1 INTRODUCTION

It is stated in the contractual work package description that Task 2.1 of the OWEE project aims to *"define the maturity of the technology currently available for offshore wind farms"*.

This aim is to be achieved through collation and interpretation of relevant information in relation to the following key technological issues (a "state-of-the-art" summary):

- Size and configuration of wind turbines suitable for offshore installations
- Support structure design
- Installation, decommissioning and dismantling
- Operation and maintenance (O&M), reliability
- Electrical transmission and grid connection

The following companies are involved in Work Package 2.1, having responsibilities as stated.

- Garrad Hassan and Partners (GH) – work package co-ordinator and electrical transmission and grid connection
- ENEA – size and configuration of wind turbines
- Kvaerner Oil and Gas (KOG)– support structure
- Germanischer Lloyd WindEnergie GmbH - standards
- VTT – installation and decommissioning
- Vindkompaniet (VKAB) – O&M

CONTENTS

2 SIZE AND CONFIGURATION

2.1 Scaling Trends

2.1.1 Scaling laws

Considering all designs upwards of 30 kW (and not exclusively the largest which are demanded for offshore projects), there are approximately 75 commercially marketed wind turbine designs. This number counts as distinct designs of different scale and type of a particular manufacturer but excludes minor variations like the same having the same tower top system on alternative towers (higher or lower, steel or concrete, tubular or lattice type etc.)

Scaling trends need to be interpreted with great care. Data indiscriminately lumped together may suggest spurious trends or at least provide only superficial descriptions rather than insight into basic issues like the inherent specific costs (cost per kW or cost per kWh) trend with up-scaling. Some of the main issues are:

- ***Geometric similarity*** – with strict geometric similarity, volume, mass and cost of items will tend to scale as the cube of any characteristic dimension. Very small turbines (say < 30 kW output power rating) are generally too dissimilar to the larger turbines for valid interpretation of inherent scaling rules if all sizes are grouped together.

- ***Parametric similarity*** – designs basically similar in concept (e.g. 3 bladed, pitch regulated with glass epoxy blades and tubular tower) may have significantly different choice of key parameters. Tip speed is a key parameter that very directly influences the tower top mass and cost of a wind turbine. Different ratios of power rating or tower height to diameter will also clearly influence mass and cost. These influences can sometimes be effectively considered by normalisation processes allowing more data sets to be grouped together.

- ***Duty similarity*** – machine designs, mass and cost are influenced by the class of design site, i.e. the severity of the design wind conditions.

- ***Stage of development*** – the latest and largest wind turbines are at the most advanced state of knowledge of the manufacturers with ever increasing emphasis on cost and mass reduction inducing minor and sometimes more major innovations in the design. This can obscure intrinsic scaling trends that would apply if all sizes were at the same stage of technical maturity.

Needless to say there are also many other factors which complicate scaling comparisons like manufacturers prejudices for electric or hydraulic systems, for simple heavy structures or more lightweight optimised structures and more flexible blades etc. Finally in moving beyond technical issues to costs – and the main motive in addressing the technicalities of scaling is to get insight into how they will influence costs of large offshore wind turbines – a large number of non-technical factors are added (exchange rates, labour cost variations globally, marketing ploys, etc.)

It is not intended or appropriate to produce an extended technical discussion on wind turbine scaling issues which has been much addressed in the literature, but it is necessary to update information especially when this project is focused on offshore and the most relevant information is from the very latest machines. The foregoing preamble has therefore been offered as a health warning regarding scaling data presented herein and elsewhere.

2.1.2 Summary review of large turbines

In order to get a snapshot of the current maturity of wind technology especially as it affects large offshore wind turbines, summary information has been extracted (excepting Table 2.1.2.1) from Windkraftanlagen Markt 2000 & 2001 [GH Ref. 1] and from Windenergie 2000 & 2001 [GH Ref. 2]. It represents in part an up-date of material provided [GH Ref. 3] (P Jamieson, GH) to the document [ENEA Ref. 3].

Diameter

	Blade manufacturer	Largest blade size
1	Abeking & Rasmussen Rotec	Largest blade 40m for MBB, Aeolus II wind turbine.
2	Aerpac (recently purchased by Enron)	Size range up to 48 m
3	Borsig Rotor	39 m blade for Nordex 2.5 MW is the next prototype.
4	LM Glasfiber	Up to 38.8 m available– larger blades planned.
5	NEG Micon Aerolaminates	50 m blade about to be made and tested.
6	NOI Rotortechnick GmbH	Currently working on 39 m blades with 55 m blade for a 5 MW turbine planned this year.
7	Polymarin-Bolwell Composites	Latest blades up to 37 m length.
8	TECSIS	Currently supplying 34 m blades.

Table 2.1.2.1 Large rotor blades (GH Review)

The upward trend in machine diameter is well illustrated by examination of the activities of rotor blade suppliers (Table 2.1.2.1). In addition to those companies specifically manufacturing rotor blades, companies like Enercon and Vestas who manufacture their own blades are clearly interested in large offshore machines and wind turbine systems with rotors up to 120 m diameter for 5 MW rating and perhaps as high as 140 m for 6 MW rating are under consideration.

Power rating

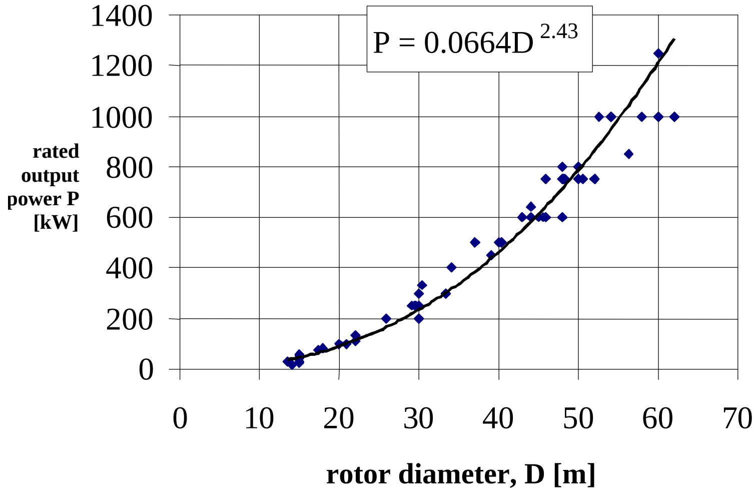

Figure 2.1.2.1 Power rating of wind turbines up to 62 m diameter

The power rating of wind turbines has typically been based on the assumption of a wind shear typical of European land based sites with a 1/7 power law applying to variation of wind speed with height above ground. This implies a rotor power variation as diameter to the power (2 + 3/7) i.e. 2.43, and it can be seen (Figure 2.1.2.1) that for a wide range of land based turbines up to 62 m rotor diameter there is an exponent of 2.4 in reasonable conformity with this.

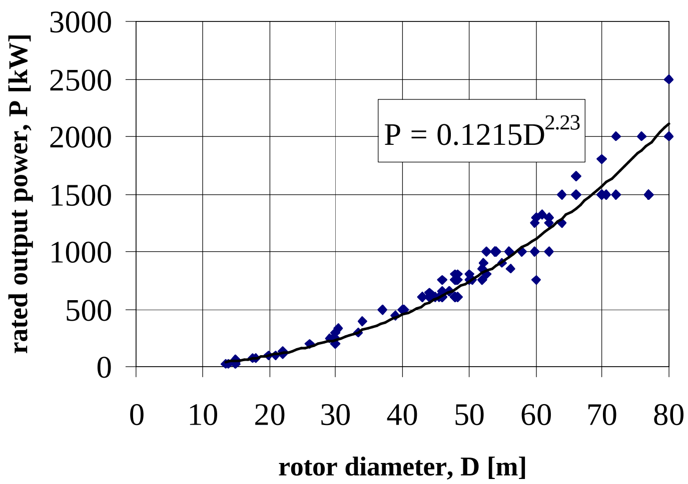

Figure 2.1.2.2 Power rating of wind turbines

It is apparent, however, (Figure 2.1.2.2) with the largest offshore wind turbines included, that the exponent in the rating trend has reduced. This is logical since there is reduced wind shear on offshore sites and certainly the 80 m turbines are targeted for such sites. It is also the case that unnecessarily high towers offshore will only exacerbate the problem of larger machines having low fundamental frequencies approaching the peak in the wave spectrum.

Tip speed

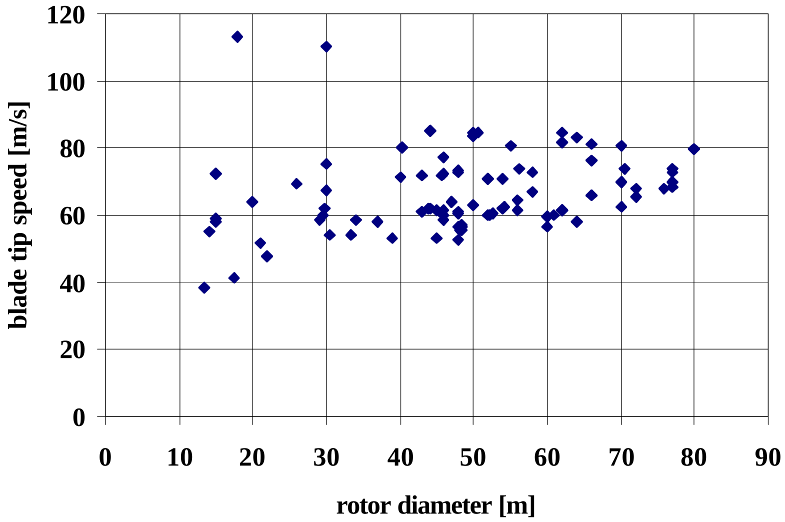

Figure 2.1.2.3 Design tip speed (maximum steady state)

The tip speed of wind turbines is relatively constant (Figure 2.1.2.3) being limited on European land based sites primarily by acoustic noise. Most machines of the leading manufacturers have tip speed lower than 70 m/s although a few machines, not generally market leaders, adopt high tip speeds above 100 m/s. Apart from acoustic considerations, a higher tip speed is advantageous, implying lower torque for a given power rating and lighter and cheaper tower top systems.

Design	Power [kW]	Control concept	Tip speed [m/s]	Ratio (offshore/land)
Vestas V66 (land)	1650	Pitch reg., variable slip	66	1.21
Vestas V80 (offshore)	2000	Pitch reg., variable speed	80	
Nordex N60	1300	Stall reg., fixed speed	60	1.33
Nordex N80 (offshore)	2000	Pitch reg., variable speed	80	
Bonus 1300 (land)	1300	Active stall, fixed speed	62	1.10
Bonus 2000 (offshore)	2000	Active stall, fixed speed	68	
NEG Micon 1000/60 (land)	1000	Stall reg., fixed speed	57	1.19
NEG Micon 2000/72 (offshore)	2000	Active stall, fixed speed	68	

Table 2.1.2.2 Trends in tip speed comparing offshore and land based turbines

The largest machines that are exclusively directed at the offshore market (Table 2.1.2.2) exploit significantly higher tip speed. Acoustic noise is probably much less of an issue for offshore projects. Table 2.1.2.2 indicates that, specifically in the offshore context, increase in design tip speed between 10% and 35% has already occurred. It is likely that this trend of rising tip speed for offshore designs will continue especially to reduce top weight and cost of machines in the 5 MW range.

Hub height

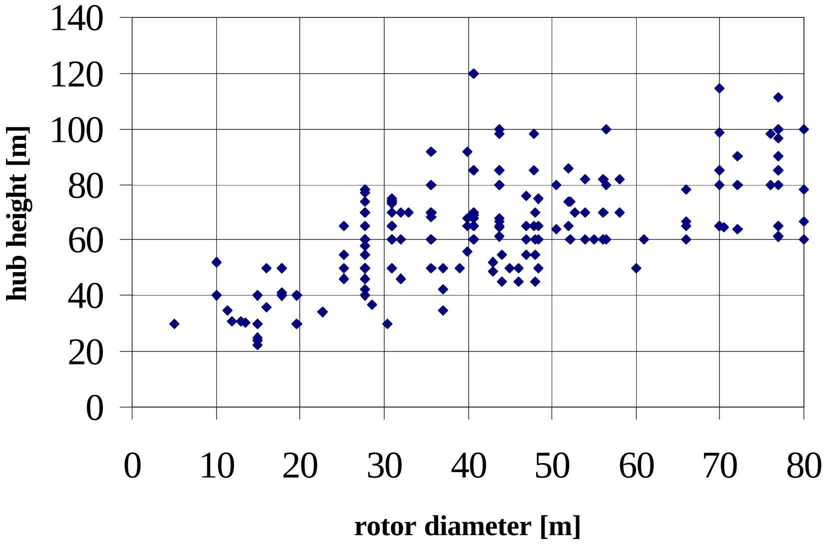

Figure 2.1.2.4 Hub height variation of wind turbines

For land based wind turbines, hub height rises in proportion to diameter (Figure 2.1.2.4) with the caveat that, at any given diameter, there will often be a wide range of alternative tower heights available to suit the demands of specific sites. The data (Figure 2.1.2.4) shows a levelling in the increase of hub height with diameter at the largest sizes. It is suggested that for best economics, offshore wind turbines in an environment with reduced wind shear will have hub heights that are minimal for safe clearance of the blade tips from extreme waves.

Safety and control

Pitch control (with independent actuators on each blade) in combination with variable speed predominates among the largest wind turbine designs. Of 16 distinct machine designs on or over 70 m diameter 14 adopt this configuration. The two exceptions are the designs of NEG Micon and Bonus which use stall regulation with dual speed operation.

Less than 10% of designs over the whole size range from 30 kW upwards are fixed speed. Many different options are exploited in order to achieve some degree of speed variation – dual speed with pole switching, high slip as with Vestas Optislip, doubly fed induction generators giving moderate range of variable speed and direct drive systems with wide range variable speed.

Over the whole size range there are still roughly equal numbers of pitch regulated and stall regulated designs but, as has been mentioned, pitch regulation dominates among the largest wind turbine designs.

2.1.3 Size and mass trends in offshore context

Onshore commercial, grid connected, wind turbines are today generally supplied in the rotor diameter range 45-80 m (rated power, 600-2500 kW). Semi-offshore wind turbines from 1990 up to now have been in the rotor diameter range of 30-45 m (rated power 220-600 kW).

Commercial offshore wind turbines, up-scaled from the onshore turbines, are today made by 10 manufacturers, in the rotor diameter size range of 65-80 m (rated power 1500-2500 kW). New offshore turbine prototypes are under design with rotor diameters up to 120 m. It remains to be seen however where the technical and economic barriers to further up-scaling exist, i.e. rotor diameters greater than 120m.

Offshore designs which exploit higher tip speeds than land based machines of similar diameter or rating should become less rather than more expensive even accounting for marinisation.

In Fig 2.1.3.1 the power ratings of onshore wind turbines, installed in Germany Ref.[2], are reported against year of installation (dots). For comparison in the same time scale, the power rating of existing turbines is shown (squares) for semi-offshore conditions up to 1998, while afterward the applications are real offshore. The much increased rating of the offshore designs is very evident.

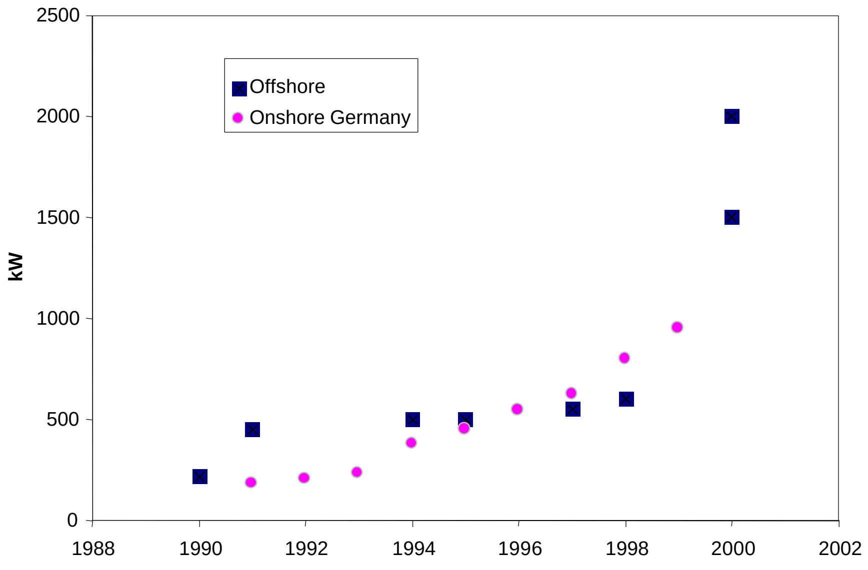

Figure 2.1.3.1 Rating trends in land based and offshore wind turbines

Fig 2.1.3.2 compares current commercial offshore turbines, derived by up-scaling and marinisation of onshore ones, with new prototypes most of which are still in the design phase. A further large increase in turbine size is evident with the new offshore models.

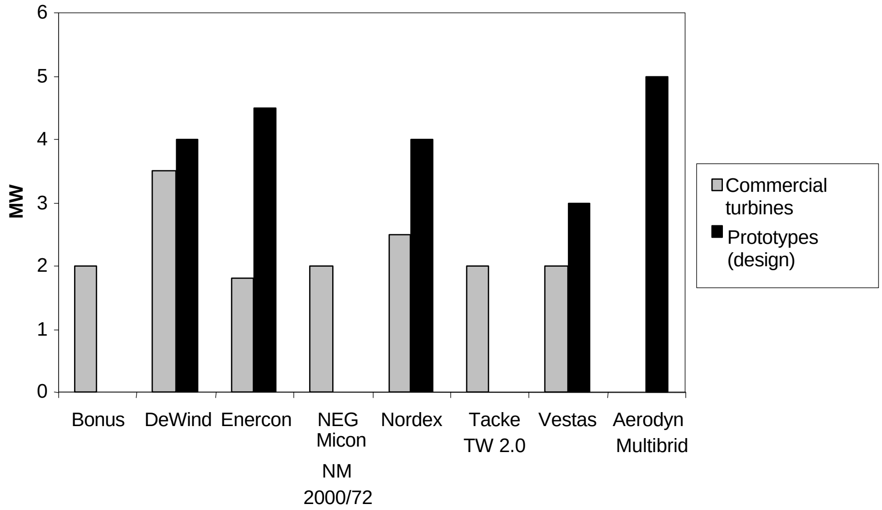

Figure 2.1.3.2 Commercial offshore turbines and forthcoming prototypes

Figure 2.1.3.3 shows substantial technology progress in reducing blade weight and cost. This inference comes from the trend line exponent being 2.3 rather than 3 as would apply from simple scaling rules relating design bending moment and structural material demands to rotor diameter. Higher tip speed of offshore turbines will result in relatively lighter rotors.

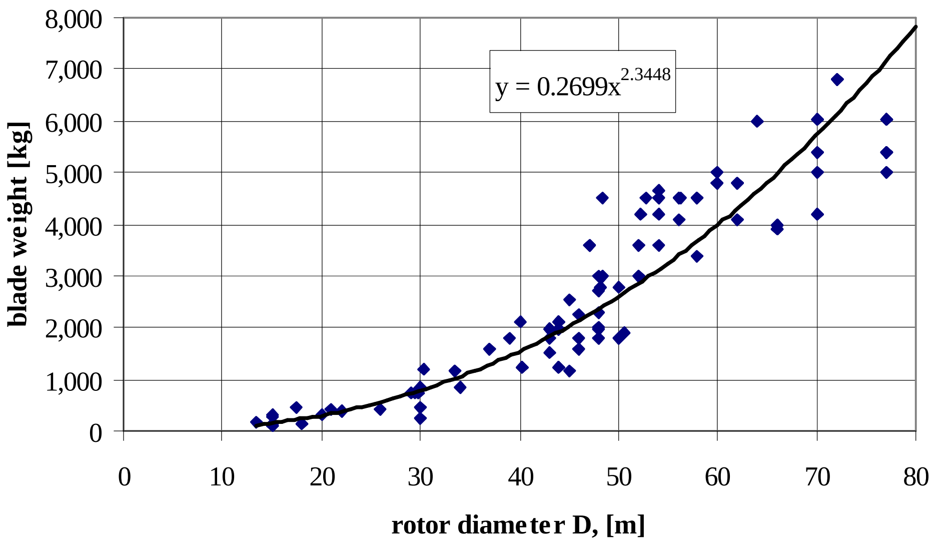

Figure 2.1.3.3 Blade mass related to rotor diameter

In Figure 2.1.3.4, the nacelle mass appears to increase as about square of diameter rather than diameter cubed as might be expected from a torque related component. This again reflects substantial ongoing technology progress and the trends already mentioned towards higher tip speed for the largest offshore wind turbines. It should however be noted that the data of Figure 2.1.3.4 includes both direct drive and gearbox based drive trains. Extrapolation of nacelle mass to large scale offshore wind turbines should treated with some caution.

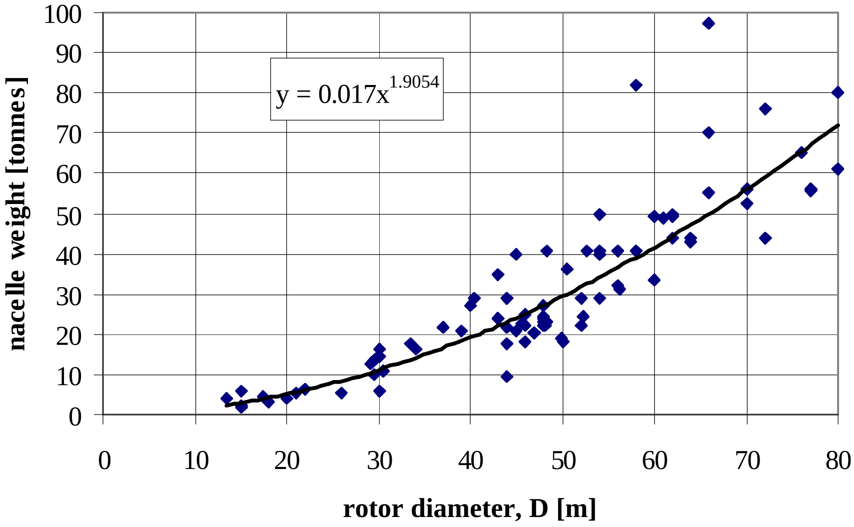

Figure 2.1.3.4 Nacelle mass v rotor diameter

In Fig 2.1.3.5, the ratio of blade mass to swept area is only slowly increasing whereas a linear increase would be expected from a mass or volume to area ratio. This is essentially an alternative presentation of the trend in Figure 2.1.3.3. The results depend on the blade number (almost always 3) and material used, generally glass composite. Lower specific rotor weights are expected from carbon fibre blades (especially in the context of increased tip speed of offshore machines) and two bladed turbines. The dispersion of data about the best-fit value is considerable but decreasing for the large size turbines, where design is better optimised.

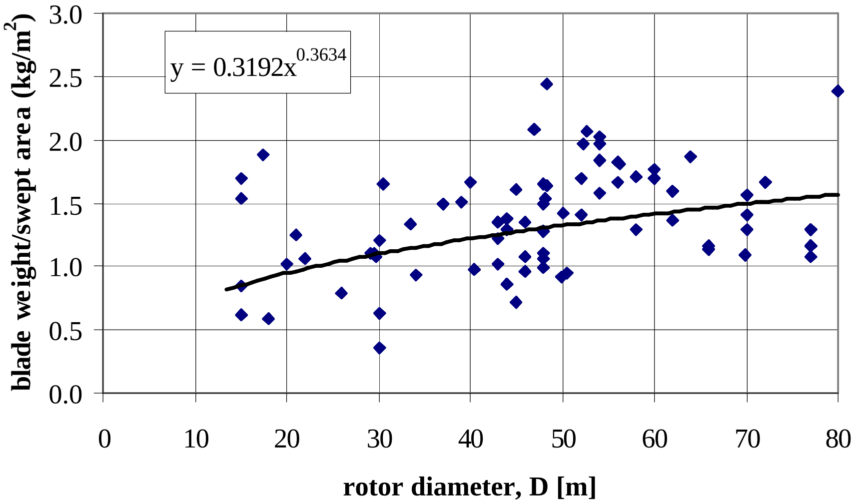

Figure 2.1.3.5 Rotor mass/ swept area ratio

In Fig 2.1.3.6, the hub height to rotor diameter ratio, for onshore turbines, is constant (about 1) above 40 m rotor diameter. With reduced wind shear offshore, the ratio may even decrease further depending on tip clearance in relation to extreme wave heights and tidal range.

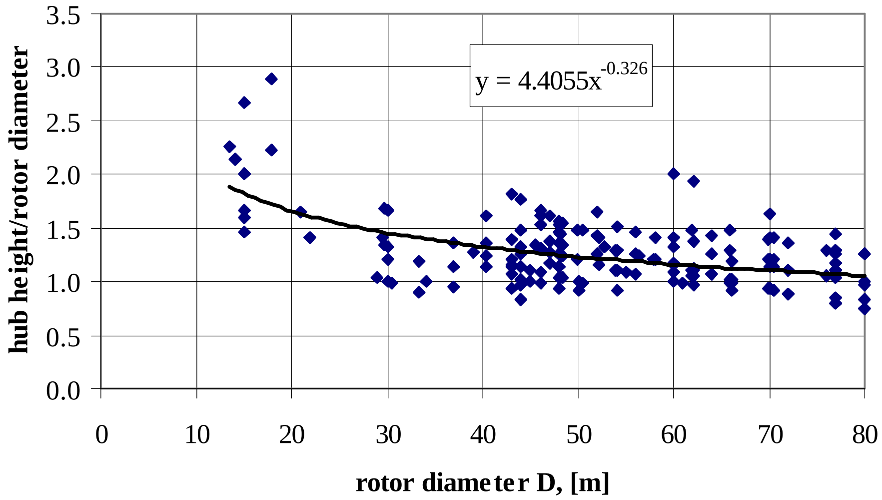

Figure 2.1.3.6 Hub height/rotor diameter ratio

2.1.4 Large wind turbine cost trends

Fig 2.1.4.1 from ENEA Ref.. [4] is shows the breakdown of capital cost of a typical offshore wind farm. In terms of CAPEX alone, turbines are about 40 – 45% of cost, much less than about 70% which is typical for land based projects, but clearly still a major item. Taking into consideration O&M costs, turbine costs are about 65% of total lifetime costs onshore and are expected to be about 30% offshore (Opti-OWECS reference).

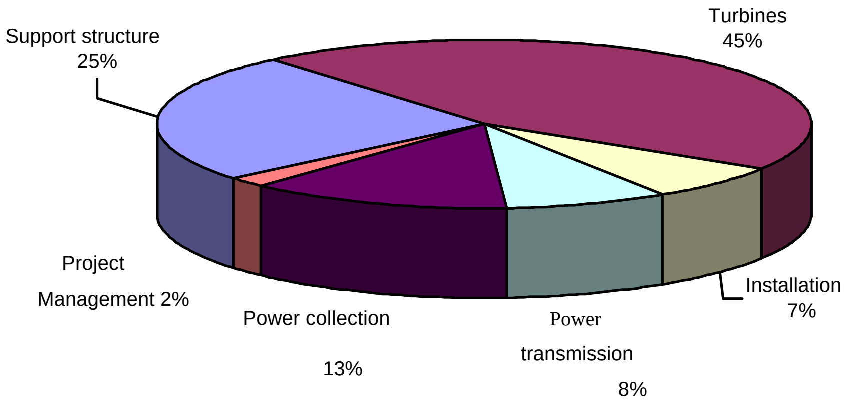

Figure 2.1.4.1 Breakdown of initial capital cost

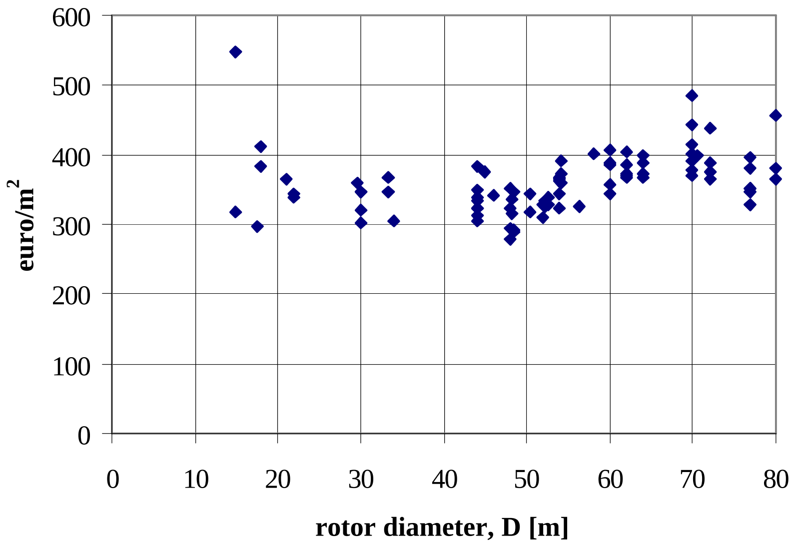

Figure 2.1.4.2 Cost per unit swept area v diameter

Figure 2.1.4.2 reveals a rising trend of medium and large size (30 – 70 m diameter) land based machines in cost/m^2 with increasing rotor diameter. This may not be immediately obvious, but the key is to discount the data above 75 m diameter which applies to the offshore designs with increased tip speed. It is expected that the offshore machines (at a given tip speed) will display the same rising cost trend but on separate curves (ref. EWEC NICE 1999) related to design tip speed. Much of the vertical dispersion in Figure 2.1.4.2 and many other cost curves is due to the same turbines being offered with different tower heights. Normalisation to take account of tower height and tower cost could considerably reduce the apparent scatter.

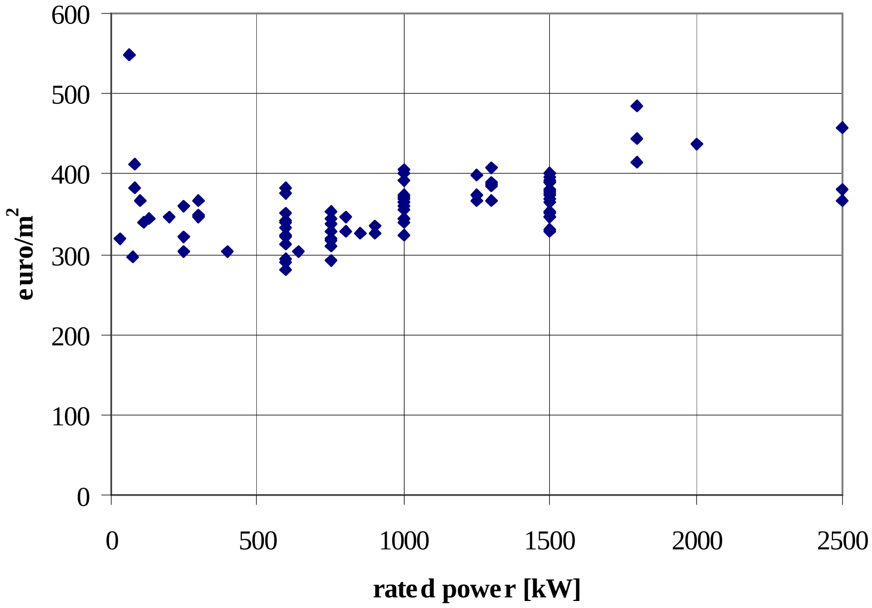

Figure 2.1.4.3 Cost per unit swept area v rated power

The same type of trend is apparent (Figure 2.1.4.3) in relation to rated power.

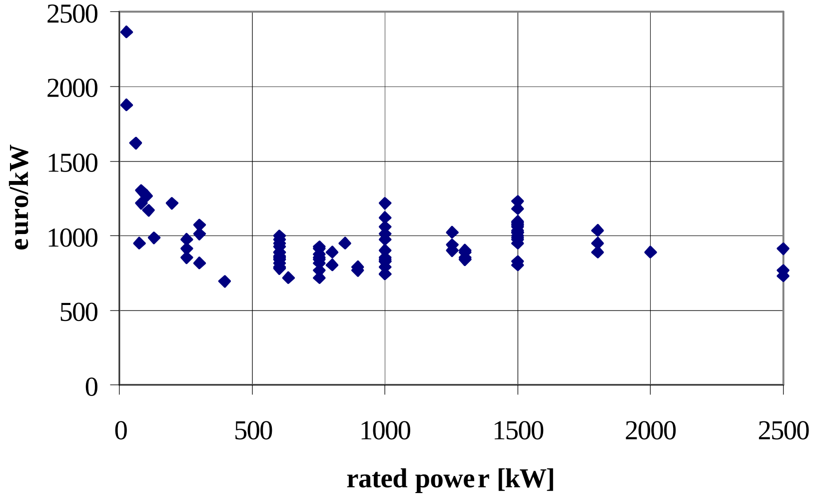

Figure 2.1.4.4 Cost per kW v rated power

The appearance of reduced costs of the largest offshore machines is even more striking in Figure 2.1.4.4. The costs are based on list prices published in the same year (Windkraftanlagen 2001 and Windenergie 2001) and the 2 and 2.5 MW machines come out very well in terms of cost per kW because of the higher tip speeds (Table 2.1.2.2) and especially the higher ratio of rating to rotor diameter.

For onshore turbines the specific cost of foundation (ECU/kW) is decreasing with power rating as form Fig 2.1.4.5 of ENEA Ref.[3]. A similar trend is expected in offshore projects especially when it is argued that a driver for having much larger unit turbines offshore is to have cost efficient foundations.

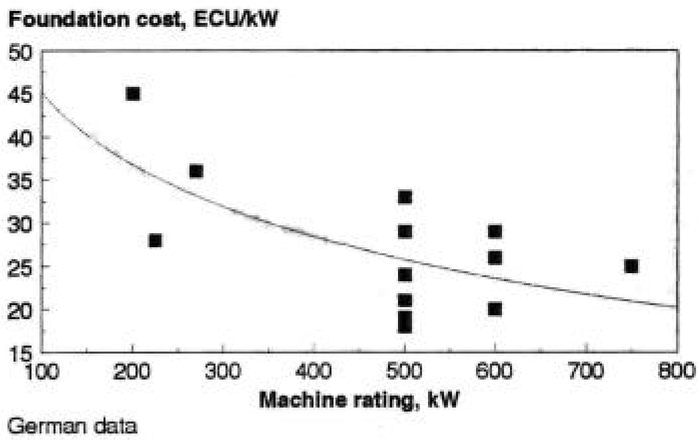

Figure 2.1.4.5 Foundation cost v rated power

Turbine availability is one of the most important parameters to be considered in the design of an offshore turbine. It connects directly to accessibility for maintenance and reliability. It affects the primary value, electricity production and Fig. 2.1.4.6, source ENEA Ref.[4], shows clearly that much improved reliability is demanded if reduced accessibility is not to impact strongly on availability. Current operational experience and offshore O&M is discussed in detail in Section 6. O&M demands will impact considerably on costs of offshore wind turbine systems and affect optimum scale for minimum cost of energy.

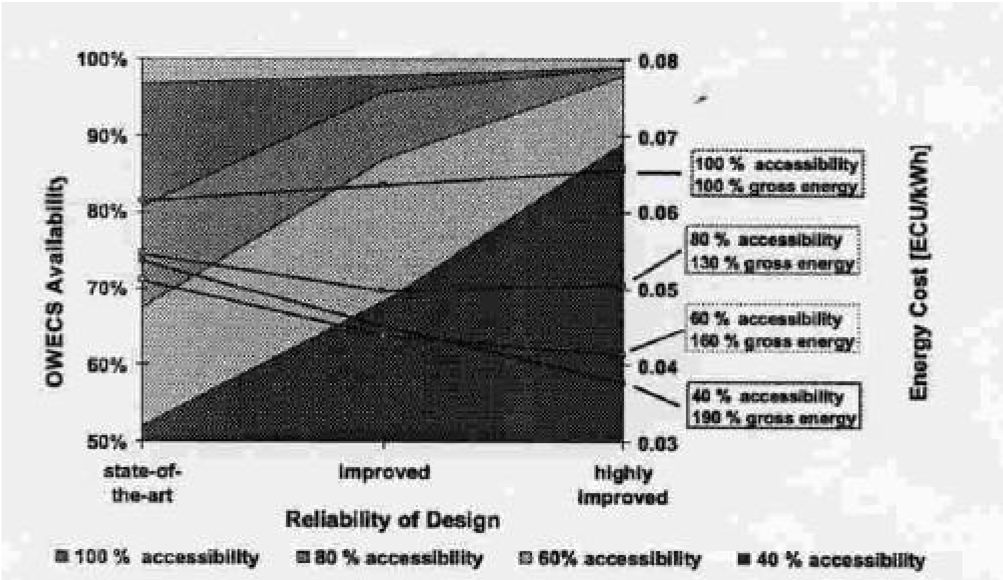

Figure 2.1.4.6: Availability vs. improved reliability

2.1.5 Summary of trends in offshore wind technology

Summarising the evaluations of size and cost trends;

- By turbine designers choice and reflecting wind shear conditions, rated power is generally scaling as $D^{2.4}$ on land and a bit closer to D^2 offshore. With lower wind shear offshore, specific power (W/m^2) is increasing up to around 500 W/m^2. It should be noted, however, that the choice of specific power (or rated wind speed) is also driven by the site annual mean wind speed, the breakdown of cost of energy and the predictability of power production in the future spot market.
- Under conditions of true similarity in design style, state of technological progress and design specification, it remains that costs of large turbines are expected to scale cubically with rotor diameter
- Considering historical data over the range of machine sizes, the cubic scaling law regarding system masses and costs appears closer to a square law with ongoing technology development
- The trends in published price data of machine for land based projects shows a gently rising cost/kW for rotor diameters of 40 m and greater. (This does not conflict with the circumstance, that after consideration of balance of plant and maintenance costs, the best overall project economics on land may come from utilisation of MW scale turbines)

- Offshore wind turbines are now essentially on different (lower) cost curves on account of tip speed increases in the 10 to 35% range,
- Rotor diameter and power rating is increasing. Commercial turbines are available in the diameter range 65 - 80 m and 1.5 - 2.5 MW. Prototypes are under development with respective values up to 120 m and up to 5 MW.
- The turbine cost is around 45% of initial capital cost of an offshore wind farm and, as a proportion of cost, is likely to be less on demanding sites with challenging wave climates.
- The increase of offshore turbine size is primarily driven by foundations and power collection costs. Very large unit size does not favour the inherent economics (cost/kW or cost per kWh ex factory) of the wind turbine in isolation.
- Reliability in parallel with accessibility are priority concerns for satisfactory economics of offshore wind turbines.

2.2 Manufacturers

2.2.1 General data sources on manufacturers

A list of most wind turbine manufacturers with contact details including web site references is available from Windkraftanlagen 2001 and Windenergie 2001. Salient data on all commercial wind turbines above 52 m diameter, which are considered to be large enough for offshore use and some of which are specifically offshore designs, is presented in Table 2.2.1.1

Table 2.2.1.1 Wind turbines above 52 m diameter

TYPE	RATED POWER kW	HUB HEIGHT m	SWEPT AREA m^2	DIA. M	SPEED rpm	TOWER WT kg	NACELLE MASS kg	BLADE WT kg	EURO/ kW	EURO/ m^2	PRICE EURO
Nordex N-80	2500	60	5026	80	19		80,000		736.3	366.2	1,840,651
Nordex N-80	2500	80	5026	80	19	179,000	80,000		766.9	381.5	1,917,345
Nordex N-80	2500	100	5026	80	19		80,000		920.3	457.8	2,300,813
AN Bonus 2 MW/76	2000	80	4,536	76	17	162,000	65,000				
AN Bonus 2 MW/76	2000	98	4,536	76	17	162,000	65,000				
NEG Micon NM 2000/72	2000	64	4072	72	18	113,000	76,000	6,800	889.6	437	1,779,296
NEG Micon NM 2000/72	2000	80	4072	72	18	130,000	76,000	6,800			
Vestas V80/2.0 MW	2,000	60	5,027	80	19	110,000	61,200	12,000			
Vestas V80/2.0 MW	2,000	67	5,027	80	19	130,000	61,200	12,000			
Vestas V80/2.0 MW	2,000	78	5,027	80	19	170,000	61,200	12,000			
Vestas V80/2.0 MW	2,000	100	5,027	80	19	200,000	61,200	12,000			
Enercon E-66/18.70	1800	65	3848	70	22	122,000	101,000	4,200	886.2	414.6	1,595,231
Enercon E-66/18.70	1800	85	3848	70	22	191,000	101,000	4,200	950.2	444.5	1,710,271
Enercon E-66/18.70	1800	98	3848	70	22		101,000	4,200	1036.8	485	1,866,215
Vestas V66/1.65 MW	1,650	60	3,421	66	19	87,000	55,000	4,000			
Vestas V66/1.65 MW	1,650	67	3,421	66	19	102,000	55,000	4,000			
Vestas V66/1.65 MW	1,650	78	3,421	66	19	141,000	55,000	4,000			
BWU/Jacobs MD 70	1,500	65	3,850	70	19		56,000	5,400			
BWU/Jacobs MD 70	1,500	80	3,850	70	19		56,000	5,400			
BWU/Jacobs MD 70	1,500	85	3,850	70	19		56,000	5,400			
BWU/Jacobs MD 77	1,500	61.5	4,656	77	17		56,000	5,400			
BWU/Jacobs MD 77	1,500	85	4,656	77	17		56,000	5,400			
BWU/Jacobs MD 77	1,500	90	4,656	77	17		56,000	5,400			
BWU/Jacobs MD 77	1,500	100	4,656	77	17		56,000	5,400			
Enercon E-66/15.66	1500	67	3421	66	22	130,000	97,400	3,900			
Enercon E-66/15.66	1500	85	3421	66	22	191,000	97,400	3,900			
Enercon E-66/15.66	1500	98	3421	66	22		97,400	3,900			

TYPE	RATED POWER kW	HUB HEIGHT m	SWEPT AREA m^2	DIA. M	SPEED rpm	TOWER WT kg	NACELLE MASS kg	BLADE WT kg	EURO/ kW	EURO/ m^2	PRICE EURO
Enron EW 1.5s	1500	64.7	3904	70.5	20						
Enron EW 1.5s	1500	80	3904	70.5	20						
Enron EW 1.5s	1500	85	3904	70.5	20						
Enron EW 1.5s	1500	100	3904	70.5	20						
Enron EW 1.5sl	1500	61.4	4657	77	18.3						
Enron EW 1.5sl	1500	80	4657	77	18.3						
Enron EW 1.5sl	1500	85	4657	77	18.3						
Enron EW 1.5sl	1500	100	4657	77	18.3						
Enron Wind 1.5 sl	1,500	61.4	4,657	77	18				1090.8	351.3	1,636,134
Fuhrlander MD 77	1,500	65	4,655	77	17.3	93,000	55,500	5,000	1022.6	329.5	1,533,876
Fuhrlander MD 77	1,500	85	4,655	77	17.3		55,500	5,000	1073.7	346	1,610,569
Fuhrlander MD 70	1,500	65	3,850	70	19	93,000	52,500	5,000	947.6	369.2	1,421,391
Fuhrlander MD 70	1,500	85	3,850	70	19		52,500	5,000	1005.5	391.8	1,508,311
NEG Micon NM 1500/72	1500	98	4,072	72	17.3	89,000	44,000	6,800	1056.7	389.2	1,585,005
NEG Micon NM 1500/72	1500	64	4,072	72	17.3	132,000	44,000	6,800	988.5	364.1	1,482,746
NEG Micon NM 1500/72	1500	80	4,072	72	17.3	201,000	44,000	6,800	1022.6	376.7	1,533,876
NEG Micon NM 1500C-64	1500	68	3217	64	17.3	113,000	43,000	6,000	801	373.5	1,201,536
NEG Micon NM 1500C-64	1500	80	3217	64	17.3	148,000	43,000	6,000	835.1	389.4	1,252,665
PWE 1566 (Pfleiderer)	1,500	65	3,421	66	22	220,000	70,000	3,900			
Sudwind S-70	1,500	65	3,848	70	19	95,000	56,000	6,020	971.5	378.7	1,457,182
Sudwind S-70	1,500	85	3,848	70	19		56,000	6,020	1027.7	400.6	1,541,545
Sudwind S-70	1,500	98.5	3,848	70	19		56,000	6,020			
Sudwind S-70	1,500	114.5	3,848	70	19		56,000	6,020			
Sudwind S-77 = MD77	1,500	61.5	4,657	77	17.3	80,000	56,000	6,020	1022.6	329.4	1,533,876
Sudwind S-77 = MD77	1,500	85	4,657	77	17.3		56,000	6,020	1078.8	347.5	1,618,239
Sudwind S-77 = MD77	1,500	90	4,657	77	17.3		56,000	6,020			
Sudwind S-77 = MD77	1,500	96.5	4,657	77	17.3		56,000	6,020	1094.2	352.4	1,641,247
Sudwind S-77 = MD77	1,500	100	4,657	77	17.3		56,000	6,020	1227.1	395.2	1,840,651
Sudwind S-77 = MD77	1,500	111.5	4,657	77	17.3		56,000	6,020	1182.8	381	1,774,183
Made AE-61	1,320	60	2,922.50	61	18.8	89,500	49,000				
AN Bonus 1.3 MW/62	1300	68	3019	62	19	80,000	50,000		896.7	386.1	1,165,745

TYPE	RATED POWER kW	HUB HEIGHT m	SWEPT AREA m^2	DIA. M	SPEED rpm	TOWER WT kg	NACELLE MASS kg	BLADE WT kg	EURO/ kW	EURO/ m^2	PRICE EURO
Nordex N-60	1300	60	2828	60	19		49,200	4,800			
Nordex N-60	1300	65	2828	60	19		49,200	4,800			
Nordex N-60	1300	69	2828	60	19	98,400	49,200	4,800	837.7	385.1	1,089,052
Nordex N-60	1300	70	2828	60	19				845.6	388.7	1,099,278
Nordex N-60	1300	85	2828	60	19	154,000	49,200	4,800	884.9	406.8	1,150,407
Nordex N-60	1300	120	2828	60	19		49,200	4,800			
Nordex N-62	1300	60	3020	62	19		49,200	4,800			
Nordex N-62	1300	65	3020	62	19		49,200	4,800			
Nordex N-62	1300	69	3020	62	19	98,400	49,200	4,800	853.5	367.4	1,109,503
Nordex N-62	1300	70	3020	62	19						
Nordex N-62	1300	85	3020	62	19	154,000	49,200	4,800			
Nordex N-62	1300	120	3020	62	19		49,200	4,800			
DeWind D6	1250	68	3217	64	24.8	72,000	44,000		944.8	367.1	1,181,000
DeWind D6	1250	91.5	3217	64	24.8	116,000	44,000		1026.4	398.8	1,283,000
DeWind D6	1250	65	3019	62	26.1	72,000	44,000		900	372.6	1,125,000
AN Bonus 1 MW 54	1000	50	2300	54.1	22	54,000	40,000	4,650	828.3	360.1	828,293
AN Bonus 1 MW 54	1000	60	2300	54.1	22	60,000	40,000	4,650	859	373.5	858,970
AN Bonus 1 MW 54	1000	70	2300	54.1	22	90,000	40,000	4,650	899.9	391.2	899,874
DeWind D6	1000	68.5	3019	62	25.2			4,100	1120	371	1,120,000
DeWind D6	1000	91.5	3019	62	25.2			4,100	1222	404.8	1,222,000
Enercon E-58	1000	70	2642	58	24	130,000	82,000	3,400	1060.9	401.6	1,060,931
Fuhrlander 200/1000	1000	70	2180	52.7	22				741.4	340.1	741,373
Fuhrlander FL 1000	1,000	70	2642	58	22	95,000	40,500	4,500			
Fuhrlander FL 1000	1,000	82	2642	58	22	120,000	40,500	4,500			
Fuhrlander FL 1000	1,000	70	2463	56	22	95,000	40,500	4,500			
Fuhrlander FL 1000	1,000	82	2463	56	22	120,000	40,500	4,500			
Fuhrlander FL 1000	1,000	70	2290	54	22	95,000	40,500	4,500	741.4	323.7	741,373
Fuhrlander FL 1000	1,000	82	2290	54	22	120,000	40,500	4,500	833.4	363.9	833,406
MWT 1000 (Mitsubishi)	1,000	60	2,463	56	21	63,000	32,000	4,100			
NEG Micon NM 1000/60	1000	70	2827	60	18	114,000	33,500	5,000	971.5	343.6	971,455
NEG Micon NM 1000/60	1000	80	2827	60	18	114,000	33,500	5,000	1007.2	356.3	1,007,245

TYPE	RATED POWER kW	HUB HEIGHT m	SWEPT AREA m^2	DIA. M	SPEED rpm	TOWER WT kg	NACELLE MASS kg	BLADE WT kg	EURO/ kW	EURO/ m^2	PRICE EURO
Nordex N-54	1000	60	2290	54	22	90,200	50,000	4,200	833.4	363.9	833,406
Nordex N-54	1000	70	2290	54	22	105,000	50,000	4,200	843.6	368.4	843,632
Nordic 1000	1,000	60	2,290	54	25	45,000	29,000	3,600	787.4	343.8	787,389
Enron Wind 900s	900	60	2,206	55	28						
NEG Micon NM 900/52	900	60	2,140	52.2	22	72,000	24,500	4,200	772.6	324.9	695,357
NEG Micon NM 900/52	900	74	2,140	52.2	22	97,000	24,500	4,200	795.3	334.5	715,809
Frisia F 56/850 kW	850	70	2489	56.3	25	74,000	31,000	4,500	956.4	326.6	812,954
Fuhrlander FL 800	800	70	2,180	52.7	22	88,000	40,500	4,500	894.8	328.4	715,809

2.2.2 Geographical regions

Some information relating to wind turbine and component manufacturers in southern European countries is given below.

Italy

There is blade manufacture and Vestas turbine assembly by IWT, Taranto

Spain

Table 2.2.2.1, based on Wind Power Monthly, July 2000, indicates the status of the leading Spanish turbine manufacturers/developers.

Manufacturer	Installed cap city (MW)
Gamesa	1520.9
MADE	426.0
Ecotécnia	285.1
Desarrollos Eólicos	131.9
TOTAL	**2363.9**

Table 2.2.2.1 Spanish wind turbine manufacturers

Greece

Information on Greek manufacturers actively working in wind turbine manufacture as supplied by CRES is given below:

Manufacturer	
PYRKAL SA (? ? ?? ? ? AE)	Wind turbine manufacturer (up to 1-1.5 MW)
GEOBIOLOGIKI SA (G? O? ?? ? ? G?? ? AE)	Wind turbine blade manufacturer (up to 19 m, up to 30 m under development) www.angelopoulos.gr
M.+G. TSIRIKOS SA (? +G ? S?? ?? ? S ? ? ? ?)	Wind turbine gearing manufacturer
METAL INDUSTRY OF ARKADIA – C. ROKAS SA (? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ?? ? ?? ? ? ? ?? S, X.?? ? ? S ABEE)	Wind turbine tower manufacturer & electrical systems www.rokasgroup.gr
V?? ? ?? SA (BIOMEK AE)	Wind turbine tower manufacturer
METKA SA (? ? ? ? ? AE)	Wind turbine tower manufacturer www.metka.gr
VIEX SA (BIE? ? ?)	Wind turbine tower manufacturer

Table 2.2.2.2 Greek manufacturers

2.2.3 Summary of blade manufacturers

Table 2.2.3.1 summarises the main players in the wind turbine blade manufacturing industry.

	Blade manufacturer	Capacity	Technology	Comment
1.	Abeking & Rasmussen Rotec	Largest blade 40m for MBB, Aeolus II wind turbine.	Glass epoxy and glass polyester	Best established of the German manufacturers having mainly supplied German wind turbine manufacturers.
2.	Aerpac	Over 8000 blades supplied, 620 from their new Scottish factory since 1997. Size range 7 m to 48 m	Employing resin infusion system for glass epoxy blades.	Major blade manufacturer, second to LM in market share. Recently taken over by Enron.
3.	ATV	All carbon blades up to 14 m length. Hybrid blades using carbon reinforcement up to 32 m length.	Carbon and hybrid epoxy. The only company making one piece all-carbon blades.	Recovering their market position after significant technology problems in production of medium-sized blades for Tacke Windtechnik. Now owned by Caterpillar.
4.	Borsig Rotor	A new company founded end 1999. 31 m prototype blade manufactured (March 2000) 850 blades anticipated production in 2001. 39 m blade for Nordex 2.5 MW is the next prototype.	Glass epoxy.	Manufacturing plant in Rostock. Technical input is from Walter Keller who had founded Aero Construct which later became LM Aero Construct. Supplier for Nordex and Südwind.
5.	Enercon	Large number of blades for their E40 and E66 turbines especially.	Glass epoxy.	Manufacturing blades exclusively for their own projects. Have also sourced blades in quantity from Aerpac.
6.	Euros	24.5 m (Sept. 1999) and 27.5 m (March 2000) blades load tested. Blades first in operation (June 2000)	Glass epoxy	Aerodyn designs. Euros started in 1997 supplying blades for machines in 600 kW – 1.5 MW range.
7.	LM Glasfiber	Around 36,000 blades supplied. LM claim a 49% world market share. Blade supply from 11 m to 38.8 m. Blade manufacture on 12 sites world wide.	Glass polyester. Carbon tubes in tip brakes and carbon reinforcement in largest blades.	Long established as the world's leading supplier of wind turbine blades. Have always been more diverse than rotor blades. Leading supplier of lightweight composite parts for the European rail industry.
8.	MFG	They claim to be the leading US producer of large rotor blades over 20 m.	Glass epoxy.	Manufacturing blades primarily for Enron Wind Corporation.

Table 2.2.3.1 Summary of wind turbine blade manufacturers

	Blade manufacturer	Capacity	Technology	Comment
9	NEG Micon Aerolaminates	Over 1000 large blades manufactured. 15 m to 31 m. 50 m blade about to be made and tested.	Wood epoxy – the only major supplier of wooden blades.	Principally supplying NEG Micon. Recent major expansion of manufacturing capability. Set up on the Isle of Wight with direct shipping facilities.
10	NOI Rotortechnick GmbH	Currently working on 39 m blades with 55 m blade for a 5 MW turbine planned this year.	Glass epoxy	Aerodyn designs. Founded in 1999, first blade produced October 1999.
11	Polymarin BV	Around 2000 blades supplied. Blade lengths up to about 26 m..	Glass epoxy primarily and carbon epoxy to a limited extent	Started in 1982.
12	Polymarin-Bolwell Composites	Over 800 blades for 600 and 750 kW wind turbines. Latest blades up to 37 m length.	Glass epoxy.	Canadian offshoot of Polymarin now 50% owned by Australian Bolwell Corporation. Set up in 1995 to supply large blades to US market.
13	TECSIS	70% export production to US and Europe. Hundreds of 25 m blades supplied. Currently supplying larger blades (34 m) for EWC projects in US.	Glass epoxy construction.	Brazilian manufacturer. Their main market is in the US for Enron Wind Corporation. Have also supplied Enercon.
14	Vestas Wind Systems	Thousands of blades produced for own turbines. World market leader in wind turbine supply.	Glass epoxy, spar/shell construction using prepregs.	Well established in-house blade manufacturing technology producing low mass flexible blades.

Table 2.2.3.1 Summary of wind turbine blade manufacturers (continued)

2.2.4 Current status of blade technology

There are a variety of design styles and manufacturing processes that are successfully in competition and no clear suggestion that a particular route of design or manufacture is definitely superior. Polyester resin is cheaper but inferior in preservation of final dimensional quality of a product and inferior in strength to epoxy resin. There has been a general move towards epoxy. New entrant blade manufacturers are using epoxy and Aerpac had switched to epoxy some years ago.

Large blades are requiring higher specific strength materials. This has undoubtedly driven the increasing use of epoxy resin and is also driving the widespread use of carbon reinforcements in large blades. The demand for high strength blades of low solidity in conjunction with diminishing carbon fibre costs may drive the industry in the direction of carbon epoxy. Carbon prices are falling and if it were used in significant quantities in blades for offshore machines, that could become by far the largest outlet for high quality carbon fibres and prepregs. This could then drive further cost reduction.

Wood composite blade manufacture is now a proven technology. Wood epoxy has good low temperature characteristics and is a cost effective blade material system. Wood may be more limited than other higher strength composites for very large blades. Wood is definitely unsuitable for very flexible blades. The spar and shell design, both manufactured using prepregs, is particularly favoured by Vestas. It has advantages in realising fast production with good quality control and suits manufacture of lightweight, flexible blades. These advantages are offset by a premium in the material components.

There are a number of interesting developments but no sign of any radical development in blade technology that would sideline present manufacturing technologies.

2.3 Offshore Prototypes

Nordex, Vestas and Enercon are known to be investigating designs in the 5 MW, >100 m rotor diameter range, and Aerodyn and NEG Micon are involved in a 6 MW design. (NEG Micon expect to install a 3MW prototype in 2002). Parallel activities of the blade manufactures in development and testing of blades for rotor diameters above 90 m is noted in Table 2.2.3.1.

The ScanWind 3.5 MW, 90 m rotor diameter design utilising the ABB Windformer concept has been much publicised and a 500 kW system (generator only) has been laboratory tested. A 3 MW Windformer system is planned for Nasudden III (land based but coastal site) and it is expected that these developments will prepare the technology for offshore applications.

2.3.1 Offshore projects

A total of 8 offshore projects are currently operational worldwide: the early projects were relatively small scale and shallow or sheltered waters. Not until Blyth Offshore came online, exposed as it is to the full force of the North Sea, could any be described as truly offshore.

Location	**Country**	**Online**	**MW**	**No**	**Rating**
Vindeby	Denmark	1991	4.95	11	Bonus 450 kW
Lely (Ijsselmeer)	Holland	1994	2.0	4	NedWind 500 kW
Tunø Knob	Denmark	1995	5.0	10	Vestas 500 kW
Dronten (Ijsselmeer)	Holland	1996	11.4	19	Nordtank 600 kW
Gotland (Bockstigen)	Sweden	1997	2.75	5	Wind World 550 kW
Blyth Offshore	UK	2000	3.8	2	Vestas 2 MW
Middelgrunden, Copenhagen	Denmark	2001	40	20	2 MW
Utgrunden, Kalmar Sound	Sweden	2001	10.5	7	Enron 1.5 MW
		Totals	**80.4**	**78**	

Table 2.3.1.1 Offshore Projects

Ireland, Belgium, Germany and the Netherlands are also expressing serious intent in developing their offshore resource. Proposed projects include:

- Mouth of the Western Scheldt River, Holland, 100 MW
- Ijmuiden, Holland, 100 MW
- Horns Rev, Denmark, 150 MW
- Laeso, Denmark, 150 MW
- Omo Stalgrunde, Denmark, 150 MW
- Gedser Rev, Denmark, 15 MW
- Rodsand, Denmark, 600 MW
- Lillgrund Bank, Sweden, 48 MW
- Barsebank, Sweden, 750 MW
- Kish Bank, Ireland 250 MW+
- Arklow, off County Wicklow, Ireland 200 MW+

Utilising megawatt-plus class machines, these projects will generate higher volumes of electricity from the more constant wind regimes experienced at sea and are likely to play a major role in power generation in the future.

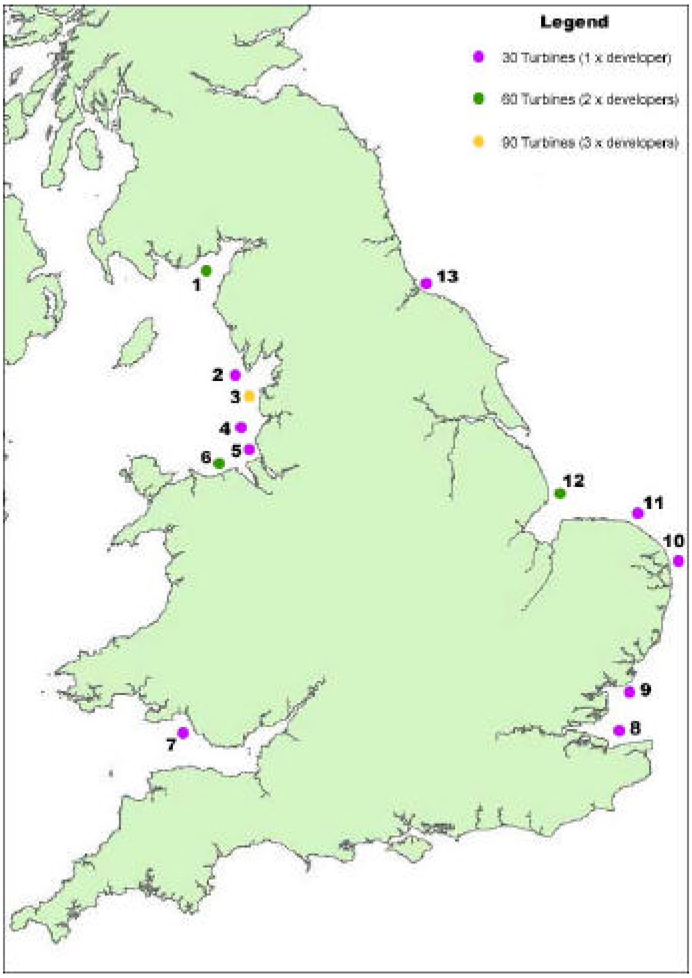

Figure 2.3.1.1 Potential offshore sites around the UK

As of April 5th 2001, according to a press release of the Crown Estate, 18 wind farm developers have successfully pre-qualified to obtain a lease of seabed in UK waters for the development of offshore wind farms. The net capacity of the sites in consideration is between 1000 and 1500 MW.

The EWEA have estimated that 5 GW of the 60 GW predicted for 2010 will be coming from the offshore sector.

The above data is taken from www.offshorewindfarms.co.uk

2.4 Gearboxes in the Offshore Context

The majority of turbines currently supplied to the onshore market use a gearbox to increase the rotor speed to a speed compatible with the generator, ~1000 or 1500 rpm. Almost all gearboxes, regardless of power rating, tend to conform to a standard pattern for turbines up to the current maximum size of • 2MW. The gearboxes are three stage units, the first, input, stage is planetary and the two higher speed stages are parallel with helical gears.

It is not clear whether this current gearbox concept will be applicable for larger, offshore turbines. Gearbox design is generally determined by input torque and the required speed increase ratio. As power and, hence, rotor diameter increase the torque and ratio increase. In an offshore turbine the increases are offset to some degree by a relatively higher rotor speed compared to a land based machine. However, it is likely that for larger machines > 3MW an additional gearbox stage will be required. Therefore, the complexity of the gearbox may be increased beyond that currently being used or designs based on a lower generator speed (rpm) may be used to compensate for this effect.

Throughout the development of the modern wind turbine there have been periods when the frequency of failure of gearbox components has been above normal, acceptable levels. The gearbox is one of the more costly components and there is always a large incentive to reduce costs. As wind turbine technology has developed the loading calculations used to select gearboxes and other component have been refined. These factors mean that over time, the safety margins of gearboxes have reduced. This appears to result in a cycle of events. A period of stability is followed by an increased level of failures. The wind turbine and gearbox industries react to the failures, increase margins and a further period of stability ensues.

Gearboxes for use in offshore environments may be more complex. The increased complexity may lead to increased probability of failure. There are only a small number of failure modes that can be rectified in situ. Therefore, to repair a failed gearbox will entail the removal of the unit from the turbine with significant cost and time implications.

The above issues suggest that there is a reasonable possibility that direct drive technologies may prove more attractive than they currently appear to be in the onshore market.

These comments are based on GH engineers' experience in due diligence and are not attributable to any specific published source.

2.5 Future Trends

As has been discussed, there is direct evidence of the following trends; 1) tip speed increases, 2) up to 33%, more use of carbon in blades, at least as reinforcement if not yet as a complete base material system, and 3) the appearance of more direct drive systems in new wind turbine designs, especially ScanWind as a large scale system targeted for offshore.

All these developments are logical from a technical/cost standpoint.

- **Higher tip speeds** gives lower torque and less mass and cost of tower top systems.
- **Carbon blades** or more carbon in blades – very large blades demand higher specific strength materials.
- **Direct drive with permanent magnet generator (PMG)** – direct drive does not have a cost or weight advantage over conventional geared systems but especially in the PMG type of design, it constitutes a simpler power train than the gearbox/high-speed generator combination and may be more reliable.

Floating wind energy systems have major potential benefit in allowing utilisation of windy areas near population and electrical demand centres where there are no shallow sea water sites. A study (FLOAT) identified such sites off the east coast of Ireland and in the Aegean.

At present, costs of moorings and of the floating platform (with the need for some lengths of flexible transmission lines) would appear to be much greater than the cost of fixed sea bed foundations in shallow water. However, technical progress in these areas plus new system concepts including, for example, integration with an appropriate type of wave device may bring floating systems nearer to economic feasibility.

Other ideas which may warrant future work are multiple rotors fixed on a single pile.

2.6 Bibliography

2.6.1 R&D plans/needs

Offshore Wind Energy Network. OWEN (Research Requirements Workshop, Final Report of G.Watson RAL April 1999).

Papers from journals and conferences:

(a) Wind Engineering 1989 vol. 13, n.8 (“Cost modelling of HAW Turbines” F. Harrison page 315)
(b) WEGA 1 : Hau,J. Langenbrinck, .Palz-Springer Verlag 1993
(c) European Wind Energy Conference 1994 in Thessaloniki (Economic Optim. of HAWT Design Parameters of Collecut-Univ Ukland , page 1244; Tecnic.and Economic Develop.of W.E.in Germany of Molly, DEWI page. 1251)
(d) OWEMES 94 Conference Rome – (Cost of offshore wind energy in UK North Sea, Simpson-WEG, page 267)
(e) European Wind Energy Conference 1996 in Goteborg ("Wega II Large wind turbine Scient. Evaluation Project" Christiansen Elsam page 212)
(f) WEGA2, EUR 16902 EN-1996
(g) OWEMES 97 La Maddalena (“Opti-OWECS preliminary cost model” of Cockerill/Harrison-Univ. of Sunderland; "Structural and economic optim. Of OWEC" of Kuen pag 165)
(h) OWEE website (Opti-OWECS Final Report Vl.0 .August 1998 of Kuehn et Al.-TUD)
(i) EWEC 1999 in Nizza (“Struct. and economic Optim of Bottom mounted OWECS” of Kuehn TUD page 22; “Techn.Develop. for Offshore” of Jamieson GH&P page 289; “Experience with 3000 MW w.Power in Germany” of Durstewitz et Al. ISET page 551)

(j) Wind Engineering vol. 24, n.2,2000 ("Wind Energy Technology: status review" of D. Milborrow page 65)
(k) Technology Development For Offshore, P. Jamieson & D C Quarton. EWEC 99, Nice, March 1999

2.7 References

2.7.1 ENEA

1. World turbine Market 1999:Types-Technical Characteristics-Prices
2. D. Milborrow. Wind energy technology, status review, wind engineering Vol. 24, n°2 2000.
3. European Commission, A plan for action in Europe - Wind Energy –The Facts, 1999
4. M. Kuehn et Al. Opti-Owecs, final report Vol. 0.
5. WEGA Large Wind Turbine, EUR 16902,1996

2.7.2 GH

1. Windkraftanlagen Markt 2001, SunMedia GmbH.
2. Windenergie 2001, Bundesverband WindEnergie Service GmbH
3. P. Jamieson, Common fallacies in wind turbine design, BWEA Proceedings 1997, pages 81-86.

3 SUPPORT STRUCTURE

3.1 Design Development – Piled Foundations

3.1.1 Operational experience

Piled foundations have been used throughout the world for supporting offshore oil and gas platforms and there exist well-established recommended practices and guidelines for the design of piles and grouted connections:

API RP2A, American Petroleum Institute, Recommended Practices for Planning Designing and Constructing Fixed Offshore Platforms
NORSOK N004 Design of Steel Structures.

Fixed offshore oil and gas platforms are generally supported by 3 or 4 legs with either a single pile driven through the leg or one or more skirt piles arranged around each leg, the piles connected to the leg by means of grouted sleeves. The piles are hollow steel tubulars ranging in diameter from 914mm to 2743mm.
In benign, shallow waters, a single pile has been used to support the topsides and as a conductor for drilling the well. In some cases, the conductor itself has been used to support the topsides. Conductors diameters are between 508mm and 914 and are normally either driven or drilled and cemented.

Nearshore marine construction of jetties and mooring dolphins has often used piles of greater diameter than those used offshore, but the depth of penetration and the means of installation have been different.

OWEC's have been supported on single monopiles, effectively a downwards extension of the tower and generally using methods developed from marine construction. They have ranged in diameter from 2.1 m at Bockstigen (Gotland) to 3.7m at Lely and have been installed by driving or by drilling and cementing (rock socket).
Large diameter tubular piles are a well-established design as indicated above. However, unlike an oil platform, the foundation supporting an OWEC is subjected to a much larger proportion of live load compared to dead load. This means that the foundation experiences larger shears and bending moments and relatively small axial compression. The design of monopile foundations should consider cyclic loading of near-surface soils and the potential for loss of soil contact at the surface (post-holing). Rock-socketed piles are unlikely to be susceptible to this effect.

3.1.2 Piling techniques

There are four main means of installing piles:

- Above-surface steam, hydraulic or vibration hammers
- Underwater hydraulic hammers
- Drill-drive
- Drill and grout

Pile driving is a faster and less weather sensitive means of installing piles than drilling and normally results in greater pile capacity than a drilled pile. There are however several disadvantages compared with drilling and grouting:

- The act of driving will sometimes damage the pile head and the pile may not be driven truly vertical. In order to connect the tower, this could entail cutting the head level and true and prepping it for either welding on of a flange or direct welding of the tower. This problem was overcome at Utgrunden by using a sleeve, incorporating the tower connection flange, that slid over the pile and could be adjusted to grade and level. Once in position, the annulus between sleeve and pile was grouted.

- During pile driving, accelerations both lateral and vertical of up to 50g will be observed. Any attachments to the pile will need to be designed for this or retrofitted. This would include access ladders and walkways, anodes, J-tubes etc.

Drill-drive would be slower than simply driving and would suffer all the disadvantages of driving. It is generally only used to assist driven piles in reaching target penetration in hard soils.

Drill and grout has been successfully used for some monopile foundations and is the only method if penetration of rock is required. The benefits of drill and grout are:

- More controlled placement of the pile without damage and to a tight tolerance is possible. This permits bolting on of the tower without top of pile preparation and eliminates the need to retrofit ladders, boat landings etc..

3.2 Design Development – Gravity Foundations

3.2.1 Operational experience

Gravity foundations or gravity base structures (GBS) have been used extensively in the Norwegian sector of the North Sea, mainly in deep water, for example Troll and Sleipner. The UK sector has also used gravity foundations in deep water, but more recently in shallower water: Ravenspurn and Harding.
GBS are generally buoyant for floatout, tow and installation and are then ballasted with water, iron ore or grout to provide sufficient on-bottom weight to resist overturning. The GBS normally consists of a series of open and or closed cells that form the base and one to four legs that are integral to the design, provide stability during temporary conditions and support the topsides.

To date gravity foundations for OWEC's have been similar in appearance to onshore foundations with the connection to the tower raised above Highest Astronomic Tide. Examples are Middelgrunden, Vindeby and Tuno Knob

The gravity foundation has advantages for installation over a monopile in that the complete OWEC can be assembled on-shore in a dry-dock as one unit and no drilling or piling equipment is necessary. However, the efficiency of the installation operation does depend on the dry-dock being located close to the OWEC's site, thus minimising transport times. Additionally, a specially modified transportation/installation vessel is needed.

3.2.2 Design configuration

A variety of different configurations have been used to date and it is likely that optimisation for particular site-specific developments would result in more solutions. The likely future of gravity foundations as water depths increase are discussed below.

Solid concrete plate foundation – Middelgrunden, Vindeby

These are extensions of onshore foundations and are likely to increase significantly in weight as water depths increase, although the plate could be made to contain additional heavy ballast as an alternative to simply adding concrete mass.

Concrete box caisson (filled) – Tuno Knob

The caisson does not rely purely on the mass of concrete to provide stability and would probably not increase in mass quite so significantly as the solid plate.

Steel caisson – proposed

This would be similar in form to the plate foundation with provision for the heavy ballast.

3.3 System Dynamics

The OWEC is dynamically sensitive to excitation caused by a complete rotation of the rotor and passage of the blades past the tower. This gives two periods that must be avoided to ensure that resonant response does not occur.

For example: for a three-bladed rotor with a rotation speed of 22 revs/minute the natural period T of the OWEC must be as given below.

- stiff-stiff natural period $T < 0.8$sec
- stiff-soft natural period $1.0\text{sec} < T < 2.4$sec
- soft-soft natural period $T > 3.0$sec

It is normal to define the exclusion period as the calculated period +/- 10%

3.3.1 Sea bed conditions

The natural period of the OWEC is critical as discussed above and depends on the following:

- Mass of the system
- Stiffness of the tower
- Stiffness of the combined substructure and foundation.

(Note: substructure is defined as the element between the tower and the seabed, foundation is defined as the element at seabed and below.)

The monopile is potentially the least stiff of the foundations options and, particularly in slightly deeper water, is likely to be of the soft-soft type. However, it was observed at Lely that the behaviour of two of the OWEC’s was stiffer than predicted, and that one was stiff-soft rather than soft-soft. It was fortunate that the exclusion period was avoided, although it must be noted that this was purely chance.

Multi-pile substructures are likely to have more predictable natural periods, being less dependent on the lateral stiffness of the surface and subsurface soils.

For any design, sensitivity studies must be undertaken to ensure that, even with upper and lower bound soil properties, the predicted range of OWEC natural periods does not fall within the exclusion period.

Scour of the seabed can also significantly affect the foundation stiffness. Scour protection will be necessary where granular surface soils exist in areas where the seabed can experience high currents or wave particle velocities.

3.3.2 Wave excitation

Offshore structures generally have adequate fatigue resistance if their natural period is less than about 4 seconds. Above this level, design against fatigue is not impossible, but is more difficult.

Current demonstration OWEC projects: Middelgrund, Lely, Vindeby, Blyth are in very shallow and generally sheltered water (2m-10m) and the behaviour of the foundation is little influenced by wave dynamics.

In deeper water, and particularly with monopiles and monotowers, it is likely that the natural period of the OWEC will be greater than 3 seconds, a soft-soft foundation, and will be more susceptible to wave-induced fatigue damage. Aerodynamic damping is a result of rotor rotation and affects fore-aft first order motions. This will reduce the observed fatigue damage due to waves compared to that predicted using a theoretical undamped system.

3.3.3 Structure types

Up to 20m water depth, it is likely that the drilled and grouted monopile will be the most cost-effective solution, with the concrete plate foundation as an alternative.

Above 20m, it is likely that the natural period of an OWEC on a monopile will exceed 4 seconds, with potential problems for fatigue resistance, although aerodynamic damping would help to reduce the dynamic response.

A concrete gravity structure is theoretically suitable for depths greater than 20m although the weight and cost of such a structure could be prohibitive. It could be designed either to be self-floating or barge transportable. The former would require the structure to be constructed in a dry dock, although it is noted that the Middelgrunden structures were constructed in a dry dock and were not self-floating.

Steel structures would be suitable for these depths and would probably not be excessively heavy. It is likely that they would be supported by small (36-48in) piles rather than gravity or suction foundations, although a heavily ballasted steel caisson may be cost-effective. Such structures could either be of lattice tower or monotower construction. A lattice tower would probably be lighter than a monotower, but because of the large number of members and joints, would be more expensive to fabricate and would require significantly more inspection and maintenance, particularly in the splash zone. The lattice tower is likely to have a higher natural period than a monotower, and could therefore be more fatigue-susceptible.

A monotower is a large diameter central tube supported by three or four small diameter piles. The piles are connected to the tube by means of grouted sleeves and tubular braces. The benefit of the monotower is its simple construction, but it would still have a higher cost per tonne compared with a monopile. The turbine tower would be bolted to the monotower, just as for a monopile, thus the operational experience at Lely, Vindeby and Blyth regarding O&M, access, control rooms, workrooms would be transferable. Separate provision would be necessary if a lattice tower were to be used.

An alternative monotower concept is to use a large diameter tube with pile sleeves attached closely to the tube with shear plates – similar to a large offshore platform ‘leg bottle’. It is anticipated that three 36in-48in piles would be suitable for this purpose, and they could be driven, speeding up the installation process. The cost per tonne would be between a monopile and a braced monotower. Pile weight would be lower than the monopile so overall cost should be less.

The optimum concept for a particular site should be assessed by detailed analyses of all concepts and their site-specific costs:

- CAPEX:- engineering, fabrication and installation.
- OPEX:- inspection, maintenance, repair, visit intervals, support and/or accommodation vessel/unit requirements.

3.4 Icing

Sea ice is a consideration in the Baltic but not in the UK or Dutch sectors of the North Sea. However, since the sea ice is annual ice up to about 600mm thick, structures can be designed to resist it by providing sloping faces to the substructure at sea level. This reduces the ice pressure by inducing bending in the ice and breaking sheets into small pieces.

At Bockstigen, the monopiles have an octagonal form of ice protection made of stainless steel and filled with concrete.

3.5 Breaking Waves

Foundations could be designed using conservative assumptions of the effects of breaking waves compared with non-breaking waves and this would probably not be a significant cost item for a 1 or 2 OWEC development.

However, the economics of large OWECS rely on economy of scale and optimisation of all aspects of design to remain economically attractive. Better understanding of breaking wave phenomena for generic and site-specific wave environments is therefore necessary.

3.5.1 Operational experience

Breaking waves can cause both local damage to offshore structures and impose significant global forces. A single column structure such as a monopile or even a monotower is more susceptible to global forces compared with a multiple legged jacket structure because the wave force is applied instantaneously to a single discrete element rather than to an array of elements. A phenomenon known as ‘ringing’; a dynamic response to the high frequency components of a wave train, has been observed on a single column concrete gravity structure in the Norwegian sector(Sleipner). It has been suggested that a similar phenomenon can be observed with breaking waves acting on a monopile in shallow water.(Structural Dynamics of Offshore Wind Turbines subject to Extreme Wave Loading – N Rogers – Border Wind)

At the EPSRC OWEN workshop ‘Structure and Foundations Design of Offshore Wind Installations March 2000, NDP Barltrop discussed breaking waves and their effect on shallow structures. The effects of breaking waves upon the Bockstigen monopile structure are investigated in this study.

It should be noted that the occurence of breaking waves is not applicable for existing Dutch offshore windfarms as they are located in inland water.

3.5.2 Modelling

Because the behaviour of waves in shallow water is so dependent on local topology it may be difficult to predict whether waves would tend to break. There may well be local knowledge, existing model test information from coastal defence programmes or measurements that would indicate whether breaking waves had been observed.

Model testing would be a useful means of investigating the behaviour of waves at a particular site and with representative models of an OWECS give information on wave run-up, celerity, particle velocities and steepness. Current and wind can significantly alter the steepness of waves in shallow water, and should be considered in any testing programme.

3.5.3 Research for offshore wind

Direct research into breaking waves in relation to offshore wind energy is currently being undertaken under the Engineering and Physical Sciences Research Council (EPSRC) Renewable and New Energy Technologies (RNET) ‘Dynamic Response of Wind Turbine Structures in Waves’ NDP Barltrop University of Glasgow et al.

At the Bockstigen demonstration project the monopile and tower are strain gauged and measurement of the dynamic behaviour the OWEC and metocean and meteorological measurements are underway.

3.6 Design Developments

Garrad Hassan are further developing Bladed for Windows and Germanischer Lloyd have undertaken development under Joule 1 (Jour 0072) Study of Offshore Wind Energy in the EC

The OWEN / ESPRC Workshop April 1999 identified research priorities in this area as:

A need to improve the prediction of environmental conditions for input to the design calculations, including:

- The relationship between extreme winds and waves.
- Improvement in metocean predictions for sites of interest
- Improved models of boundary layer, turbulence and machine wakes in maritime areas
- Predictions of wind and wave directions
- The determination of loading due to breaking waves and other shallow water effects

A decision as to whether components (namely turbine and support structure) are treated in an integrated way during design, reducing conservatism.

To develop improved understanding of the structural dynamics of offshore wind structures

To assess the reliability of existing spectral wave models

To assess importance of wave-driven fatigue on offshore wind structures

To investigate the suitability of different types of foundations for offshore wind energy applications, for example, their response under cyclic loads and their dynamic characteristics.

To routinely monitor the performance of offshore anemometry masts and wind turbine structures – with the data used to refine models and designs

To assess the available methods of determining and measuring dynamic soil properties

To investigate the economics of off-the-shelf foundation designs

4 STANDARDS

4.1 General

The issue of building permits for offshore wind turbines will depend on a large number of different agencies and institutions. This is not only due to the different technical fields involved, but also due to the impact from the marine environment (navigation, national parks, pipelines, cables, defence areas, etc.). Many European countries have appointed one authority to co-ordinate the necessary involvement of the relevant organisations. In most countries this appointment is also different depending on the distance to the shore, i. e. local, inside 12 miles or outside.

In Europe the technical design of wind turbines shall be based on the relevant European Directives. Of special importance for wind turbines is the Machinery and the Construction Product Directives. However, the Low Voltage and Electromagnetic Compatibility Directives also need to be satisfied. All of these Directives are general purpose documents which ask for harmonised standards and requirements.

A European set of building codes are the Eurocodes 1, 2, 3 which are published as ENV 1991, 1992, 1993. The Eurocodes are based on the method of analysing limit states according to ISO 2394 and do require the use of partial safety factors. Eurocode 1 defines loads, Eurocode 2 contains requirements for concrete structures and Eurocode 3 those for steel structures.

In addition to the existing IEC-standards, the European Directives, Eurocodes and a number of national codes for wind turbines, Germanischer Lloyd's Regulation for the Certification of Offshore Wind Energy Conversion Systems [1] and the Danish Recommendation for Technical Approval of Offshore Wind Turbines [25] give guidance on the special design requirements for offshore wind turbines. Further national and international codes and regulations for offshore structures may be applicable.

The design of offshore wind turbine foundations can be based on the long term experience gained in projects undertaken by the oil and gas industry. However, it has to be pointed out that for existing offshore structures, wind is generally not one of the dimensioning load components. The structural design of the offshore wind turbine has to take into account both wind loads and the structural response of the foundation which may result from waves, currents or ice.

Extended remote control is one of the design modifications for offshore wind turbines. Others are corrosion protection against marine atmosphere, boat or helicopter landing facilities and lifting gear for components.

Design rules for offshore wind turbines have been derived from codes for wind turbines and those for offshore structures. Although there is considerable experience for both of those structures their combination has revealed new load cases which need to be considered in the design, construction and operation of offshore wind farms.

4.2 GL Offshore Standard

Germanischer Lloyd's (GL) Regulations for the Certification of Offshore Wind Energy Conversion Systems (GL-OW) [1], issued 1995, are a result of the Joule 1 Offshore study [5] by merging the GL Regulations for the Certification of Wind Energy Conversion Systems (GL-W) and the Rules for Offshore-Installations (GLO). The structure and main components of these Regulations are described in [6].

In the meantime since the first issue of the regulation, new knowledge has been gathered on offshore wind and wave conditions and some pilot wind farms have been constructed. There is a strong requirement to bring the GL-OW Regulations in line with new developments.

Review of the Regulations is underway consisting of following points:

1. Resolve insufficiencies and errors found in planning and certification procedures: Several offshore wind farms are in the planning or design stage.. These include wind farms in Denmark, Germany and the Netherlands where Germanischer Lloyd WindEnergie GmbH (GL-Wind) is actively incorporated as a certification body.

2. Incorporate results from applications in pilot farms: GL-Wind is participating in the EU research project 'Offshore Wind Turbines at Exposed Sites' (OWTES), being undertaken by AMEC Border Wind, Delft University of Technology, Germanischer Lloyd WindEnergie, PowerGen Renewables Developments and Vestas Wind Systems under the leadership of Garrad Hassan and Partners [8].

   The aim of this project is to improve the design methods for wind turbines located at exposed offshore sites in order to facilitate the gradual, cost-effective exploitation of the offshore wind energy resource available in the EU. This aim will be met through the achievement of a number of project objectives. These include to;

   - establish a database of environmental and structural load measurements.
   - evaluate the database of environmental and structural measurements in order to derive a thorough understanding of the aerodynamic and hydrodynamic loads and their influence on the dynamic response of the offshore wind turbine and its support structure.
   - use the database of measurements to enable validation and enhancement of state-of-the-art-methods for computer modeling and design analysis of offshore wind turbines.
   - undertake parametric analyses for investigation of the complex relationships between fatigue and extreme loading, the design characteristics of an offshore wind turbine and its support structure, and the site wind, wave, current and sea bed conditions.
   - investigate the robustness of design calculations for offshore wind turbines with respect to variations in the environmental conditions, wind turbine and support structure design concepts and methods of analysis.
   - provide a critical appraisal of present design procedures and certification rules for offshore wind turbines and to recommend changes where appropriate.
   - catalogue the key design requirements for offshore wind turbines for sites where the environmental conditions are severe.

   The database of measurements recorded at Blyth Harbour is evaluated in order to establish a complete characterisation of the environmental conditions at the site. The characterisation will identify the correlation of wind, waves and currents. In addition, the spectral characteristics of the wind turbulence and the wave heights will be established and compared with the standard models recommended by the certification regulations for offshore wind turbines.

The measurements of environmental data and structural response will be used to examine the extent to which the assumptions underlying the current GL certification regulations for offshore wind turbines are valid for the Blyth Harbour site.

A thorough review of the current GL certification regulations for offshore wind turbines will be undertaken. Based on a critical evaluation of the project results, the validity of the assumptions and guidelines offered by the GL regulations will be examined and, where appropriate, recommendations for revision will be made.

3. Update according to scientific / technological progress.

   A number of research projects have provided valuable information on offshore specific issues. Specific subjects have been investigated separately e.g. wind resources, extreme wind and to some extent wave conditions, turbulence characteristics, joint-appearance (probability) of wind, waves, ice and current and on operation and maintenance. Some of the results are now available [9], [10], [11], [12], [13], [14], [15] and the effort is to include these in future regulations updates.

4. Harmonization with IEC.

   Considerable work has been performed by the IEC TC 88 committee, resulting in the second edition of the IEC 61400-1 in 1999 [7]. According to this standard, offshore wind turbines have to be treated as land based wind turbines of class “S”, considering marine environment. As most offshore turbines are “marinised” versions of land based turbines developed in accordance with IEC 61400-1, a harmonisation with the IEC code is of advantage. This task is scheduled for 2001-2002 and will be performed as a review of the regulations for land based wind turbines [2]. In Parallel GL-Wind is participating in the relevant national and international working groups of DIBt, CENELEC, IEC TC88 for offshore (WG03) and land based wind turbines (WG01) which will have influence on the regulation harmonisation.

4.3 Danish Recommendation for Technical Approval of Offshore Wind Turbines **(Rekommandation for Teknisk Godkendelse af Vindmøller på Havet)**

The Danish Energy Agency has issued recommendations for the approval of offshore wind farms in Denmark. Generally the standard DS472 applies, with significant changes in some parameters. A short description of the recommendation is given here:

Part 1: Introduction, applicable standards. Wind turbines to be erected offshore Denmark have to fulfill the Technical Criteria for Type Approval and Certification of Wind Turbines in Denmark, The Danish Standard DS472 and other norms and regulations stated in the Technical criteria. For the analysis of wave loading, DS449 (Piled offshore structures) and for ice loading API 2N [26] have to be applied. Further Danish national construction norms (DS409 – DS415) to be considered are named.

Part 2: Climatic parameters and safety in relation to DS472. The changes of parameters relative to DS472 are described. Annual mean and extreme wind speed as a function from distance to shore, air density and safety factors for the loads to be used for offshore wind turbines are stated. Additionally a method to be used for the calculation of wind farm influence on wind speed turbulence intensity is given.

Part3: Loads and load cases. The calculation methods and the nature of the dynamic model are described together with the loads acting on the structure. Depending on the system sensitivity some guidance on analysis methods and extent is given. Apart from the definition of the characteristic values (98% of the annual extreme value) and the coefficient of variation to be used together with safety factors, a list of load cases, based on DS472 and extended for offshore climate is stated. Recommendations on the combination of wind, wave, ice and current loading and the extraction of design loads from them are included.

Part 4: Foundations. Reference is made to DS415 (Foundation) and DS 449 (Piled offshore structures). The determination of the geotechnical category, the required pre-appraisals like measurements or laboratory experiments are considered together with inspection requirements.

Part 5: Materials and corrosion. This section refers to the protection systems and durability of the support structure up to the nacelle. Corrosion protection is considered. Regulations to be applied for concrete and steel structures are listed.

Part 6: Additional conditions such as occupational safety, lightening protection, marking, noise emission and environmental impact assessment are stated.

4.4 IEC Offshore Wind Turbine Standards

4.4.1 Review

According to the existing IEC 61400-1 standard, offshore wind turbines have to be treated as land based wind turbines of class "S". This is not a satisfactory solution and the Technical Committee 88 of the IEC set up a working group (WG03) to develop IEC 61400-3 specially dedicated to offshore wind turbines.

4.4.2 Objective of WG03

The objective of WG03 is to develop a standard for the engineering and technical requirements which should be considered during design in order to ensure the safety of systems and components of offshore wind turbines, inclusive of their support structures. This will be documented in IEC 61400-3.

IEC 61400-3 will cover only those issues relevant to offshore wind turbines, fully consistent with IEC 61400-1 and not duplicating the requirements defined in IEC 61400-1.

4.4.3 Contents

The contents of the document will be limited (at the beginning) to offshore wind turbines with support structures which are fixed to the seabed (not floating systems). It is proposed that a wind turbine be considered "offshore" if the support structure is subject to hydrodynamic loading. The main issues to be considered are: external conditions, design load cases, calculation methods, structural design, and assembly, installation erection, commissioning and maintenance.

The time schedule agreed in WG03 is shown in the following table:

Status of IEC 61400-3	Proposed Target Date
Availability of first WD (working draft)	December 2001
Circulation of first CD (committee draft)	June 2002
Submission of first CDV (committee draft for voting)	December 2002
Submission of FDIS (final draft international standard)	December 2003
Availability of IS (international standard)	June 2004

Table 4.4.3.1 Time Schedule of WG03

4.5 Offshore Environment

Apart from general rules and regulations on offshore wind turbine design, site specific environmental conditions are of interest. The influence of wind, wave, ice and soil conditions is covered by the standards for offshore, offshore wind turbine and land based wind turbine designs, together with procedures for site assessment. The certification procedure according to the site conditions is given in [1] and [16] and described in [6].

In addition to the standards normally applied for land based machinery, electrical machinery and buildings, the following may be of interest.

- Electrical conditions may have significant impact on wind turbine design, especially in conjunction with weak grid conditions. National standards or grid operator requirements will regulate electrical parameters to be fulfilled by the wind farm and the electrical installation up to the connected point on land. Additionally the grid loss probability and duration may (directly) influence load definitions in the standards.

- Operation and Maintenance and related labour safety issues are also covered by national regulations. They will have influence in access and rescue equipment and boarding platforms.

- The marine atmosphere must be considered for corrosion, as well as guidance relating to the materials to be used and electrical protection.

- Ship navigation will not directly influence turbine structural design except the collision case. National laws and international agreements determine the equipment to be installed (light marking, active and passive radar reflectors etc). The ship collision probability and load has to be considered.

- Installation, lifting and commissioning are generally covered by offshore regulation although national regulations may apply.

- Marine pollution, MARPOL, e.g. access visits must be minimised to reduce use of fossil fuels and disturbance on sea fauna.

- Dismantling. In most countries a full dismantling of offshore constructions is required by national law. In Germany by the mining law (§55(2) Nr3 Bberg).

- Air traffic markings in accordance with international and national regulations have to be installed.

- The noise problem cannot be neglected even offshore. Many large scale turbines can produce noise similar to sound levels generated from motorways.

- Site specific approach wind+wave+ice+soil conditions.

- Procedures on site assessment and certification according to GL and IEC.

- Electrical conditions – power supply power company, National O&M National Work safety influence on safety systems, accessibility, platforms etc.

- Shipping, navigation, air traffic national and international regulations and their influence on design e.g. collision, site spec. depth etc.

- Lightning protection requirements.

4.6 Offshore Industry Standards

Standards that will apply or assist in installation and erection procedures and in the design of special structures not included in wind energy related codes. These are listed in the following:

Offshore regulations

1. American Petroleum Institute, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design, API Recommended Practice 2A-WSD, 21st Edition 2000.
2. American Petroleum Institute (API), Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms –Load and Resistance Factor Design, 1993, (suppl. 1997), RP 2A-LRFD
3. American Petroleum Institute, Recommended Practice for Planning, Designing and Constructing Structures and Pipelines for Arctic conditions, API Recommended Practice 2N, 2nd Edition 1995.
4. Norwegian Technology Center (NTC), NORSOK Standard N-001, Structural Design, Rev. 3, Aug. 2000.
5. Department of Energy, (now Health and Safety Executive) 1990: Offshore installations: guidance on design, construction and certification (fourth edition) HMSO 1990 ISBN 011 4129614, replaced.
6. Det Norske Veritas, Rules for classification of fixed offshore installations 1998.
7. Germanischer Lloyd, Rules for Classification and Construction, III Offshore Technology, 2 Offshore Installations, Edition 1999
8. ISO 13819-1, Petroleum and natural gas industries -- Offshore structures -- Part 1: General requirements, 1995-12, 1st edition. To be replaced , ISO TC 67. (ISO 19900)
9. ISO 13819-2 Petroleum and Natural Gas Industries – Offshore Structures – Part 2: Fixed steel structures, 1995.
10. ISO 19903 (Draft), Offshore Structures – Fixed concrete structures.

Offshore Mobile Platforms

1. Det Norske Veritas, Rules for classification of mobile offshore installations.
2. Germanischer Lloyd, Rules for Classification and Construction, III Offshore Technology, 2 Offshore Installations, Guidelines for the Construction/Certification of Floating Production, Storage and Off-Loading Units, Edition 1999.

3. IMO, MODU-Code, Code for the construction and equipment of mobile offshore drilling units, 1989.
4. ISO 19904 (Draft), Offshore Structures – Floating systems.

Electrical Equipment

1. American Petroleum Institute, Recommended Practice for design and installation of electrical systems for Offshore.
2. IEC 60092-xxx (2000-02) Electrical installations in ships
3. IEC 60533 (1999-11) Electrical and electronic installations in ships - Electromagnetic compatibility
4. IEC 60654-2 (1979-01) Operating conditions for industrial-process measurement and control equipment. Part 2: Power
5. IEC 60654-4 (1987-07) Operating conditions for industrial-process measurement and control equipment. Part 4: Corrosive and erosive influences
6. IEC 61363-1 (1998-02) Electrical installations of ships and mobile and fixed offshore units - Part 1: Procedures for calculating short-circuit currents in three-phase a.c
7. IEC 61892-3 (1999-02) Mobile and fixed offshore units - Electrical installations - Part 3: Equipment
8. IEC 61892-6 (1999-02) Mobile and fixed offshore units - Electrical installations - Part 6: Installation

Materials and Corrosion

1. DIN EN 12495, Cathodic protection for fixed steel offshore structures, 2000.
2. DIN EN 10225, Weldable structural steels for fixed steel offshore structures, 1994.
3. Det Norske Veritas, R.P. B401, Cathodic Protection Design, 1993
4. Germanischer Lloyd, Rules and Regulations, II Materials and Welding, Part 1, Metallic Materials, Edition 1998.
5. Germanischer Lloyd, Rules and Regulations, II Materials and Welding, Part 1, Non-metallic Materials, Edition 2000.

Special Topics

1. IMO, Safety of Life at Sea Convention (SOLAS)
2. Marine pollution , MARPOL
3. International Association of Sea-Mark Administrators (AISM/IALA) Recommendations for the marking of offshore structures, Nov. 1984 /suppl. 1987).

Helicopter Platforms

1. Cap 437, Offshore Helicopter Landing Areas.
2. American Petroleum Institute, Recommended Practice for Planning, Designing and Constructing Heliports for Fixed Offshore Platforms, API Recommended Practice 2L, 4th Edition 1996.

Offshore Cranes

1. American Petroleum Institute, Specification for Offshore Cranes, API Spec 2C, 5th Edition 1995.
2. DIN EN 13852, Cranes – Offshore Cranes – Part 1: General purpose offshore cranes, 2000

4.7 EU-Project Recommendations for Design of Offshore Wind Turbines (RECOFF)

The objective of this project is to prepare guidelines and recommendations for design of offshore wind turbines. The main objective of these guidelines and recommendations is that they should serve as a basis for development of European and national standards and certification rules for offshore wind turbines. The recommendations will be addressed directly to the two standardisation bodies: the International Electrotechnical Commission (IEC) and the European CENELEC.

The existing offshore standards, mainly written for offshore oil and gas exploitation, are not suitable to cover the offshore wind energy technology. Particular review of health and safely issues for offshore work on OWECS must ne a priority. A combination of these offshore standards and the existing onshore wind energy standards is in process but technology gaps exist. In the project, readily available information will be utilized to the extent possible, and where a need is identified, research and development will be performed. The project is structured in accordance with the typical components of a standard. The main tasks are reflected in the project work packages:

1) External conditions: identification and description of wind, waves, ice etc.,
2) Computational tools: generation of loads from external conditions,
3) Design load cases: identification of a suitable number of representative load cases,
4) Probabilistic methods: new models for decision-making on load cases,
5) Structural integrity: specification of e.g. partial safety coefficients,
6) Operation and maintenance: labor safety and standard method for data collection.
7) Project management and communication: management, preparation and execution of seminars for external parties such as manufacturers.

The proposed work (3 years duration) will aim to bring together available information and expert knowledge from the wind power (Riso (coordinator), CRES, ECN, GH and GL) and offshore engineering industries. The overall methodology of the project is summarized in Figure 4.7.1.

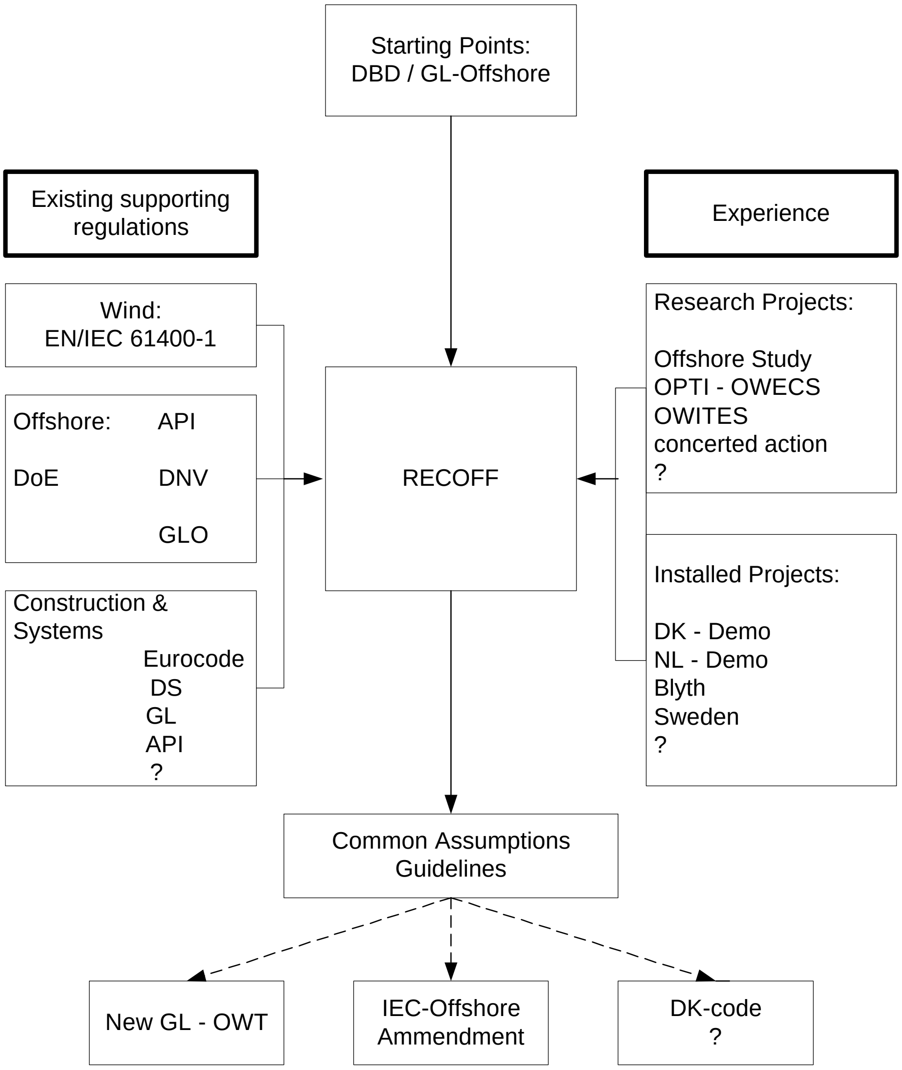

Figure 4.7.1: Overview of the Methodology used in the Project[1].

[1] Abbreviations: IEC61400-1: International standard on wind turbine safety; GL-OWT: GL regulation for the certification of offshore wind energy convertion systems (1995); API: American Petrol institute – recommended practice for planning, designing and constructing fixed offshore platforms; GLO: GL rules for classification and construction, III offshore technology (1999); DoE: UK Dept. of Energy; GL: regulation for certification….(1999); DBD: design basis for Danish demonstration offshore projects; DS: Danish Standard; DNV: Det Norske Veritas, EN: European Norm, OWITES: Offshore Wind Turbine at Exposed Sites.

4.8 References

1. Germanischer Lloyd, Rules and Regulations, IV Non Marine Technology, Part 2 Regulations for the Certification of Offshore Wind Energy Conversion Systems, Edition 1995.
2. Germanischer Lloyd, Rules and Regulations, IV Non Marine Technology, Part 1 Regulations for the Certification of Wind Energy Conversion Systems, Edition 1999.
3. Germanischer Lloyd, Rules for Classification and Construction, III Offshore Technology, 2 Offshore Installations, Edition 1999.
4. Germanischer Lloyd, Rules for Classification and Construction, III Offshore Technology, 2 Offshore Installations, Guidelines for the Construction/Certification of Floating Production, Storage and Off-Loading Units, Edition 1999.
5. Matthies et al, „Study of Offshore Wind Energy in the EC, Final Report Joule I (JOUR 0072), Verlag Natürliche Energie 1995.
6. C. Nath, “Experiences in Offshore Certification”, Proceedings of the EUWEC Göteborg 1996.
7. IEC 61400-1, ed. 2, Wind Turbine Generator Systems, Part1 – Safety Requirements, Feb. 1999.
8. T.R. Camp, D.C. Quarton, “Design Methods for Offshore Wind Turbines at Exposed Sites”, JOR-CT98-0284.
9 Bitner-Gregersen, E.M., Hagen, O., "Aspects of Joint Distribution for Metocean Phenomena at the Norwegian Continental Shelf", Proceedings of ETCE/OMAE2000, ASME 2000.
10. Myrhaug D. Slaattelid O.H., "Wind Stress over Waves: effects of sea roughness and atmospheric stability", Proceedings of ETCE/OMAE2000, ASME 20000.
11. Matthies et al, "Offshore Windkraftanlagen: Kombination der Lasten von Wind und Wellen", TU Braunschweig 2000.
12. Timco G.W., et al, "The NRC Ice Load Catalogue", Proceedings of 15th Int. Conference on Port and Ocean Engineering under Arctic Conditions, POAC'99, Vol 1, pp 444-453, Helsinki Finlad.
13. Crespo, A., R. Gomex-Elvira, S. Frandsen and S Larsen (1999) Modelisation of large wind farm, considering the modification of the atmospheric boundary layer, 1999 European Wind Energy Conference and Exhibition, Nice France, March.
14. Frandsen, S. and K. Thomsen (1997) Change in Fatigue and Extreme Loading when Moving Wind Farms Offshore; OWEMES '97, Sardinia, Italy, April.
15. Frandsen, S. (Editor), L. Chacon, A. Crespo, P. Enevoldsen, R. Gomex-Elvira, J.H● jstrup, F. Manuel, K. Thomsen and P S● rensen (1996) Measurement on and Modelling of Offshore Wind Farms, Ris● -R-903(EN) report.
16. IEC 61400-22, Wind Turbine Certification.
17. American Petroleum Institute (API), Fixed offshore platforms, Working Stress Design, 1993
18. American Petroleum Institute (API), Fixed offshore platforms, Load Resistance Factor Design, 1989.
19. Draft ISO 13819-2 Petroleum and Natural Gas Industries - Offshore Structures - Part 2: Fixed steel structures.
20. IMO, MODU-Code, Code for the construction and equipment of mobile offshore drilling units, 1989.
21. Cap 437, Offshore Helicopter Landing Areas.
22. Det Norske Veritas, Rules for classification of fixed offshore installations.
23. IMO, Safety of Life at Sea Convention (SOLAS).
24. Health & Safety Executive: Offshore installations: guidance on design, construction and certification (fourth edition) HMSO 1990 ISBN 011 4129614.

25. Danish Recommendation for Technical Approval of Offshore Wind Turbines (Rekommandation for Teknisk Godkendelse af Vindmøller på Havet), Danish Energy Agency 2001.
26. API Recommended practice 2N, “Recommended practice for planning, designing and constructing structures and pipelines for arctic conditions”, 1995.

5 PROJECT EXPERIENCE

5.1 Methods Used

The installation sequence of an offshore wind turbine depends on the foundation structure chosen. An offshore wind farm requires much closer integration of the design and construction activities than an onshore wind farm because of the additional challenges of operating at sea. Some basic principles, including construction, for typical offshore foundations are given in Table 5.1.1.

Foundation type	Size (diameter)	Weight	Construction sequence
Gravity base	12 – 15 m	500 – 1000 tonnes	1. Prepare Seabed 2. Placement 3. Infill Ballast
Monopile	3 – 3.5 m	175 tonnes	1. Place Pile 2. Drive Pile
Multipile	0.9 m	125 tonnes	1. Place Base 2. Drive Pile
Bucket (caisson)	4 – 5 m	100 tonnes	1. Place Base 2. Suction Installation

Table 5.1.1 Basic principles of typical foundations for offshore wind turbines [1]

Each type of foundation will be subject to construction constraints. A gravity base foundation requires the seabed to be prepared in advance and the toe of the structure to be protected against scour. An advantage is that the structure can be constructed onshore, thereby reducing offshore operations. The monopile is easy to install (drive) with proper equipment but large stones in the seabed can make it difficult or even impossible. If the pile needs to be driven into the bedrock (granite), expensive site works have to be undertaken. A comparison of the construction differences for monopile and gravity base foundations is summarised in Table 5.1.2.

Construction phase	Gravity base foundation	Monopile foundation
Onshore construction	Local to site	No constraints
Transport offshore	More complex	Lift onto barge
Pre-placement activities	Seabed preparation	None
Placement	Lift or float-over	Lift
Fixing	Grouting	Pile driving
Installation of tower / turbine	Potential obstruction to lift	No hindrance to lifting

Table 5.1.2 Construction differences for monopile and gravity base foundations [2]

5.2 Problems Encountered

Time delay at sea is the most significant problem related to offshore project engineering. As hired equipment is used for installation, all downtime will prove costly. Project developers try to minimise delays by pre-assembly and onshore testing of installation procedures. Any problem or design error detected at sea causes time delays and equipment downtime.

- At Middelgrunden some of the interconnecting cables were damaged when the foundations were installed. The problem was foreseen with spare cables available and a covering insurance.

– At Bockstigen downtime was caused by high winds preventing the jack-up barge from being operated. Jack-up barges cannot be safely deployed during heavy sea conditions.

Construction time for a driven pile foundation from a floating barge was initially shown to be less costly than using other methods. Due to weather downtime, the overall installation durations have been similar for gravity base foundations and driven pile foundations installed either from a jack-up vessel or floating barge.

The weather downtime allowance required for a 50 unit wind farm is considerable, approximately doubling the floating barge installation duration. It has been proposed to install the structure in two pieces (first the foundation unit followed by the assembled support tower, nacelle and rotor as one unit) compared to three pieces (installing each of the foundation, support tower and nacelle and rotor units in a separate operation) to save in construction time.

5.3 Design Options

5.3.1 Assembly design

Offshore wind turbines are most likely to be installed from either a jack-up barge or a floating crane vessel. The choice will depend on the water depth, the crane capability and vessel availability. The crane must be capable of lifting the structures, with hook heights greater than the level of the nacelle to enable the tower and turbine assembly to be installed. Existing crane vessels have not been specifically designed for installing offshore wind turbines. For large offshore wind farms, greater than 50 units, significant time (and therefore cost) savings could be made by using an installation vessel purpose built for the task. This philosophy has been adopted elsewhere in the civil engineering industry.

So far, the installation process had held two phases. First the foundations are build and then the turbines are installed on top of the foundation. Usually turbines are erected as on land, i.e. first the tower in segments and then the nacelle and the rotor.

In the case of Middelgrunden, the first tower segment was pre-installed and transported on the foundation. The control board, switchboard and the transformer were located at the bottom of the tower during transportation and lifted in place, at intermediate floors, on site.

The total build duration for a multi-unit wind farm is likely to take several months. All installation operations will be subject to weather constraints and there will inevitably be periods of non-operation/weather down-time. This can be minimised by scheduling installation operations during the relatively calm summer months, when both wind speeds and wave heights are most frequently within safety limits.

5.3.2 Transportation

The monopile foundation, i.e. a steel cylinder, is usually transported to the site on barges. Alternatively it can be capped and sealed at the ends and floated to the site.

At Vindeby and Tunø Knob, the caissons were floated to the site and filled with ballast. At Middelgrunden, the foundations were transported with a barge, that lifted the foundations several meters from the seabed and transported them one by one to the site.

The Opti-OWECS report suggests transporting the whole turbine in one piece. Two alternative tower and wind turbine transportation orientations were considered, i.e. a vertical and a near horizontal orientation. In the near horizontal orientation the barge space requirements govern the size of the barge required whilst in the case of the vertical orientation, the transportation stability requirements govern. Transportation in the vertical orientation is not regarded as feasible without substantial bracing to limit the bending moments at the base of the tower.

An amphibian vessel for transporting, installing and maintaining assembled wind turbines has been patented in the Netherlands [3].

5.3.3 Erection

All installation methods have their advantages as well as disadvantages. The decision will depend on assembly design, foundation structure, site conditions and to some part on the approach adopted for maintaining the structures.

It is often anticipated that tower units complete with the nacelle and rotor could be installed as a single unit at a rate of two per day (24 hour working) during the summer months (May-August). Under these circumstances vessel downtime of around 50% is anticipated i.e. a rate of 1 tower per day accounting for downtime with a total installation period inclusive of mobilisation of 4 months. However, the temporary storage of the turbines to be installed may constitute a problem.

The Opti-OWECS report [4] presents a good summary of the options available for installation of the tower (inclusive of nacelle and rotor etc.):

Jack- up Installation
Jack-up lift appears at first glance to be the obvious method of installing the tower, nacelle and rotor. It forms a stable base from which to carry out the operation and is the preferred choice for carrying out the piling operation. However, its inherent stability and hence lack of manoeuvrability poses problems for the installation of the tower. Offloading tower elements from a floating barge and lifting them into place will most likely require a form of piecemeal construction with the tower, nacelle and rotor all installed as separate items. The same jack-up barge can be used for driving the monopile and for installing the turbine.

Semi-Submersible Installation
Lifting from a vessel is in principle most straight forward method of installation. Semi-submersible crane vessels represent the most stable floating platform from which to carry out offshore construction work. Existing vessels, however, are designed for more remote offshore operation and have difficulties operating in shallow water depths.

Ship Shaped Vessel, Flat Bottom Barges and Land Based Cranes
Ship shaped vessels and flat bottom barges offer appreciably less stability for carrying out construction work and are consequently subject to weather delays. Ship shaped vessels with rotating cranes offer the best performance. As a result, they are in heavy demand and are attracting appreciable day rates. Flat bottom barges with sheer leg cranes of a suitable size are in far greater supply and offer a cost effect approach to tower installation despite weather delays. One way of combining the benefits of rotating crane with adequate reach but at a lower day rate is to use land based cranes. Such a system is adopted quite satisfactorily in sheltered locations.

Float-Over Installation
The Opti-OWECS report presents a float-over installation, where the tower is erected and floated out in the vertical orientation before being floated-over then lowered down onto the pre-installed pile. The tower is erected at the quay side on a dummy pile and is stabilised by a pin which is housed in the tower and lowered into the pile. The tower is secured to a barge in the vertical orientation ready for transportation. The vessel required for this operation may need to be specially built although modifying an existing vessel is also an option. The vessel takes-on the tower at the quay side where it is moored adjacent to the tower and securely seafastened. Then, possibly on a rising tide, the barge is deballasted allowing the tower to be detached from the dummy pile. Once in a safe water depth, the barge is ballasted for the tow. On arrival at the site the vessel is deballasted, if necessary, and safely moored over the offshore installed pile. Then follows the operation of ballasting the vessel down so as to safely transfer the support for the tower onto the pile. The sea-fastening is then released leaving the vessel to be towed away.

5.4 Other Sources, Further Area of Work

Offshore wind energy structures and their foundations must be designed to accommodate exposed weather and equipment workability, with support towers designed to be compatible with the available construction equipment. Additional work is required in:

- Improved dissemination of knowledge of offshore marine related construction procedures and techniques amongst designers/developers.
- Optimise the cost-effectiveness of offshore wind structure installation operations by making use of novel construction sequences and scenarios.
- Investigation of reducing fatigue loading by introduction of inherent flexibility, i.e. flexible towers, compliant couplings, etc.
- Reduction of fatigue loading through more sophisticated control. (Benefits of greater sophistication to be balanced against potential reliability problems.)
- Investigation of the technical and economic feasibility of 're-useable' foundations.
- Identification of suitable European test sites with offshore type conditions, e.g. islands.

5.5 RTD Priorities

The highest uncertainty in offshore installations relate to time delays and costs in use of rented equipment. Also, it is important to minimise the time needed for offshore operations as any unscheduled downtime. There is a clear need for installation vessels that can withstand more severe weather conditions and operate for longer periods of the year. Special installation vessels, designed for installing offshore wind turbines are possible, and perhaps a necessity, when offshore wind energy installation becomes a continuous all-year activity. Cost control efforts should be focused on the overall installation process, and dissemination of areas for economic improvements identified.

A longer term objective should aim for an integrated design, where the foundation and the turbine is installed as one piece. The installation procedure should at least be simplified and include a minimum of operations offshore.

The projected overall cost for an offshore wind farm should account for decommissioning costs which include an allowance for shifts in environmental ground rules or other fluctuating cost factors. The offshore oil and gas industry is currently facing the issue of decommissioning offshore installations and subsea wellheads, the cost of which exceeds previous conservative estimations.

5.6 References

1. Watson, Gillian (Ed.) OWEN workshop on Structure and foundations Design of Offshore Wind Installations. Final Report. http://www.owen.org.uk/workshop_3/ws3final.pdf
2. *ibid.*
3. J.F. Rikken & J.Klop, “Studie naar goedkopere concepten voor de ondersteuning van een offshore windturbine” (Dutch language). KEMA Report No. 99560396-KPS/SEN 00-3035. November 2000.
4. Martin Kühn et al. Opti-OWECS Final Report Vol. 4: A Typical Design Solution for an Offshore Wind Energy Converting System. Delft University of Technology. Report No. IW-98140R The Netherlands August 1998

6 OPERATION AND MAINTENANCE

6.1 Introduction

Operation and maintenance of offshore wind farms is more difficult and expensive than equivalent onshore wind farms. Offshore conditions cause more onerous erection and commissioning operations and accessibility for routine servicing and maintenance is a major concern. During harsh winter conditions, a complete wind farm may be inaccessible for a number of days due to sea, wind and visibility conditions.

Even given favourable weather conditions, operation and maintenance tasks are more expensive than onshore, being influenced by the distance of the OWECS from shore, the exposure of the site, the size of the OWECS, the reliability of the turbines, and the maintenance strategy under which they are operated.

Offshore installations require specialist lifting equipment to install and change out major components. Such lifting equipment can usually be sourced locally and at short notice for onshore wind farms.

The severe weather conditions experienced by an OWECS dictate the requirement for high reliability components coupled with adequate environmental protection for virtually all components exposed to sea conditions.

Consequently, the requirement for remote monitoring and visual inspection becomes more important to maintain appropriate turbine availability levels.

6.2 Land Based Comparative Data

Operational information for onshore wind turbines has been compiled for a number of years which is directly relevant for operation and maintenance issues.

"WindStats" newsletter is a quarterly international wind energy publication with news, reviews, wind turbine production and operating data from over 12,000 wind turbines in Denmark, Germany, Belgium, USA, Sweden, Spain and The Netherlands.

However, WindStats provides very limited information for 1 MW plus turbines. A more relevant source of operating information is provided by turbine manufacturers who either have data in their publicity material or will usually provide data on request.

The overall picture of turbine availability is very good for all major manufacturers who have turbines in full production. For instance, Vestas V66, Enercon E66, Bonus 1.3 MW, Nordex 1.3 MW, Enron/Tacke 1.5 MW all have fleet-average availability of at least 97%. Information on maintenance effort to achieve this is practically unavailable, except through fault reports published in Germany and Denmark (summarised in WindStats).

Monthly wind turbine statistics for Sweden are published by SwedPower AB, and are available on the internet at www.elforsk.se/varme/varm-vind.html.

Published statistical information on the availability, accessibility and reliability of offshore wind turbines is presently limited to site specific information released at the discretion of wind farm operators. Therefore we are dependent on published data from the few existing truly offshore wind farms constructed since 1991. Current offshore wind farms are mostly small in comparison to onshore wind farms, although large scale wind farms, typically around 100 machines, are anticipated.

Operation and maintenance data for onshore wind turbines are readily available as detailed above. However, the environmental conditions associated with offshore installations renders this current machine data inadequate.

6.3 Offshore O&M Models

Maintenance strategies have been developed in the Opti-OWECS project using Monte Carlo simulations. A simple expert system has subsequently been developed based upon analytical trend curves determined from a large number of Monte Carlo simulations [1].

In the Monte Carlo model, the site accessibility as well as the failures of the wind turbines in the OWECS are simulated stochastically on an hour to hour basis. The response in terms of deployment of maintenance and repair crew, and equipment, is simulated simultaneously in the model. This results in the determination of the instantaneous and overall availability of the OWECS and of the instantaneous and overall costs associated with the adopted maintenance strategy under the assumed site conditions

As mentioned above, 'expert systems' [2] have been developed which represent the trend lines found from the far more comprehensive Monte Carlo simulation model. This simple approach enables the assessment of availability and O&M costs for a given OWECS with its O&M strategy as a function of distance to shore and site (wind) conditions. The analytical functions used in this expert system have also been used for the concept evaluation. With them, the OWECS availability and O&M costs could then be determined and optimised for a range of scenarios. [3].

6.4 Maintenance Strategies

The availability of a wind turbine largely depends on the O&M strategy adopted by the operators of a wind farm. Given the limited amount of offshore O&M data, strategic planning is in its infancy, however a number of options were developed in the Opti-OWECS study:

1. No maintenance: Neither preventative nor corrective maintenance are executed, and major overhauls are performed every five years or so. One of the few alternatives is exchanging a whole turbine if availability drops below a predefined minimum or after a certain amount of operational hours. Given the current level of turbine failure rates, this option is not presently viable.

2. Corrective maintenance only: Repair carried out soon after a turbine is down, or, alternatively, wait until a certain number of turbines are down. No permanent maintenance crew is needed

3. Opportunity maintenance: Executing corrective maintenance on demand and taking the opportunity to perform preventive maintenance at the same time. No permanent maintenance crew is needed

4. Periodic maintenance: Scheduled visits performing preventative maintenance, and corrective actions performed as necessary by a permanent dedicated maintenance crew.

The Opti-OWECS study concluded that O&M strategy should be optimised with respect to localised energy production costs rather than pure capital or O&M costs. Further, the availability of OWECS with commercial offshore wind turbines without significantly improved reliability and without optimised operation and maintenance solution may be unacceptably low, e.g. 70% or less.

In conclusion, given current reliability and failure modes of commercial offshore wind turbines, which have been adapted from onshore models, a reduced level of preventative and corrective maintenance is not a viable option at this stage in the development of the offshore wind energy industry.

6.5 O&M Offshore Experience

6.5.1 Availability

Onshore wind turbines are now enjoying availability levels in excess of 97% with appropriate routine servicing and responsive maintenance actions. However, in practice, this typically equates to visiting a wind turbine four times a year, either for regular service or for repair tasks. [1].

Vestas cite a comparison between availability rates for the Fjaldene onshore wind farm and Tuno Knob offshore wind farm [4]. Average availability for Fjaldene is quoted as 99.3% mainly due to the proximity of this windfarm to Vestas' Central Service Department.

Tuno Knob average availability is quoted as; 97.9%, 98.1%, and 95.2% for the years 1996 to 1998 respectively. [5].

6.5.2 Operational expenditure

As stated above, operating expenditure for offshore wind farms is considerably higher than the equivalent onshore facility. Offshore operations are in the region of five and ten times more expensive than work on land, and these costs are exacerbated by inflated prices prevalent within the offshore oil and gas industry. For example, the day rate for an offshore lifting vessel, which will be well over capacity for the wind industry, will typically cost at least ten times that of an appropriate land based crane.

Also, onshore equipment can be sourced and mobilised within a short period of time, usually within hours, and available on site within a day. Offshore lifting cranes are uncommon, and will generally have to travel a considerable distance to an offshore wind farm site, hence the requirement for careful scheduling of such vessels movements. The economics of a large wind farm (e.g. 100 machines) may justify the purchase of a dedicated purpose built lifting vessel which would be available during installation and for maintenance throughout the wind farms lifetime. However, it is commercially expedient to dispense with the need for expensive lifting vessels after installation and hire lifting equipment during scheduled major overhaul. Given relatively calm sea conditions, it is possible to use a floating barge to transport and operate a land based crane offshore. The floating barge need only be a crude construction incurring minimal expenditure, hence be procured and stored for and at a dedicated wind farm.

General maintenance tasks are carried out using less specialised equipment which is generally purchased for the design life of the wind farm.

Operation and maintenance costs mainly related to the wind turbine can account up to 30% and more of the energy costs. [6]. Recent discussions with leading wind turbine manufacturers have indicated that O&M costs, given 95% availability warranties (excluding weather constraints, and dependent on the scale of the project), is approximately £30,000 per turbine per annum for the UK market. The cost of operation and maintenance for the first year of operation may be higher.

6.5.3 Serviceability

The service demand of the present generation of offshore wind turbines in terms of man-hours is in the order of 40 to 80 hours [7]. Service visits are paid regularly, (except in the more demanding first year) about every six months. A more major overhaul will be undertaken every five years, and will take around 100 man hours to complete. [1].

Experience from Tuno Knob show that the total number of service visits have been about 35 to 70 visits per year, an average of approximately 5 visits per turbine per annum. The number of cancelled visits (last moment cancellations due to weather) makes up about 15% relative to the number of service visits realised. [8].

6.5.4 Access for maintenance

Gaining access to an OWECS for routine servicing and emergency maintenance is difficult or impossible in harsh weather conditions due to wave heights, wind speeds and poor visibility. The traditional and obvious method for transporting personnel and equipment is by boat, which is limited to relatively benign sea states. Wave heights above one metre present serious concerns for health and safety issues and damage to equipment.

Since the beginning of offshore wind farm development, suggested methods for gaining safe access have included:

- Helicopter
- Underwater tunnels
- Wheeled platforms for turbines in close proximity to the shoreline
- Amphibious vehicles where caterpillar tracks transport a platform over a firm and stable seabed
- Small hovercraft or ice roads for frozen seas.

For the present discussion, only the principle advantages and disadvantages of boat (plus jack-up) or helicopter access will be considered:

Boat Access

Advantages:
- well proven method of inshore transportation
- relatively cheap equipment expenditure

Disadvantages:
- impractical for wave heights greater than 1m (dependent on vessel)
- transfer of personnel and equipment difficult in rough conditions

Jack-up

Advantages:
- vessel can be raised above waves to provide a stable access platform
- heavy equipment can be transferred

Disadvantages:
- requires firm seabed conditions
- existing jack-up vessel designs are too large, hence purpose built designs are necessary
- high capital cost of vessel
- installation sequence must be previously defined (cable installation later on)
- sensitive to wave conditions during deployment and retraction of legs

Helicopter Access

Advantages:
- sea state is not a major issue
- quick transfer of personnel and equipment from land to turbines

Disadvantages:
- cost of equipment and qualified operating staff
- turbine must be shut down and locked prior to boarding, and flying is restricted to good visibility and wind conditions
- not possible to use for certain wind turbine fault conditions (for instance yaw bearing failure)
- expensive and cumbersome (landing platforms needed on each turbine)

Helicopter access is routinely used for oil and gas installations and offshore lighthouses, however it is unlikely that this mode of transportation can be reasonably considered for OWECS.

From recent reported experience, it has not been possible to access Vindeby turbines in heights of more than 1 metre using an 8 metre launch, but nevertheless turbines reportedly had an accessibility of 83% for the time during the first 12 months of operation in 1992. However, during the worst month accessibility fell to 45%. It was found that the conical foundation amplified the waves, making boat landing more difficult especially in winds from the north or north-west. Access was limited to wind speeds of less than 7-8 m/s from the north or north-west and 12 m/s from other directions. Solid ice around the foundations and blocking the boat's nearby home harbour also prevented access for several weeks, although this amount of ice was unusual. The travelling time of approximately 30 minutes in each direction also affected availability and maintenance. [9].

At Tuno Knob a 32 foot fibreglass boat (forward control fishing boat with flat stern) .is used for the service rounds The boat weighs about 11 tonnes and is equipped with a 185 hp diesel engine. [8].

In conclusion, there are a number of current projects addressing the issue of improved access to offshore wind turbine installations. Most focus on maintaining existing boat access methods with emphasis on addressing the issue of motion compensation or complete removal of the vessel from the water at the turbine location. The potential for using small purpose built jack-up vessels with integral craneage is also a possibility assuming a sufficiently large wind farm is to be serviced. However, access using small purpose-built landing craft continues to present the most pragmatic and economic solution.

Improvements made to the base of OWECS to facilitate safe personnel access include:

- Fixed platforms fixed to tower above splash zone with fender posts to absorb vessel impact
- Flexible gangways extended from the vessel and held in the lee of the OWECS base.
- Installation of friction posts against which the vessel maintains a forward thrust during transfer
- Facility for winching the vessel out of the water during harsh sea conditions
- Winch / netting for personnel and equipment

As mentioned above, there are significant advantages in eliminating the need for specialist lifting vessels currently necessary during overhaul or major component replacement. For a number of current offshore wind turbines, craneage facilities (either permanent or temporary) within the nacelle are capable of lifting some of the heaviest components. At Tuno Knob, special electrical cranes were installed in each Vestas V39 turbine to allow replacement of major components, such as rotor blades or generators, without using a large and expensive floating crane. However, all other currently available turbine models require external cranes for the more demanding lifts, although Vestas claim to be able to change rotor blades with on-board cranes on their V80 2 MW machine.

6.6 Designs for Reduced Maintenance

The issue of accessibility can also be addressed by improvements in offshore wind turbine reliability. Both planned and, more importantly, unplanned maintenance levels can be reduced by increasing the reliability and hence availability of the turbine. Particular emphasis is being placed on reliability issues from component level through to overall design improvements such as corrosion protection and component siting.

NEG Micon's new 2 MW turbine has a fibreglass cabin within the nacelle which encloses the transformer, power and control cabinets within a controlled nacelle environment.

6.6.1 Component reliability

Rotor blades

Current OWECS utilise a three bladed configuration, and it appears that this will continue to be the popular choice of turbine manufacturers. However, two bladed configurations incorporating alternative hub structures may see a rise in popularity given the opportunity to operate turbines at higher rotor speed and without visual constraints. The main advantages from a reliability perspective are the reduction in the number of components, reduced complexity of the hub and easier rotor lifting. The track record of teetering mechanisms is not favourable, and for this reason these may be avoided for offshore use.

Gearboxes

Onshore turbine manufacturers, notably Enercon and Lagerwey, specialise in direct drive generators therefore eliminating the need for a gearbox. Current offshore turbines manufactured by leading manufacturers favour geared drive transmissions. Being the widely recognised as the number one item for mechanical failure and servicing supervision, it would appear a progressive step to move to direct drive systems.

Aerodyn who are currently designing the 5MW Multibrid Technology favour a drive-train consisting of single stage planetary gears, combined with a slow rotating generator, therefore eliminating fast-running components which are prone to wear. [10]

Generators

In general, induction generators require less maintenance than synchronous generators. They do not require a DC source and being inherently more simple and robust are the most common generators in onshore wind turbines.

To protect standard induction generators from marine environments, the generators is totally enclosed with integral insulation to protect the internals from salt and high levels of moisture.

Onshore generators rely on air cooling, which is not recommended for offshore applications. Closed system water cooling or air-to-air heat exchange prevent the risk of corrosion from maritime cooling air.

Direct Drive Systems

Ring type direct drive systems have been developed for onshore wind turbines, primarily by Enercon and Lagerwey. Direct drive systems dispense with the historically problematic gearbox, where the drive train, generator and rotor rotate at the same speed of around 20 rpm for a 2 MW OWECS.

The advantages of direct drive generators are obvious; no gearbox with associated high speed rotating parts, no gearbox oil contamination and leakage, and less routine servicing, to name a few. However, the direct drive generator for megawatt turbines is extremely heavy, bulky and the large diameter required changes the visual appearance of the nacelle. The added tower top mass coupled with increased wind loading increases tower stresses and hence tower dimensions.

The ring generators developed by Enercon are multipole synchronous machines with the copper windings impregnated with resin for environmental protection. Heat is dissipated by conduction via the high surface area steel structure.

ABB’s Windformer is a large diameter gearless generator using permanent magnets rather than coils or electromagnets. No transformer is required as the power is produced at 25 kV DC, compared with AC at less than 1 kV for most turbines. Halved lifetime maintenance costs as well as arguable benefits of up to 20% higher power conversion efficiencies have been claimed [11].

Electrical & Electronic Components

Electrical and control system failures account for the highest percentage of failures. For the year 2000, failures of electrical and controls systems accounted for exactly 50% of the need for wind turbine repairs [12]. Typically, failures of this nature occur due to the number of components, poor electrical connections, corrosion, lightning strikes, etc.

Potting of electronic printed circuit boards and reduction in the number of components are necessary for offshore conditions.

Hydraulic Systems

Elimination of problematic hydraulic systems employed in yaw damping, blade pitching and breaking systems should be realised wherever possible. Electrical actuation is preferable and eliminates the possibility of oil leakage leading to secondary component failure and potential fire risks.

6.6.2 Corrosion protection

The main methods of marine corrosion protection for offshore installations, recently developed within the offshore oil and gas industry, are selection of corrosion resistant materials, two-pack epoxy coatings, cathodic protection, and creation of controlled environments for sensitive equipment.

The potential wind farm sites being considered in the North and Baltic Seas present harsher maritime conditions in terms of severe sea conditions and higher salinity levels.

More work is needed in developing support structures which can withstand stresses caused by wind and wave loading, together with reductions in material fatigue strength caused by corrosion. Cathodic protection technology of subsea structures is integral in the front end engineering design, with due consideration of state-of-the-art paint systems and metal spray coatings particularly for application within the splash zone.

6.6.3 Control and condition monitoring

Surveys of machine outages reveal that around half the unplanned shutdowns on onshore turbines are caused by faults and trips in the electrical and electronic control systems. To reduce the number of unplanned visits to an OWECS, automatic re-set and remote re-set facilities are now becoming common in all new turbines. Increasing numbers of sensors and monitoring equipment are being used, and the signals categorised to register; data, minor faults requiring notification only, or major faults which shut the turbine down automatically.

Using SCADA (System Control And Data Acquisition) systems, monitored signals and alarms are transmitted between the turbine and the onshore control station. Control personnel can interact with the monitoring system to over-ride the turbine controller if necessary.

Internet connections, webcams and sophisticated vibration monitoring for example can now be utilised to detect a limited number of pending failures prior to their occurrence.

6.6.4 Back-up power

Power for the turbine controller, electrical actuators, monitoring and communications systems are drawn from the turbines gross output, or imported from the grid system.

In the event of loss of turbine power generation or lost electrical grid connection, there is no power at the isolated turbine for maintenance work or to keep turbine systems running. At

Horns Rev, it is intended to have a back-up diesel generator sited on the substation platform to provide power should the electrical connection to shore be broken.

6.6.5 Conclusions

An important aspect of future wind turbine development is the requirement to adapt existing onshore designs to cope with harsh maritime environments

As indicated in the previous sections, reductions in the lifetime O&M costs of OWECS will require the following to be addressed:

- Development of appropriate maintenance strategies for scheduled and unscheduled maintenance, reflecting the constraints on OWECS in terms of access.
- Improvement of access methods for unscheduled and scheduled maintenance.
- Development of access methods which are less sensitive to wind/wave conditions.
- Reduce time required for offshore working
- Designs for reduced maintenance by:
    - Reduction in overall number of components and simplicity of design
    - Modular design approach which facilitates the interchange of faulty modules
    - Use of high reliability integrated components
    - Re-siting of electrical units into an environmentally controlled section of the turbine
    - Implementation of offshore corrosion protection technology
    - Development of effective conditioning monitoring and remote control systems

6.7 References

1. G W van Bussel – "Reliability, availability and maintenance aspects of large-scale offshore wind farms, a concepts study", Delft University of Technology, The Netherlands, MAREC 2001 Conference Proceedings, pages 119 – 126.
2. Van Bussel, G.J.W. "The development of an expert system for the determination of availability and O&M costs for offshore wind farms". Proceedings from the European Wind Energy Conference, Nice, March 1999, pages 402 – 405.
3. Hendriks HB (et. al.) "DOWEC concepts study. Evaluation of wind turbine concepts for large scale offshore application. "OWEMES 2000 Proceedings, Sicily, April 2000, pages 211 – 219.
4. TK Petersen – "Offshore wind power – the operational aspects", Vestas Danish Wind Technology A/S, Lem, Denmark.
5. CADDET report "5 MW Offshore Wind Farm", September 1999, http://194.178.172.86/register/datare/ccr01855.htm
6. Opti-OWECS Final Report, Volume 0, para 5 (v) main conclusions.
7. Chr. Schöntag, "Optimisation of Operation and Maintenance of Offshore Wind Farms", Report IW-96-108R, Institute for Wind Energy, TU Delft, The Netherlands, November 1996.
8. Tuno Knob - Garrad Hassan questionnaire response, April 2001.
9. Smith, G.S. – "Design for improving the reliability and accessibility of offshore wind plant", MSc Degree report, Loughborough University, September 2000.
10. Aerodyn Multibrid 5MW machine, *www.multibrid.com*
11. "Competitive wind farms, does ABB have the answer?" SED Aug/Sept 2000, p27
12. WindStats Newsletter – Autumn 2000, Vol. 13 No.4, page 10.

7 ELECTRICAL

The aim of this section is to establish the state of the art, in the wind industry and in research, in offshore wind electrical technology. In particular, it summarises important technology developments that are in place, foreseen, or considered necessary or beneficial. Network connection is excluded from this document, as it is covered in Work Package 2.2. Transmission to shore is included in this document.

7.1 Electrical Systems within the Wind Turbine

7.1.1 Variable or fixed speed

Recent developments in operational strategy, variable or fixed speed, show a tendency towards variable-speed designs as can be seen in [1]. Despite this, some big manufacturers, such as Bonus or NEG Micon, still make use of fixed speed (often two-speed) technology in their large designs (≥2 MW) for future offshore applications.

A list of the operating philosophies is given in [1]. Some principal manufacturers of variable-speed machines and the technology used are outlined below:

Wide range variable speed operation – conventional
Several manufacturers have followed this route. It appears that Vestas are moving to this option in place of Optislip (see below) as converter costs reduce.

Wide range variable speed operation - direct drive
- ENERCON - direct-driven synchronous generator with wound rotor.
- LAGERWEY – direct-driven synchronous generator with wound rotor.
- JEUMONT – direct-driven synchronous generator with a permanent magnet rotor.
- SCANWIND - direct-driven synchronous generator with a permanent magnet rotor and high-voltage winding stator. (see Section 7.1.3)

Limited range variable speed
- NORDEX - ‘doubly-fed’ induction machine.
- ENRON - ‘doubly-fed’ induction machine plus optionally a dynamic VAR control system (DVAR).

Narrow band variable speed operation
- VESTAS – Induction generator with variable slip of as much as 10% by an electronically controlled resistance in series with the rotor resistance (OPTISLIP).

Wide range variable speed has well known benefits [1]. A further advantage offshore is the ability to avoid damaging resonances. This is important for offshore turbine structures, where the resonant frequencies have proved difficult to predict accurately, particularly for monopile structures, and also due to different seabed conditions. As a result such frequencies may change over the lifetime of the structure [4].

However, looking at operating statistics from wind turbines using power electronics according to the German ISET Institute [3], it also seems that availability rates for these machines tend to be somewhat lower than conventional machines, probably due to failures in the power electronics.

Therefore, special attention must be paid to the electronic converter required to interface the synchronous or induction generator to the utility grid. At the moment, wind turbine manufacturers are pushing the wind energy market with larger and larger turbine rotor diameters, which are specially suited for offshore developments. Wind turbines up to 2 MW are currently being sold as commercial products on the market. There is competition between Insulated Gate Bipolar Transistor (IGBT), Gate Turn-Off Thyristor (GTO) and integrated gate-commutated thyristor (IGCT) in the market for powers around 1 MW. However, IGBT may be favoured because of their use in motor drives of this size. For offshore applications, technologies which have demonstrated reliability with many units in industrial locations onshore will be attractive.

All the options used onshore will probably be used offshore, with the possible exception of Optislip. The only important factor in this area that is different offshore than onshore is availability, which would appear to favour fixed-speed machines, and direct-drive (because of the omission of the gearbox). It is not clear whether power electronic converters can be made reliable enough at suitable cost.

Future developments in this area are therefore expected to be:

Reliability
Work on converter design and remote monitoring to reduce downtime.

Benefits of variable speed
Work to establish whether the different conditions offshore (particularly turbulence) affect the pros and cons of variable speed.

Progress with device characteristics
Power electronic devices will get larger, cheaper and more efficient, and these may change the balance in favour of variable-speed.

Voltage and power factor
Research to optimise the converter in terms of control of power factor and voltage is likely to be useful [2].

Housing of equipment onshore
An ideal situation is to employ simple turbines offshore generating unregulated electric power as ‘raw-material’ in terms of voltage, frequency etc. Cables are laid to shore where the electricity is refined prior to grid connection. However, poor 'quality' of the generated electricity, in other words, a wide voltage and frequency range, will add cost to the electrical system within the wind farm and to shore. It is also possible to reduce the equipment required offshore (i.e. offshore transformer station) by accepting increased electrical losses in the connection to shore. However, any decision to locate complex items offshore rather than onshore must be supported by detailed analysis of the failure mechanisms and expected downtime.

There has to be a compromise between the simplicity of the electrical equipment offshore and the cost and efficiency of the transmission system to shore. It is not clear where the best compromise lies. The Scanwind/ABB Windformer concept assumes that for large distances to shore, an offshore converter station may be required to step up the DC voltage to a more economic level.

7.1.2 Direct drive

Direct-drive generators are considered above. There is scope for incremental improvement, particularly to suit the offshore environment. The principal aims are to make direct-drive cheaper, and with smaller diameters. Other types of machines may also be considered, like axial-flux and transverse-flux generators [2].

7.1.3 Scanwind: Windformer concept

The Windformer uses advanced cable technology developed by ABB's Powerformer high-voltage generator. Powerformer is capable of generating electricity at up to 400 kV, allowing it to be connected directly to the transmission system.

This has been achieved by changing the conventional stator windings consisting of mica-epoxy insulated rectangular conductor-bars to windings with circular conductors insulated with conventional solid dielectric high-voltage cable insulation materials. As a result of this, the conventional generator, the generator surge arresters, the medium-voltage generator breaker and busbars, and the step-up transformer are all replaced by one single component, as can be shown in Figure 7.1.3.1. However, this new design will also have the relatively high top mass and large torque levels typically of large direct drive systems, which can be a potential problem for future 4-5 MW concepts.

The Windformer generator operates at voltages ranging from 18 to 25 kV depending on the rotor speed. A directly connected diode rectifier is used to rectify the AC voltage from the generator. This option is taken to maximise the reliability and minimise the losses. The high voltage characteristic of the generator rectifier system facilitates the connection within the cluster of wind turbines with minimum losses. The wind turbines are all connected to a common DC node from which the energy is transmitted to a converter station.

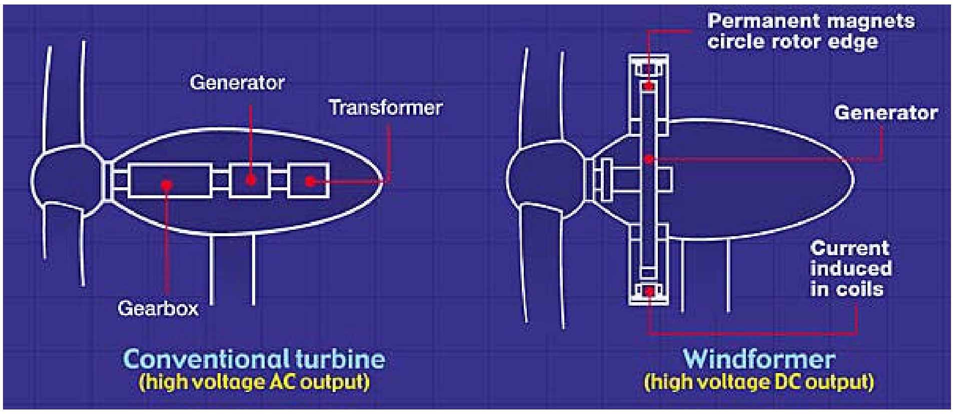

Figure 7.1.3.1 Diagram comparing conventional and Scanwind concepts (Source *http://www.newscientist.com/news/news_224335.html*)

The principal claims for this concept are:

Higher energy production (see below)
Control of reactive power in order to control steady-state voltage and voltage fluctuations (flicker): this is also possible with most variable-speed concepts in principle, and with all turbine concepts if HVDC is used for transmission to shore.

Simple integration with HVDC transmission to shore, saving cost and losses
Low maintenance / high availability, due to the omission of the gearbox and power electronics (except for the diodes, which are very reliable).

High energy production
There are no published figures so this claim cannot be quantified. However, there are some positive factors which are likely to lead to higher energy production:

- Losses in the DC-transmission cable vary with the DC-level, which varies with the rotational speed of the turbine.
- Mechanical losses associated with the gearbox are avoided.
- The generator is likely to have high efficiency due to the permanent magnet rotor and its design.
- Losses related to the step-up transformer are avoided (typically 1% of annual production).
- The diode rectifier has lower losses than the active rectifiers habitually used in variable wind turbines.

GH estimate that the most that can be saved from gearbox, generator and transformer losses is probably about 10%.

7.1.4 Voltage level for output

The Scanwind concept has a benefit in avoiding the turbine transformer. This benefit is available to all design options if the generator is designed for a voltage sufficiently high (probably above 10 kV) to be suitable for interconnection of the turbines within an offshore wind farm. The technology exists to do this, but the effect on generator cost is significant. No commercial turbine manufacturer uses high-voltage generators, onshore or offshore. There would be advantages in studying the technology and the costs of high-voltage generators (up to 35 kV) in volume production.

7.1.5 Control system and SCADA

Turbine control systems are not expected to be different in principle offshore. However there is likely to be considerable effort to improve reliability, as control systems are a significant source of downtime. This effort will cover:

- formal techniques for estimation of reliability;
- redundancy of components (principally sensors) and complete subsystems;
- condition monitoring:
  - remotely via the SCADA system;
  - locally within the turbine controller;
- increased numbers of sensors to allow improved remote diagnosis, either manually or automatically by the SCADA system (perhaps by an expert system).

7.1.6 Robustness

This is a vague term, but it is intended to cover the need offshore for items of equipment to cope with a wider range of conditions. Principally these are environmental conditions, although temperature range is expected to be more benign offshore than onshore. In particular, it is likely that in the life of any offshore wind turbine, there will be periods when, due to cable failures, there is no power on the turbine for heaters and dehumidifiers for periods of several weeks or months. Is it cheaper to accept an extended recommissioning phase after such an event, or to design the turbines to allow generation to recommence after restoration of supplies without maintenance? This question can only be answered by studying the likelihood of cable failures, the restrictions on access to the turbines, and the effect of extended outages on individual components.

Electrical conditions, such as voltage range and voltage steps, could also be allowed to become more extreme if it resulted in an overall system (wind turbine to network connection point) which produces lower cost-of-energy. It is no longer necessary or perhaps even desirable to design turbines as though they will be connected directly to the distribution system.

7.1.7 Earthing and lightning protection

Earthing and lighting protection is an issue that should be addressed as offshore structures may be more exposed to positive polarity lighting strokes. Positive downward lightning is more destructive than the more common negative strikes, due to higher peak currents and charge transfers. This should be further investigated in order to establish and improve protection arrangements for offshore structures. It would be useful to have the same understanding of lightning phenomena offshore as is now available onshore.

7.2 Electrical Systems within the Wind Farm

7.2.1 Voltage level

This issue has been partly addressed above. In the Middelgrunden offshore wind farm, 30 kV XLPE cables dug into the ground are used within the wind farm. The idea of using oil-insulated cables was also carefully considered, but the tenders showed that the XLPE cable solution was by far the cheapest. Eventually authorities decided due to environmental concern not to allow oil-cables anyway. On the other hand, for the Horns Rev offshore wind farm to be built in Denmark [6] with an initial capacity of 150 MW, the cables within the wind farm will be operated at 22 kV nominal voltage and then a transformer station will increase the voltage up to 150 kV for transmission to shore.

A voltage of 36 kV within the wind farm is thought to be the highest which is acceptable, due to the cost of switchgear for higher voltages.

There may be a benefit in development of switchgear at these voltage levels specifically for offshore wind turbines. Such switchgear would ideally be highly reliable, able to withstand humidity and salt, and require no maintenance.

7.2.2 Cable laying techniques

Conventional cable laying vessels are expensive and may have too large a draught to operate in relatively shallow waters. There is a need to develop new techniques for installing the relatively short cables within the wind farm (~ 1000 m lengths). Hauling the cables within the wind farm could be relatively straightforward and could be handled by winches temporarily mounted on the foundations, or on simple barges.

There is also a need to consider new techniques for cable recovery and repair, which can be carried out in most sea states.

7.3 Transmission to Shore

7.3.1 Voltage level

Three possible options could be used for connecting an offshore wind farm:

(a) multiple medium voltage links (up to 35 kV)
(b) single high-voltage link (100 to 200 kV)
(c) HVDC link.

According to [13]:

- the first option appears to be the cheapest for distances offshore of a few kilometres and relatively small wind farm size (say up to 200 MW);
- the second option is appropriate for longer distances offshore and larger wind farms;
- the final option is appropriate for distances to shore above 25 km and for power levels of more than 200 MW.

In the Middelgrunden wind farm, (40 MW and 3 km to shore), the first option has been selected. Each turbine contains a 690 V/30 kV transformer in the bottom of the tower. From the central turbine of the wind farm two 3 kilometres long parallel 30 kV XLPE cables connect the wind farm to the national grid at the nearest point on shore. At this point 500 MW coal-fired power plants are situated, and provide an excellent point of connection for the wind farm. The tenders showed that two parallel cables, equal to the cable used between the turbines, are the cheapest solution.

However, higher installed capacity is expected for future offshore developments. Possible technical solutions will range from 150 kV or 400 kV for multiple wind farms to one 150 kV cable for a wind farm alone. HVDC is discussed below. In the Horns Rev Wind Farm [6], the solution finally chosen is one 150 kV cable for this wind farm alone. Later expansion of the site may result in a ring system. Three single-conductor cables or one three-conductor cable will be used to connect the wind farm to shore. Both types can be made with XLPE insulation and the three-conductor with fluid filled (oil/paper) insulation as well, although as seen before, environmentally-speaking oil insulation presents disadvantages.

7.3.2 Offshore substations

If voltages greater than 33 kV are used for the links to shore, then an offshore substation will be required, containing a step-up transformer. Unfortunately, there is no precedent for a small substation located at sea. It is likely that offshore transformer stations would be a three-legged steel structure with all the equipment necessary and supplied as a “turnkey” solution. Packaged substations are available, but these are usually used as emergency replacements or for quick installation in remote areas. The manufacturers are cautious about offering these for offshore installation. The reticence may disappear if a sizeable market appears.

For any site, there is some optimisation required to decide the number and size of offshore substations. A single large substation is likely to be cheaper due to the structure costs, but a failure results in the loss of the output from the entire wind farm. The same argument applies to the cable link to shore. It is likely that offshore wind farm design will include formal assessment of these risks, in order to select the optimum configuration.

The main item in the offshore substation will be the transformer, but there will also be medium-voltage switchgear and possibly high-voltage switchgear.

An emergency diesel generator may be included in the equipment. Due to the rough weather conditions and difficulties with access, electricity supply cuts for prolonged periods are possible. It may be justified to equip the station with a diesel generator in order to keep all essential equipment, such as climate conditioning, control and safety systems operating during these periods. The diesel generator could also supply the auxiliary loads in the wind turbines.

For large onshore wind farms, it is likely that on-load tap changers on the transformer would be required for voltage control. There is the same need for offshore wind farms, but maintenance requirements would be excessive. Table 7.3.2.1 summarises failures in substation transformers, where it can be seen that mechanical failures, and in particular on-load tap changer failures, are the most common cause of outage [11].

Origin	**Less than 1 day**	**1 to 30 days**	**More than 30 days**	**Total**
Mechanical	24.3	20.5	8.3	53.1
Dielectric	7.1	7.9	15.8	30.8
Thermal	2.3	4.6	2.3	9.2
Chemical	1.1	-	-	1.1
Unknown	5.8	1.4	1.6	2.8
Total	**36.2**	**34.6**	**29.2**	100

Table 7.3.2.1 Substation transformers.
Failures with forced and scheduled outage, as a percentage of total number of failures.

Solid-state load tap changers for medium power transformers (15 kV to 34 kV) with conditioning monitoring are being investigated, and it is claimed that they could reduce maintenance costs by 50-80% while increasing safety, reliability and power quality. This could be a line of research for higher voltage applications in conjunction with capacitor and reactor compensation [7].

The alternatives to on-load tap-changers are:

- specifying the turbines to be able to operate with a wide voltage range, so that voltage control is unnecessary;
- fitting off-load tap-changers, which are cheaper and smaller, and accepting that occasionally it will be necessary to shut down the wind farm for a few minutes in order to adjust the tap position.

The conclusion is that there is a need for detailed consideration of offshore substation design. It is likely that there will be a substantial market for such products, and there is substantial scope for detailed design to produce high availability and low cost.

7.3.3 HVDC

Since the establishment of the HVDC industry over 40 years ago, the technology and its application has undergone dramatic transformation. Nowadays, fast progress in the field of power electronics devices with turn off capabilities such as IGBT and GTO, makes Voltage Source Converters (VSC) more attractive for HVDC applications. To date, there are three manufacturers that have developed the state-of-the-art HVDC technology suitable for offshore wind farms; ABB, Alstom and Siemens.

As an example case, Siemens Power Transmission and Distribution Division has outlined a preliminary version of a possible 675 MW offshore DC/AC-Converter Station as can be seen in Figure 7.3.3.1 [10]. The dimensions of this station would be approximately 50 m in length, 50 m deep and 28 m in height. As shown, it would be designed with a platform for helicopter access for maintenance operations.

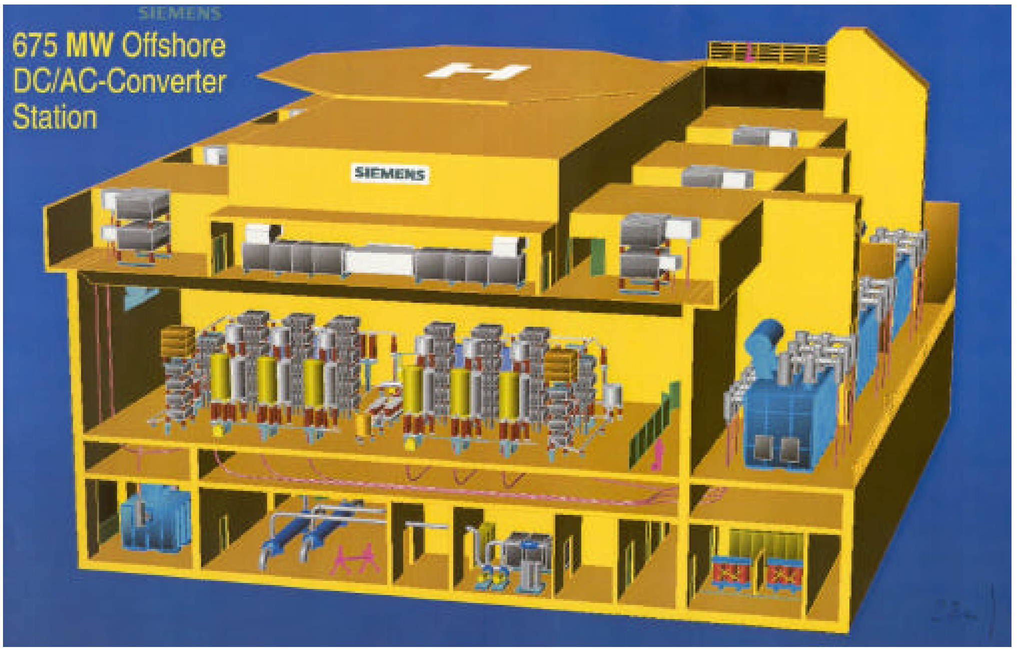

Figure 7.3.3.1 675 MW Siemens Offshore DC/AC-Converter Station

HVDC by ALSTOM [8]

Alstom makes use of conventional technology based on thyristor devices. Thyristor converters in conventional HVDC always require reactive power. Additional power components such as switched capacitor banks or Static Var Compensators (SVC) must be used in order to supply the reactive power demand of the converter station.

HVDC-Light by ABB [9]

The technology uses IGBTs as opposed to the thyristors used in traditional HVDC systems. The IGBTs are characterised by switching very fast between two fixed voltages. PWM and low pass filtering are used to achieve the desired AC waveform. Active and reactive power can be controlled by the PWM switching technique. As less components are required than conventional designs, the area required for a converter station is 20% lower.

HVDC^{PLUS} by SIEMENS [10]

The HVDC^{PLUS} converter is also equipped with IGBTs, and the important characteristics are similar to HVDC-Light. The technology can deal nowadays with up to 200 MW offshore capacity through a single sea cable. Future developments, with Light Triggered Thyristors (LTT), will be able to cope with up to 600 MW capacity. Recently, SIEMENS has been awarded the contract for the HVDC converter stations of a 500 MW submarine cable link between Northern Ireland and Scotland. For the first time in a commercial HVDC system, direct-light-triggered thyristors with integrated overvoltage protection will be used for the AC/DC converter stations.

Published cost information is not available to allow a comparison of the technologies, but it can be concluded that for the distances and power levels being considered for offshore wind farms, HVDC is more expensive than a conventional AC solution. Nevertheless, HVDC may well be used for offshore wind, because:

- Restrictions in building new overhead power lines onshore may require underground cables onshore, which narrows the gap between AC and HVDC.
- HVDC allows the entire offshore wind farm to operate at a variable frequency, which can give some benefit in energy capture.
- HVDC provides independent control of reactive power at the shore converter station, which could be of great benefit to the network operator, and could allow the network connection point to be on a weaker section of network, closer to the landfall.
- HVDC provides almost no contribution to fault currents, which in many areas are a major limitation on the connection of new generation of any type.

7.3.4 Cable installation

Submarine cables are vulnerable to damage by shipping, unless buried or otherwise protected. Burial is often the preferred method, although in some conditions other techniques are appropriate. Available information on actual likelihood of this sort of damage in the likely sites for offshore wind farms is sparse [12].

The major risk of damage is from ships' anchors and trawl equipment. The risk therefore varies greatly with location. It is also affected by seabed conditions. In areas with a hard bottom, anchors and trawl gear will not penetrate: therefore, the cable could be buried to a shallower depth than in areas with soft soils. Consequently, in a softer sea bottom, the cable would need deeper burial to have adequate protection, though the cost of burial would be lower.

To date, there are no developments on minimum standards for cable route surveys. There are several industry standard techniques for subsea cable route surveys:

- Multibeam bathymetry is for developing seafloor topography along a proposed route and enables large swaths to be surveyed with a single pass of the survey vessel. Various systems are available on the market. Basically the higher the system frequency, the greater the resolution and data density, but the shorter the system range.

- Side scan sonar is for seabed imaging. Side scan provides excellent target detection and seabed classification capabilities.

- Sub-bottom profiling is for the collection of data concerning shallow geological and sedimentary conditions. The technique is an essential component in pre-installation surveys for buried marine cables.

There may be scope for development of new techniques and equipment suitable for route selection and installation of cables for offshore wind farms, particularly as the water depths will generally be shallower than for cables for other applications.

7.3.5 Energy storage

The connection to shore forms a greater fraction of the project cost than for the equivalent grid connection for onshore wind farms. This connection to shore will have a capacity factor of 0.3 to 0.4, depending on the site wind conditions. In other words, it is approximately three times larger than it needs to be, in terms of the energy it transmits per year. There is therefore some scope for examining techniques for storage of energy offshore, one benefit of which would be to reduce the size and cost of the connection to shore. Recent developments in fuel cells may possibly lead to energy storage which is cheap, reliable and small enough to be located offshore. This is considered a 'long shot', but worth investigation [14]. There may also be benefits in electricity trading, and in reducing the adverse effects of large wind penetrations on national electricity systems. The planned Laesø offshore wind farm in Denmark will include a small installation onshore, to investigate these latter benefits [15].

7.4 Summary

In conclusion, it can be said that there are many areas where technical developments are expected which will improve the economics and reliability of offshore wind farms. Some of these will arrive because of developments in other industries and in onshore wind, but others are specific to offshore wind and are therefore more risky.

There are also several areas where the risk is too high for commercial wind farm developers or turbine manufacturers, and which are therefore suitable for pre-competitive or collaborative investigation.

7.5 References

[1] Gardner P, *Generators and Drive Trains*, Wind Directions, Jan. 2000

[2] Dubois M, *Review of Electromechanical Conversion in Wind Turbines*, TUDELFT, April 2000.

[3] ISET, http://www.iset.uni-kassel.de/index_eng.html

[4] Smith G, *Design for Improving the Reliability and Accessibility of Offshore Wind Plant*, September 200, MSc project, CREST.

[5] Middelgrunden wind farm, http://www.middelgrunden.dk/summary/40MWoffshore.htm

[6] Christiansen P, Jorgensen K, *Grid Connection and Remote Control for the Horns Rev 150 MW Offshore Wind Farm in Denmark*.

[7] *Substation Operation and Maintenance*, EPRI , http://www.epriweb.com/pf99/trgt054.html

[8] Alstom, http://www.tde.alstom.com/systems/en/pes/products/hvdc.htm

[9] ABB, http://www.abb.com

[10] Siemens, http://ww.ev.siemens.de/en/pages/lighttri.htm

[11] Heathcote M.J., *J & P Transformer Book*, 12th edition, Newnes, 1998. ISBN 07506 1158 8.

[12] Lyall G, *Minimum Standards for Subsea Cable Route Surveys*, UnderWater Magazine, Nov/Dec2000, http://www.diveweb.com/telecom/features/novdec2000.01.htm

[13] Rogers N, Border Wind Ltd, *Offshore Wind Energy*, MSc course, Loughborough University

[14] IIR Conferences, *Commercially Viable Electricity Storage*. Conference, London 30 & 31 January 2001. www.iir-conferences.com

[15] Windpower Monthly News Magazine, September 2000. *British storage for Danish offshore wind.*

[16] Variable Speed Drives
VALLIADIS SA (? ? ? ? ?? ? ? S AE): Manufacturer of electrical generators for wind turbines; Contact: Mr. G. Koulepis; tel: +1-2817217, 2832602; valiadis@hol.gr; www.valiadis.gr; Research conducted at the National Technical University of Athens focuses on permanent magnet generator design, gearless generator design, artificial intelligence techniques, a.o.

[17] Flexible Cables
FULGOR – GREEK ELECTRIC CABLES SA; Production & deployment of submarine power cables; Contact: Mr. N. Boutopoulos; tel: 6852100; nboutopoulos@fulgor.gr; www.fulgor.gr

8 GENERAL REFERENCES

References generally listed in text at the draft except as stated below.

DEWI refer for general information and reference list to:

Söker, H. et al.: North Sea Offshore Wind - A Powerhouse for Europe. Technical Possibilities and Ecological Considerations. A Study for Greenpeace. Hamburg, Germany: Greenpeace, 2000. (Section 3). Can be downloaded from:
www.greenpeace.de->Themen&Kampagnen->Energie&Solar->Wind
(http://www.greenpeace.de/GP_DOK_3P/STU_LANG/C04ST05.PDF)