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Potential for Floating Offshore Wind Energy in Japanese Waters

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ABSTRACT

The prospects for large scale commercialisation of sea-bed-mounted offshore windfarms are currently excellent, with the existing small-scale prototype windfarms currently being joined by the first large-scale parks in the shallow seas off the Danish, German, Swedish, Dutch, Belgian, British and Irish coasts. However other countries, including Japan, have much more limited regions of the shallow waters suitable for such developments and hence other concepts will also need to be utilised if offshore wind energy is also to become a major source of energy there.

KEY WORDS: wind-energy, Japan, offshore, deep-water, floating, resource estimate, review

INTRODUCTION

With bottom-mounted wind turbines promising to become a common feature across the shallow seas of Northern Europe, the question arises of what the prospects are for the generation of power in the deeper waters there and elsewhere in the world, such as around Japan.

This paper reviews recent floating offshore wind energy studies and identifies the most critical aspects that will need to be addressed for the concept to be successfully implemented. It draws on the conclusions from a recent research project investigating the feasibility of multiple-floating-offshore-windturbines (MUFOW), which estimated that the costs of this concept (large semi-submersible vessel) were currently uneconomical. The reasons included the massive structure necessary to withstand the wave loads and the additional equipment, such as moorings, necessary. However, the scope of that project was limited to that particular concept and others may potentially become cost-effective if both the wind energy and the offshore engineering industries continue to develop innovative and cost-reducing technologies at the rate achieved over the past decades.

This paper reviews previous and current floating wind energy activities and offers a prognosis for future development with an estimate of the potential resource in Japanese waters. To date, such activities have been limited to feasibility and design studies, with the high cost of the floater and in particular of the mooring systems, inhibiting the realisation of any of the proposed concepts up to now. The potential resource is estimated here using satellite measurement derived ocean wind speeds (SSM/I data sets) and ocean bathymetry (ETOPO 6) data. The wind speed data was gathered by making use of the close correlation between the wind speeds at the water surface and the surface roughness, and hence also with the power of reflected and scattered microwave pulses. The bathymetric data covers the entire globe in a 2-minute grid and allows for the accurate prediction of sea depths, and thus suitable areas for both conventional (up to -50 meters in depths) and floating offshore (-200 m) wind power plants.

We show that the technical potential of seabed-mounted offshore wind power plant energy yields in Japan is approximately the same as current electricity supply. To be fully competitive with carbon-based energy sources, offshore wind power will have to show larger potentials for electricity supply in general, and in particular for the population centres on the main island Honshu (in contrast to outlying islands) where suitable offshore sites near the coast are scarce. Sites of high wind speeds are limited and can be better exploited if such areas can be enlarged by the utilisation of floating offshore devices. These could also serve to more equally distribute utility access to offshore wind power. Furthermore, floating offshore systems should prove popular in Japan where land-based transport routes for large machinery are difficult, and may work as an incentive for the ship-building industry in the country.

Last year saw the construction of the first offshore windfarms using MW sized wind turbines, as a precursor to the very large windfarms that are planned to be built over the next few years in the shallow seas surrounding Denmark, Sweden, Germany, Netherlands, Belgium, Britain and Ireland. These windfarms will consist of tens to hundreds of such MW-sized turbines and for the first time, it will be possible to build a wind-energy power station with a similar output as a conventional plant. Offshore wind energy will become a major source of energy across large regions in northern Europe and the trend of companies from the traditional energy industries becoming involved will continue. This is likely to lead to further attempts to introduce novel technology onto the market as these organisations attempt to apply their knowledge to the problem of generating large amounts of electricity from the wind, both cheaply and reliably. An important question is whether they will be successful and for this paper, whether offshore engineering companies will be able to do so for floating windfarm concepts.

PREVIOUS ACTIVITIES

To date, a limited amount of effort has gone into developing and evaluating various floating windfarm concepts, which is briefly summarised below. Several very different concepts were developed since the early 1990s, including:

- In the United Kingdom, Garrad Hassan and Technomare co-operated in the evaluation of a single turbine concept, located on a spar-buoy and kept in position using eight-point catenary moorings (Tong, 1994). This was a fairly detailed study and aspects such as type of wind-turbine (downwind, free-yawing with very-high tip-speed), multiple vs. single turbine structures, sharing of anchoring systems and tower design (lattice type to reduce wind loads and overturning moment) were investigated. The costs were estimated to be inhibitatively expensive at around twice that of bottom-mounted alternatives.
- Also in the United Kingdom, a group at University College London investigated the possibilities of locating several turbines on a single structure with the potential advantage of reduced motion response and shared moorings (hence reduced anchoring costs). This concept was developed in a PhD (Andrew Halfpenny, 1998) and an EPSRC research project (in which the first author was responsible for the wind-turbine and floating structure aspects; Henderson, 2000) to develop research tools and evaluate the idea in greater detail. The main conclusions were that it would be excessively expensive as well as difficult to construct to withstand the wave loads in regions with an attractive wind resource.
- In Italy, a group in Milan investigated placing a single turbine on to a toroidal-shaped float, positioned with tensioned moorings. The complex shape was chosen to minimise wave motion response but had the disadvantage of being difficult and expensive to build (Bertacchi, P. et al, 1994).
- More recently, also in Italy, a proposal has been made to locate electrical generating and desalination plant on a floating pontoon to provide temporary supplies to island communities during the holiday season (Cesari, F. and Gaudiosi, G., 1999). This could possibly develop into a niche market for floating windenergy.
- In Japan, the JOIA (Japanese Ocean Industries Association) is co-ordinating a group of interested parties to evaluate the potential for floating wind energy in that country; the first phase was completed in 2001 (JOIA, 2001) and further work continues with the results of the next stage expected to be complete during this year (2002) and with the ultimate objective being to develop a prototype by the end of the decade. Regarding which concepts would be most suitable for the relatively deep waters around Japan, preliminary conclusions are broadly similar to those identified in this paper.
- and currently in the Netherlands, a feasibility study is being undertaken by the Technical University of Delft, ECN, MARIN, Lagerwey under the co-ordination of TNO. This project is focusing on floating concepts for the shallower waters around the Dutch coast and a report is expected towards the end of this year (2002).

THE RESOURCE IN JAPANESE WATERS

Five regions have been designated to compute the technical potential of offshore wind power generation around Japan, shown in Fig. 1. Table I elaborates on the regional potentials. The maximum water depth is set to -50m to ensure that the wind power converters are within suitable distance to shore. Waters between Japan and South Korea can be shallower than -200m; this would lead to overestimate the technical potential in this area.

Japan may technically generate more than three quarters of its electricity demand by offshore wind power. Japan's location at the eastern edge of the Asian continent leaves her with little continental shelf. A steep slope leads to some of the deepest trenches of the world's oceans on her eastern side. Only the shallow Tsushima Strait between Korea and Japan forms a bridge to the continent. Shallow waters are rather uncommon around Japan.

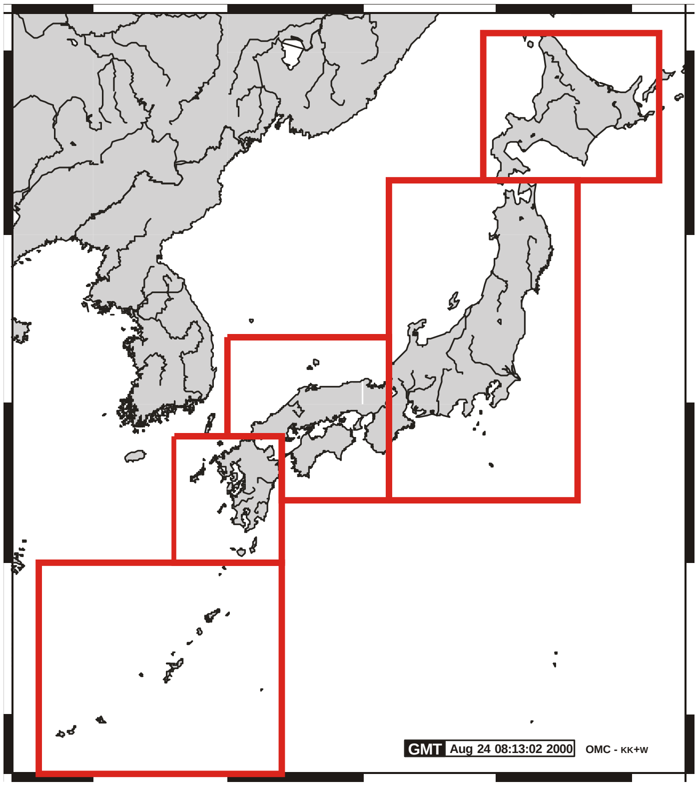

Fig. 1: Regions in computing the technical potential of offshore wind power generation in Japan

Table I estimates of the technical potential of offshore wind power generation potential in Japan, and comparison with local electricity supply.

v = average yearly wind speed [m/s] (1996);
A = suitable area [103 km^2] (50% of shallow waters up to -50 m);
W = energy yield [TWh/a];
I = energy intensity [GWh/a km^2];
Sel = local electricity supply [TWh/a].

Table I: Technical Potential for Wind-power Generation in Japanese Waters

Region	**v**	**A**	**W**	**I**	**Sel**
Hokkaido	8.31	11.8	123	10.43	31
North-Central Honshu	7.71	18.2	154	8.5	524
Western Honshu	7.81	15.9	142	8.93	101
Kyushu	7.5	14.8	113	7.66	80
Okinawa	7.32	24.4	176	7.20	7
World	6.91	5461	36990	6.74	15000

Note that these are conservative values due to spacing (10D uniform, resulting in 1.23 turbines per km^2), arithmetic average wind speed resulting in underestimation of output by approximately 50%, 50% exclusion zone, and 3 MW turbine size. Electricity supply data for Japan from the Federation of Electric Power Companies Japan (1999), world offshore potential by Leutz et al. (2001).

Wind speeds are higher around northern Japan, as expected by the latitude. Still, even in southern Okinawa, wind speeds are only slightly below the world average of 7.5 m/s annually. Some locations off the main island of Honshu, and the northern island of Hokkaido exhibit exceptionally good wind regimen.

The results and assumptions of our study shall be compared with similar studies in Table 2. The two previous studies by Nagai et al. (1997) and Fujii (1999) do not consider a maximum water depth of installations. Instead, the distance to shore is limited to 3 km. This may be a reasonable approximation for most locations around Japan. For the western shore of Korea, this would lead to a gross underestimation of wind power potentials. The distance to shore reflects the length and cost of underwater electricity cables, i.e. an approximation of the distance to the grid or user. The shoreline is not equivalent to the grid. Since the geographical locations of coastal grids around the world were not available, we opted for the general exclusion zone of 50% of all areas less than 50 or 200 m deep. This also includes national parks, oyster and fish cultures, shipping lanes, military exercise ranges, pipelines, cables, and the like.

Table II shows the technical electricity generation potential from offshore wind power in Japan. It compares the results and assumptions for three studies, applying the most plausible scenarios.

Table II: Results and Assumptions for Three Studies

	Nagai et al.	**Fujii**	**present study**
Year	1997	1999	2001
Annual potential, TWh	268	765	708
Wind speed at elevation, m	40	40	50
Maximum water depth, m	-	-	-50/-200
Maximum distance to shore, km	3	3	-
Exclusion zones	Okinawa	Okinawa	50%
Turbine spacing, D (rotor diameter)	10 x 3	10 x 3	10 x 10
Turbine rating, MW	0.5	0.5	3.0
Installation capacity, MW/km2	10.4	10.4	3.7

All three studies compared in Table II result in offshore wind energy potentials in the same order of magnitude. Nagai et al. use wind speed data obtained from some 47 lighthouses around Japan. The error for windspeeds from landward wind directions may explain the difference between their study and Fujii's and ours.

A further point is the exclusion of Okinawan waters in both previous studies, which account for roughly 25% of predicted yields. An exclusion zone restrains errors due to geographical imbalances.

Wind power generated in Okinawa cannot be used in central Japan, as there is no grid connection. Even within Okinawa, islands are rarely connected, and wind energy there is fed into an island grid mainly dependent on diesel generators. The local disproportion of conventional electricity supply in Japan, and offshore wind power potentials can clearly be observed in Table I.

The areas of the monopolistic electricity utility services approximately coincide with the sectioning in Fig. 1. The border cutting across Honshu has its actual equivalent in the division of 50/60 Hz usage zones between eastern and western Japan. In any case, the 50% exclusion factor can theoretically incorporate this problem of regional imbalances.

The moderately high density of wind turbine clusters, proposed by our predecessors to be 10D x 3D where D is the rotor diameter of the turbine, seems high enough to result in efficiency penalties, which should be considered. Larger turbines have been designed, and even the 3 MW machines proposed here, are probably the lower end of the offshore turbine size of the future.

Using satellite measured wind speeds brings the advantage of automatization of simulations. Adding the convenience of bathymetric data, as in our study, allows for simulating technical offshore wind energy potentials for any location around the globe. Incorporating an exclusion zone of some kind reduces the responsibility for making grave errors when areas under consideration become smaller. For example, in a place like Tokyo Bay, although shallow, the erection of wind turbines faces considerable restrictions due to heavy shipping traffic. Once a good offshore site has been identified automatically, other means of evaluation, such as sea charts must be consulted.

An Example

To illustrate the effect of allowing floating offshore wind power and moving into waters up to -200 m deep, the following example is calculated. One may plot the bathymetry of an area under consideration in a three-dimensional way, as shown for the Tsugaru-kaikyo, the strait between Honshu and Hokkaido islands, in Fig. 2.

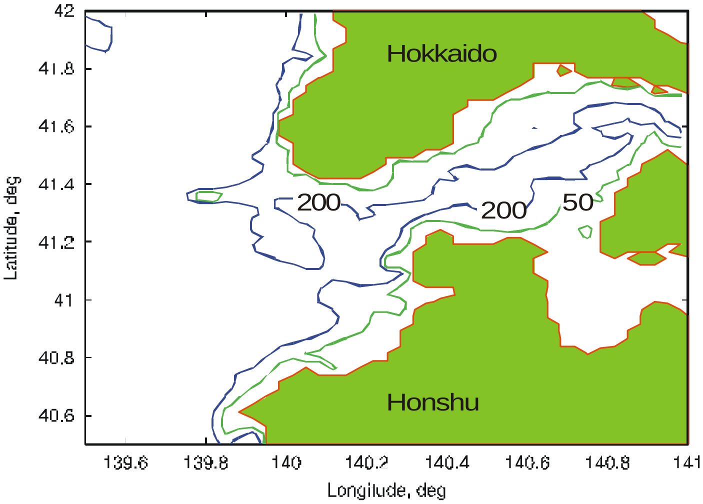

Fig. 2: Bathymetry of the Tsugaru-Kaikyo between Honshu and Hokkaido, Japan

Of the area pictured, 2169 km^2 is less than -50 m deep, and not in the exclusion zone of 50%. Under the assumptions of 10D inter-turbine spacing, and 3 MW size turbines, 8.0 GW of turbines (2667 machines) could be placed here. Under a wind regimen of 8.31 m/s (1996), 22.5 TWh of electricity could be produced annually.

For waters up to -200 m deep, the area almost doubles to 3926 km^2. The average wind speed rises slightly to 8.35 m/s for the same year. As a consequence, the expected potential for offshore power generation is 41.5 TWh, for wind turbines of the same size and spacing.

The monthly mean offshore wind speeds around Cape Tappi compare well with the data measured onshore. Cape Tappi is Japan's prime wind generator testing site, and wind speeds have been documented, for example in Ushiyama and Matsumiya (1995). Cape Tappi offers very favourable wind speeds during winter. The lower monthly wind speeds in summer still reach and exceed 6 m/s, which makes Tsugaru-kaikyo a good offshore wind location.

The example makes clear that offshore wind power potentials can be significantly enlarged by taking into account floating offshore wind power for deeper waters.

Inter-annual variability of wind power

Since the wind energy is a natural form of energy and the humanity cannot control its flow, it is crucial to assess, besides the potential of the energy, how variable the annual electricity generation will be. If the variance is too large, wind power will not be very reliable as a source of energy. Danish Wind Industry Association (2001) states that output from wind turbines, in the case of Denmark typically, has a variation of some 9 to 10 per cent. The SSM/I satellite data is available from 1988. The annual electricity generation calculated using the SSM/I figure and Scenario 2-2 of Fujii (1999), the output is found to stay within 10 per cent of the mean output most of the time (Fig. 3). This suggests that the output can be expected to be relatively stable.

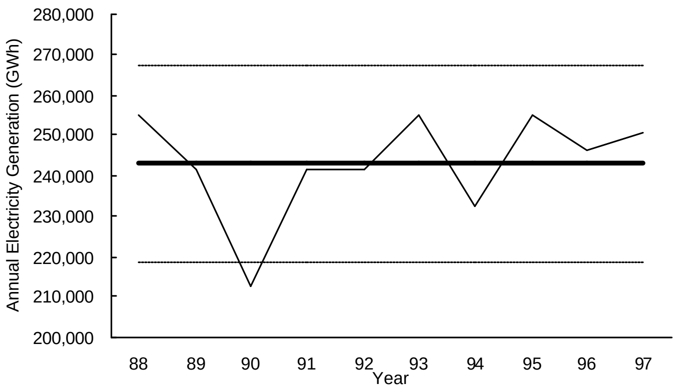

Fig. 3: The inter-annual variability of Japanese offshore wind power (Fujii, 1998).

This observation alone does not, however, the reliability of wind power. For example, it is not possible to predict the influence of long-term fluctuation because of the relatively short observation. Moreover, hourly and daily variations, on which the SSM/I data does not provide much information, are also important to assess the reliability of wind power. More detailed observation will be required to fully estimate the variability of wind power generation.

THE TECHNOLOGY OF THE SUPPORT STRUCTURE

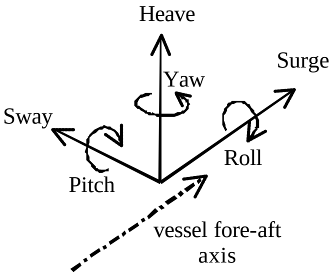

Fig. 4: Vessel Motion Nomenclature

Primary objectives when selecting a concept for any energy generating project are cost, reliability and safety. It is not yet clear which types of floating windfarm concepts will deliver this most effectively, hence the main factors and the more promising options are briefly described with their relative merits below. The nomenclature used for describing vessel motion in the translational and rotational directions are shown in Fig. 4.

Generally speaking, waves do not induce significant yaw motions on to floating structures because of the symmetry of the structure but motion in all other degrees of freedom will generally be present. (Yaw motion could be present due to coupling and misalignment between wind and waves). Note that the wind-turbine community use the word "pitch" for the rotation of the blade to adjust the angle of attack, while the offshore community use this word for rotations of the vessel in the "nodding" direction. The most important wind-technology nomenclature is shown in Fig. 5.

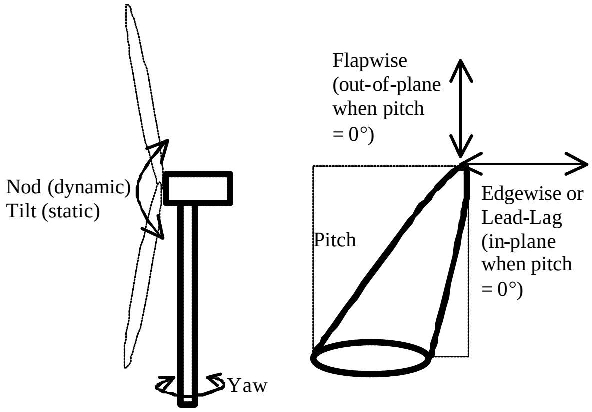

Fig. 5: Wind-turbine Nomenclature

Design Choices

- *location of the main structure*; placing the main structure below the water surface delivers two very desirable benefits: (i) reduced wave loads (hence reduced structural design loads), (ii) reduced motion response of the vessel.
- *single or multiple* turbines; a multiple turbine vessel is able to share anchoring and power systems but will be more massive.
- *steel or concrete*; concrete is cheaper, less dense, heavier for the same structural strength, more durable (longer lifetime) but weaker (particularly in tension for which pre-tensioning with steel cables is needed).
- *moorings*; Catenary moorings are heavy chains, which provide stiffness (resistance to displacement of the vessel) by their weight. They are difficult to use in very shallow water. Tensioned moorings are a relatively recent development and have become popular for offshore installations in the last couple of decades but are still relatively expensive. They allow the vessel to move in the surge, sway and yaw directions only and hence would reduce fatigue loadings on the turbine-rotor (which is sensitive to pitch motion);

Floating vessels for hydrocarbon offshore applications generally require relatively tight station-keeping tolerances (typically 10% of water depth) as the drilling or oil/gas extraction lines need to be reasonably straight in order to function and a failure of the line could result in environmental damage. For this reason and in order to keep individual line sizes (and prices) down, eight-point catenary moorings are often used, as the station-keeping can be maintained using the seven remaining lines, should one fail.

For a floating structure supporting wind-turbines, the station-keeping requirements could be relaxed and fewer lines would be necessary. Moorings would need to ensure that there was sufficient separation between turbines to reduce wake-induced fatigue damage and to ensure that structures did not contact and damage each other should one line fail.

- *fixed direction or weathervaning* (for a multiple turbine vessel); it has been found that turbine wakes prevail over longer distances at sea, due to the lower ambient turbulence; therefore, turbine separation distances will need to be greater and allowing a multiple-turbine vessel to weathervane will be very beneficial. Turret moorings are a widely-used technology for FPSOs (Floating Production, Storage and Offloading vessels) and allow the structure to turn into the waves without twisting the moorings and oil or gas lines. The technology is, however, expensive.

Candidate Floating Platforms

Candidate vessels for supporting offshore windfarms include the following:

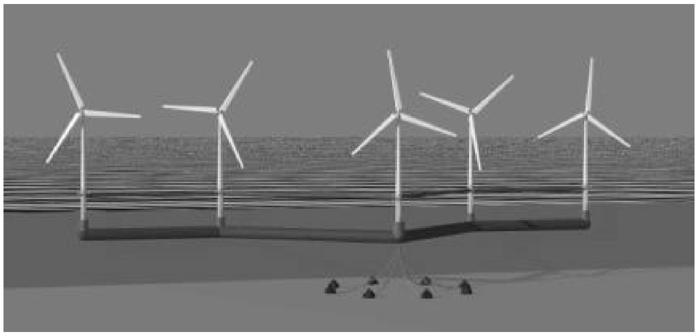

Fig. 6 Semi-Submersible

- *Semi-Subs* (Semi-submersible Fig. 6); these were the original low-motion vessel concept, with the main structure being located below the water line, where wave loads are reduced; station keeping is maintained using catenary moorings and the water-plane cross-section area is kept low with a resulting low stiffness and hence long natural periods and low deck-payload; the main challenges include designing a sufficiently strong structure to cope with the wave loads and developing cost effect yawing mechanisms for the structure.

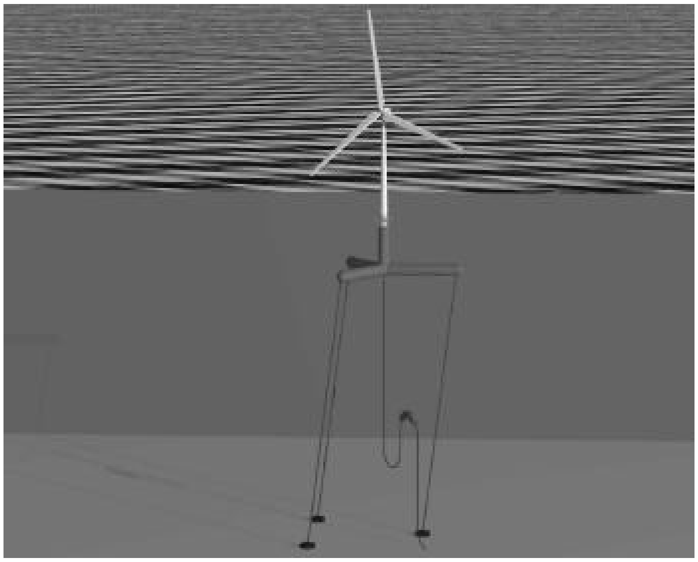

Fig. 7 Tensioned Leg Platform

- *TLPs* (Tension Leg Platforms, or TBP, Tensioned Buoyant Platforms, Fig. 7); a more recent low-motion concept, with a similar submerged structure as the semi-sub but the structure has excess buoyancy which is countered by tensioned moorings; the costs have fallen dramatically over the last decade and a new mini-TLP concept is currently being developed for harvesting marginal hydrocarbon resources; the main challenges include developing cost-effective installation techniques.

- *Spar-buoys* (Fig. 8) are large floating vertical-columns, possibly with with storage space for oil. For floating windfarm applications, the main structure would be moved below the water-line to reduce motion response and since little payload is needed; the main challenges include minimising static and dynamic vessel motion response to turbine and wave loads.

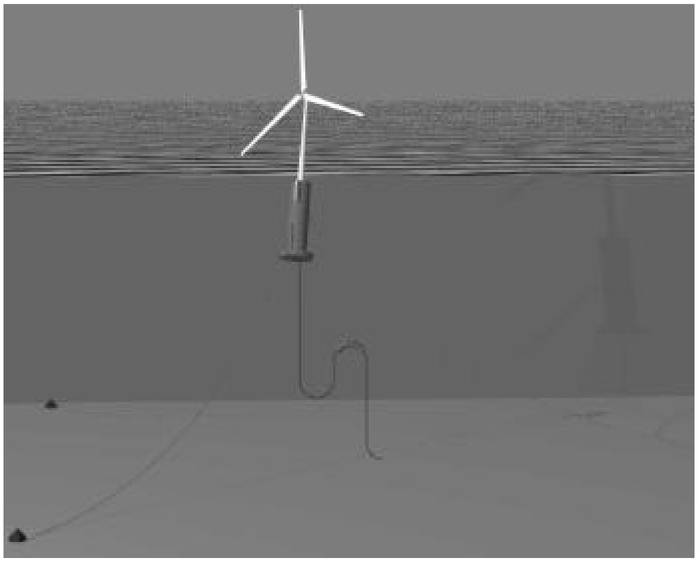

Fig. 8 Spar-buoy

- *Spaceframes* (Fig. 9); also called jacket-structures, are generally bottom-mounted structures located up to medium water-depths but the concept could also be applied to floating vessels. The structure consists of a framework of slender members, hence wave loads are lower and are predominantly drag rather than inertia induced and the large cross-section results in a relatively stiff structure; the main challenges include developing cost effect yawing mechanisms for the structure.

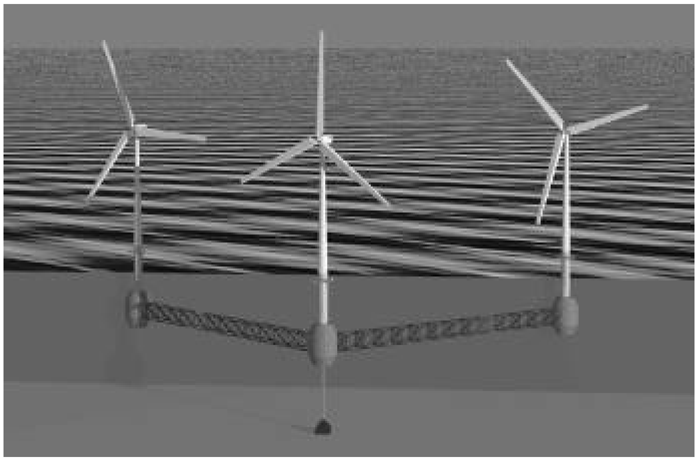

Fig. 9 Space-frame Vessel

THE EFFECT OF WAVE-INDUCED MOTION ON THE WIND-TURBINE

Locating a wind-turbine on to a moving vessel will induce additional aerodynamic and inertial loads. This section makes a simple qualitative analysis of the likely impacts of the wave-induced vessel motion on the loads experienced by the turbine, the effect on power output being likely to be minimal. Both blade root flapwise and tower base loads are considered as they are particularly susceptible to vessel-motion induced loads. Other components that would also need to be considered are the rotor shaft and the yaw bearings and drive.

For the simple quantative calculations, a generic variable-speed variable-pitch turbine has been assumed of the type likely to become the most commonly used in the future bottom-mounted offshore windfarms:

Table III: Turbine Rotor Parameters and Assumptions

rotor diameter	D	100m;
rotor frequency	f_R	15 rpm
	ω_R	1.57 rad/s
number of blades	N_b	3
radius of gyration of rotor	r_g	16.7 m
total thrust load	T_t	500 kN
power output	P_r	3.5MW
thrust moment arm	r_t	30m
mass of blade	m_b	12.5 tonnes
thrust / wind-speed slope	dT_t / dU_∞	50 kN / m/s

Table IV: Turbine Tower Parameters and Assumptions

tower top mass	m_{tt}	240 tonnes
tower height	h_n	65 m
tower mass	m_t	260 tonnes

Table V: Environmental Parameters and Assumptions

wind speed	U_∞	20 m/s
wind turbulence	I	12 %
wave height	H_w	10 m
wave period	T_w	12 s
	ω_W	0.52 rad/s
translational vessel motion response	RAO_{123}	1
rotational vessel motion response	RAO_{456}	0.5

- $\therefore$ torque (on each blade) = $\overline{Q_b} = \frac{P_t}{w_R.N_B} = \frac{3.5\times10^6}{1.57\times3} = 743\ kNm$
- $\therefore$ std. dev. of windspeed = $\sigma_U = U_\infty.I = 20\times12\% = 2.4\frac{m}{s}$
- $\therefore$ std. dev. of peak surge velocity $\hat{\dot{x}}_1 = w_w.\frac{H_w}{2}.RAO_{123} = 2.6\frac{m}{s}$
- $\therefore$ std. dev. of peak surge acceleration
$$\hat{\ddot{x}}_1 = {w_w}^2.\frac{H_w}{2}.RAO_{123} = 1.3\frac{m^2}{s}$$
- $\therefore$ std. dev. of peak pitch velocity
$$\hat{\dot{q}}_5 = \frac{{w_w}^3}{g}.\frac{H_w}{2}.RAO_{456} = 0.037\frac{rad}{s}$$
- $\therefore$ std. dev. of peak pitch acceleration
$$\hat{\ddot{q}}_5 = \frac{{w_w}^4}{g}.\frac{H_w}{2}.RAO_{456} = 0.019\frac{rad}{s^2}$$

Blade Root Flapwise Loads - Trends with Turbine Size

Flapwise (in the direction of the free-wind stream) blade root loads are sensitive to surge, pitch and yaw motions but this section will focus on pitch, as an example. If we consider the effect that increasing the turbine size has on the relative magnitude of the existing loads against the new motion-induced loads, we can conclude whether fewer larger turbines or more smaller turbines are most appropriate for use in floating windfarms.

Considering fixed-base turbines, the dynamic and static loads at the blade root will be proportional to the thrust, which is proportional to the swept-area. Hence, taking account of the moment arm, the fixed-base loads are proportional to the diameter cubed.

$$M_{flapwise\ fixed} \propto {D_{rotor}}^3 \qquad \text{Eq. 1}$$

Turning to the gyroscopic load, this is proportional to the product of the inertia, the gyroscopic precession and the rotor speed:

$$M_{gyroscopic} = I_{rotor}.w_{precesion}.w_{rotor} \qquad \text{Eq. 2}$$

By analysing existing turbine blade weights, a trend of blade weight against rotor diameter can be shown to be approximately (CA-OWEE, 2001):

$$m_{blade} \propto {D_{rotor}}^{2.35}$$

Similarly, it can be found that the rotor speed is inversely proportional to the rotor diameter as the limiting factor is the absolute tip speed:

$$w_{rotor} \propto {D_{rotor}}^{-1}$$

If we assume that using a large turbine on a larger vessel will result in a slight reduction in the amplitude of the vessel motion, the gyroscopic precession will likewise be reduced slightly, then the relationship between turbine size and gyroscopic loads is:

$$M_{flapwise\,gyroscopic} \propto \left(D^{2.35}.D^2\right).D^{-0.2}.D^{-1} = D^{3.15} \qquad \text{Eq. 3}$$

Hence, by comparing Eq. 1 and Eq. 3 it can be concluded that large turbines will experience slightly greater motion-induced loads than smaller turbines but the difference is relatively small.

Blade Root Flapwise Loads - Simple Quantitative Evaluation

The <u>mean</u> loads at the blade root in the flapwise direction are due to the thrust on the rotor.

$$\overline{M}_{thrust} = \frac{r_t.T_t}{N_B} = \frac{30\times500\times10^3}{3} = 5MNm \qquad \text{Eq. 4}$$

Turning to the major sources of dynamic loads for a fixed-base wind-turbine in turn, first consider the effect of <u>misalignment with the wind</u>. This is typically in the order of 5 degrees due to a tracking-error in the yaw-axis and also typically about 5 degrees due to the tilt (in the vessel pitch direction) applied to the nacelle in order to give the blade additional clearance from the tower. A floating wind turbine may also have an additional heel displacement (in the vessel pitch direction), due to the turbine thrust loads.

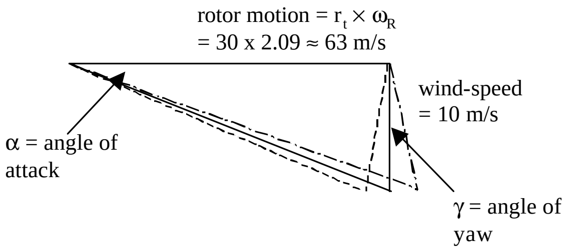

Fig. 10: Effect of Yaw on Angle of Attack

From geometrical considerations, Fig. 10, $\delta\alpha \approx \gamma / 40$; from potential flow theory, we can estimate that for a 20 ° misalignment, the lift force, and hence the loads, would vary by approximately 5% of the mean value:

Turbulence is a major cause of wind turbine fatigue. On land, it can reach 20%, whilst offshore, this figure typically reduces to 12% for the nearshore sites of interest, hence using the wind-speed standard deviation, an estimate of the turbulence induced loads would be as follows, which is 24% of the mean loads.

$$\begin{aligned}\tilde{M}_{turb} &= \frac{dT_r}{dU_\infty}.s_{U\infty}.\frac{r_t}{N_b} \\ &= 50\times10^3\times2.4\times\frac{30}{3} = 1.2\,MNm\end{aligned}\qquad \text{Eq. 5}$$

Upstream wakes can reduce the wind-speed by 50%, hence following similar lines, would induce dynamic loads equal to the mean value. Being situated in a wake is indeed the most onerous operating condition for a land-based wind-turbine, hence wind-turbines need to be separated typically by more than 5 rotor diameters.

$$\begin{aligned}\tilde{M}_{wake} &= \frac{dT_r}{dU_\infty}.\frac{U_\infty}{2}.\frac{r_t}{N_b} \\ &= 50\times10^3\times\frac{20}{2}\times\frac{30}{3} = 5MNm\end{aligned}\qquad \text{Eq. 6}$$

Now attending to the floating situation and the most interesting first, e.g. due to gyroscopic effects; this is are given in Eq. 2, with the peak gyroscopic rate being:

$$\hat{v}_P = RAO_{456}.w_w.k.\frac{H}{2}\qquad \text{Eq. 7}$$

Hence the dynamic gyroscopic loads can be estimated to be approximately 4% of the mean loads.

$$\begin{aligned}\tilde{M}_{gyroscopic} &= \left(12.5\times10^3\times16.7^2\right)\times0.5\times\left(\frac{0.52^3}{9.81}.\frac{10}{2}\right)\times1.57 \\ &= 0.20\,MNm\end{aligned}$$

Dynamic loads will also occur due to the *surge* motion, by both aerodynamics (26%) and inertia (2%):

$$\begin{aligned}\tilde{M}_{surge\ aero} &= \frac{dT}{du_\infty}.\hat{\dot{x}}_1.\frac{r_t}{N_B} \\ &= 50\times10^3\times2.6\times\frac{30}{3} = 1.31MNm\end{aligned}\qquad \text{Eq. 8}$$

$$\begin{aligned}\tilde{M}_{surge\ inertia} &= m_b.\hat{\ddot{x}}_1.\frac{r_g}{N_B} \\ &= 12.5\times10^3\times1.3\times\frac{17.5}{3} = 0.1MNm\end{aligned}\qquad \text{Eq. 9}$$

We can conclude that the effects of the wave-induced motion (26% of mean load, using conservative assumptions, Eq. 8) will be similar in order of magnitude to the fixed-base case (24%, again using conservative assumptions, Eq. 5) and hence the turbine design would not need to be modified significantly.

Tower Base Loads - Trends with Turbine Size

For a fixed turbine, the bending moment at the tower base due to the turbine thrust loads will be proportional to the swept-area and the tower-height. The trend of tower height for existing turbines can be shown to be approximately (CA-OWEE, 2001):

$$h_{tower} \propto D_{rotor}{}^{0.7}\qquad \text{Eq. 10}$$

Hence, mean tower root loads for a fixed turbine are:

$$M_{tower\ \ fixed} \propto D_{rotor}{}^{2.7}\qquad \text{Eq. 11}$$

The additional loads due to the vessel motion will be the product of the trends for nacelle mass, motion amplitude (used in Eq. 3) and tower height, Eq. 10. The nacelle mass can be shown to vary approximately with turbine size as (CA-OWEE, 2001):

$$m_{nacelle} \propto D_{rotor}{}^2$$

Multiplying the trends together gives:

$$M_{tower\ \ floating} \propto D^2.D^{0.7}.D^{-0.2} = D^{2.5}\qquad \text{Eq. 12}$$

Hence comparing the fixed, Eq. 11, and floating, Eq. 12, cases leads to the same conclusion that there is no substantial trend.

Tower Base Loads - Simple Quantitative Analysis

Considering the mean bending load at the tower base, due to the rotor thrust:

$$\overline{M}_{thrust} = T.h_n = 500\times10^3\times65 = 32.5MNm\qquad \text{Eq. 13}$$

In the previous section, dealing with the blade root loads, it was shown that the major source of dynamic loads was due to turbulence, which will impose a dynamic load of the same relative value, 24%, as in Eq. 5.

Considering effects due to the vessel motion, dynamic loads occur due to *surge* motion, from aerodynamic effects, which will be the same proportional as for the blade (i.e. Eq. 8), 26%, and inertia effects (Eq. 14) (102% of mean):

$$\begin{aligned}\tilde{M}_{surge\ inertia} &= \left(m_n.h_n + m_t.\frac{h_n}{2}\right).\hat{\ddot{x}}_1 \\ &= \begin{pmatrix}240\times10^3\times65 \\ 260\times10^3\times32.5\end{pmatrix}.1.3 = 33.0MNm\end{aligned}\qquad \text{Eq. 14}$$

Likewise loads due to *pitch* motion, from aerodynamic (Eq. 15, 24% of mean) and inertia (Eq. 16, 76%) effects will be:

$$\begin{aligned}\tilde{M}_{ptch\ aero} &= \frac{dT_r}{dU_\infty}.\hat{\dot{q}}_5.h_n \\ &= 50\times10^3\times0.037\times65 = 7.7\,MNm\end{aligned}\qquad \text{Eq. 15}$$

$$\begin{aligned}\tilde{M}_{pitch\ inertia} &= \begin{pmatrix}m_n.h_n{}^2 \\ +m_t.\left\{\frac{h_n}{2}\right\}^2\end{pmatrix}.\hat{\ddot{q}}_5 \\ &= \begin{pmatrix}240\times10^3\times70^2 \\ 260\times10^3\times35^2\end{pmatrix}.0.19 = 24.7MNm\end{aligned}\qquad \text{Eq. 16}$$

The conclusions regarding tower base loads due to the wave-induced motion are not as encouraging as for the blades. For the fixed base, the peak dynamic loads (due to turbulence) will be in the order of 26%; however inertia loads due to surge (Eq. 16, 102% of mean) and pitch motion (Eq. 14, 76% of mean) for these assumptions. Although the values for RAO used are conservative (see Table V) and more appropriate to extreme rather than fatigue cases, they are still within the range that turbines located on the smaller and more promising concepts could experience. Hence either a vessel with reduced motion or a significantly stronger tower would be needed.

DISCUSSION AND CONCLUSIONS

Whether floating offshore wind energy can be made a commercial and technological success depends predominantly on whether costs can be brought down, since the main technological challenges have already been resolved by the offshore oil and gas industry.

Regarding the coupling of the turbine on to the vessel, the effect that the vessel-motion has on the turbine was evaluated and found to be manageable while the effect that the turbine has on the vessel depends on type of vessel; for massive structures, such as semi-submersibles, it is minimal (Henderson, 2000), while smaller structures, such as spar-buoys, could be more susceptible but not necessarily so (Tong, 1994).

It should be noted that the design philosophy used by the offshore industry is very different from that used by the offshore wind energy industry. For oil and gas structures, the critical factors are:

- *time*; delays in starting production result in delayed revenues and have a large effect on profits as hydrocarbons are highly valuable commodities
- *reliability*; lost or delayed production also results in a relatively large loss of revenues and hence profits
- *safety*; the design of any structure that houses both living quarters along with large volumes of highly combustible materials needs to follow stringent safety guidelines; oil is a highly toxic and persistent pollutant and risks of discharge into the environment must be minimised.

The priorities for offshore wind energy projects will not be the same. The previous criteria are reweighted to take account of the lower value and different nature of the product:

- *time*; the capital intensive nature of such projects will mean that timely completion will also be important for offshore windfarms.
- *reliability*; the relatively low value of the commodity (electricity) being generated means that reliability will have a lower (but not low) priority; the windfarm must be available for generating for a high proportion of the time but not at an excessive additional capital cost penalty;
- *safety*: since generally the structure will be unmanned, particularly during storms, more economical designs will be able to deliver a better level of security to the operating personnel than is currently enjoyed on offshore engineering installations. However, the risks should be examined and set at a significantly lower level, as offshore windfarm operators may not want to pay the same premium levels of pay as oil and gas operatives currently enjoy.

The main technological challenges are likely to lie among the following aspects:

- *dimensions*; multiple-turbine-vessels may require large amounts of materials, which will make them uneconomic;
- *wave loads*; the large area projected by multiple-turbine-vessels to the waves can mean that the resulting loads will be high and possibly beyond the structural bearing capabilities of any appropriate material;
- *stability*; the turbine-thrust multiplied by the tower moment-arm results in large overturning moments;
- *motion response*; to minimise fatigue damage, particularly due to gyroscopic loads, vessel motion response must be minimised; note that this requirement is contradictory to the structural load requirement;
- *anchorage*; anchoring in shallow water can be difficult and expensive; in particular, catenary moorings perform poorly.

These aspects mean that prospects for floating offshore windfarms are not yet assured. However, there are reasons for optimism, which include:

firstly, that the cost difference is smaller than those that both the wind energy and offshore engineering industries have previously overcome; for example, the costs of current tension leg platform vessels have fallen to about one fifth of the original prototypes; of course, each subsequent cost reduction is more difficult than its predecessor,

secondly, that to date, proposed floating windfarm concepts have consisted of applying existing offshore technology and vessel concepts to the problem; relatively little effort has been applied to reviewing fundamentals, such as the differences between the basic performance requirements of offshore and wind energy engineering with respect to floating vessels,

thirdly, the offshore engineering industry has an excellent track record of developing novel concepts when faced with new challenges; none of the concepts shown above (Fig. 6 to Fig. 9) existed more than a few decades ago,

and *finally*, offshore engineering tends to design each structures to be unique; an array of floating offshore windturbines would require large numbers of identical support structures, the manufacture and installation of which would bring economies of scale. Perhaps capitalising on the current effort by niche offshore players to produce standardised cost effective structures for marginal fields could deliver some of the required cost reductions.

However, the challenges should not be underestimated and floating wind energy's prospects are longer term with full-scale commercial realisation, if it can be done, being more likely in the next decade than the current; the last decade has seen developments in wind energy engineering that only the most optimistic would have predicted, hence this decade should be long enough to see the first development and testing of prototypes.

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