with partial avoidance of a cable laying ship. Though it is considered to be success, the system aspects have not been fully considered, specifically, investigation of overall dynamics. It is however, acceptable to sheltered sites [12].

In the Swedish version, however the support structure design intended as a small-scale prototype system while installation procedures are adapted from onshore to offshore. The entire unit has been fully assembled and commissioned prior to towing to the final destination so that in-situ work was minimised.

This approach may look promising if strong experience is available at sub-system level. Nonetheless, this procedure might not achieve the best performance that is feasible in the nearby future because of the lack of system integration in the economic optimisation and the dynamic analysis and how these features are adapted to system design [8,11].In the aforementioned approaches, the direct mix of onshore and offshore techniques eventually led to conservative design.

14.3 Integrated overall design approach

This is a developed version of the previous approaches with more consideration to particular properties of the constituents. Still, sub-system design is done in parallel based on the state-of-the-art knowledge in wind engineering and offshore technology. However, the solutions are governed by overall criteria such as: global economics, actual site conditions, entire system dynamics, transportation and installation as well as operation and maintenance strategies. This is the typical design approach for most structures.

Therefore at least the site selection, the preliminary design and a check of the final design have to be done with respect to these global criteria. Moreover, the engineers in the different disciplines involved need assistance and new tools for judging intermediate results during the design process.

14.4 Radical design approach

This approach follows similar methodology to the last approach the difference however, is in the use of unconventional designs for the entire sub-system, which provide a major (economic) benefit for the entire system. In addition, the radical design approach requires that the (preliminary) design is governed by the offshore wind energy requirements rather than by adapting simply existing experience for the new situation. This might include: In wind turbine system one may think of the “ultimate wind turbine” an extremely flexible turbine with the absolute minimum of components, an umbrella type wind turbine which adjust their shape according to the wind loading, a multi turbine concepts or no-maintenance concepts. Unconventional support structures are proposed by the Multi Unite Floating Offshore Wind Farm (MUFOWF) concept [13,14].

Ultimately this approach might be the most promising. However, unproven or just (large) designs, do not lend themselves well for application in the demanding offshore environment.

The experience gained during the course of the other design approaches is necessary. Therefore, the radical approach is not considered feasible at the moment but may be required for very large offshore wind farms with a capacity of several hundred megawatts.

15. Environmental Concerns of Wind Energy

For the most part, wind power plants have little impact on the environment compared to other conventional power plants. The only concern with the use of the wind power is the noise produced by the rotor blades, aesthetic impacts and sometimes birds have been killed by flying into the rotor blades. Most of these problems have been eliminated or reduced by technological development and/or properly citing of wind plants e.g. offshore.

Offshore wind energy therefore is giving the proper solution for noise, visual impacts, moving shadows and illusion by locating wind farms in (no-man’s land) high in the seas. Through proper location and alignment, other problems can eliminate some of the concerns namely: i) Impact on birds either by effects on their living and feeding and hence breeding habitat or by blocking their migration roots and thus the risk of collision. ii) Impacts on fish, fishery and sea mammals and marine fouling. iii) Impacts on air and ship traffic roots. v) Impacts on electromagnetic communications. vi) Impacts on seabed mining.

Fortunately, all these negative aspects are either has been addressed by the technology or under thorough investigation and are therefore on their way to be eliminated. Because of the public awareness and sensitivity of these issues, public acceptance is a corner stone in planning these projects, due to its political effects on decision makers, many studies were devoted to environmental consequences of offshore wind energy some of them are completed, some are still underway, and definitely many will follow and be parallel to this energy. Among the reported literature, reference is made to British Wind Energy Association, Metoc Plc, and European Commission web sites [11,12], collectively they form very good background for highlighting the main environmental concerns and paving the road for more environment friendly energy.

16. Conversion of Wind Energy

How can the variations in the wind velocity over a period of time be converted into an annual energy output in kilowatt-hours (kWh) for the wind turbine?

Starting from a time series of wind velocity and integrating the power in a series of small time intervals over the specified period, this can be done from a turbine power characteristic with the cumulative distribution of wind speeds. The variation of wind speed with height needs to be taken into account, then a value representing the speed at the given hub height is chosen. Depending on local wind speeds, a turbine will produce an annual average power that is some proportion of its maximum rated power, typically up to 30%. Assuming the wind turbine will be available to operate for 95% of the time, the overall annual load factor or capacity factor would then be 0.3 x 0.95 or 28.5%.

Studies relating power output (kW) to wind speed shows that optimum power is extracted between speeds of 5 m/s and 13 m/s [6,5,1], and with speed below 5 m/s (usually known as the cut-in wind speed) there is not enough energy in the wind to overcome the mechanical losses within the turbine. While the number of hours per year when the wind speed exceeds 13 m/s is quite small, therefore typical speeds within the mentioned range is widely used in rotor design. The hub height wind speed at which the turbine produces its maximum or rated power is known as its rated wind speed.

There are two main techniques for limiting or regulating the power of the wind turbine. Pitch regulation rotates the wind turbine blades mechanically in order to reduce their aerodynamic efficiency, thereby lowering C_p (coefficient of performance known as ‘Betz limit’). Stall regulation allows the blades to go into condition of aerodynamic stall when the wind speed is high; the blades are not mechanically moved. Stall regulation also reduces aerodynamic efficiency, limiting the power which must be transmitted by the drive train to the generator.

17. Rotor Function

In principle, there are two different types of wind energy conversion devices: those which depend mainly on aerodynamic lift and those which use mainly aerodynamic drag.

Low speed devices are mainly driven by drag forces acting on the rotor. They generally move slower than the wind, and their motion reduces rather than enhances the power extraction. The torque at the rotor shaft is relatively high.

There are many types of wind rotors in use, which are dependent on the purpose and function, such as electricity generation (high speed or lift type) whereas water pumping (low speed or drag type). For the same swept area (area covered by the rotor blades motion) the power extracted by a wind turbine relaying on lift forces is generally many times greater than the power from a turbine relying on drag. Although Betz limit for energy conversion applies to any type of wind turbine despite the orientation of its axis of rotation, horizontal-axis or propeller-type turbines are more common and highly developed than the vertical-axis designs. Vertical-axis wind turbines range from the drag type such as the Savonius type and cup anemometer for measuring wind speed to high speed turbines where the blades are vertical and straight with a symmetrical air foil profile or as curved in the classic Troposkien shape. The later are usually known as the Darrieus type and the shape is such the centrifugal loads are balanced by pure tension forces in the blades, thus avoiding bending moments.

Modern vertical axis machines have several advantages: they operate independently of the wind direction; hence yawing mechanism is not required; heavy gearboxes and generating machinery may be situated at ground level; as they rotate the blades do not suffer fatigue stresses from gravitational induced forces. They also have some disadvantages: they are not self-starting; the torque fluctuates with each revolution as the blades move into and away from the wind; and speed regulation in high winds can be difficult. There have not been enough indications in the published literature that the vertical axis wind turbines are proven to be as cost-effective as their horizontal-axis counterparts. Therefore, the commercial significance of vertical-axis wind turbines is somewhat limited for the time being.

Whether the rotor is allowed to run at variable speed or constrained to operate at a constant speed is decided by the designer according to the employed function. For small battery charging and water pumping turbines, it is desirable to allow the rotor speed to vary. However, for the large-scale generation of electricity it is common to operate wind turbines at constant speed. This allows the use of simple generators whose speed is fixed by the speed of the frequency of the network. Variable speed wind turbines are sometimes used for electricity generation but a power electronic frequency converter is then required to connect the variable frequency output of the wind turbine to the fixed frequency of the electrical system.

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