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Offshore Wind Power

Experiences, Potential and Key Issues for Deployment

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1 Introduction

Wind power has been growing at spectacular rates. Today it is the largest non-hydro renewable power technology. Worldwide there is 74 GW of installed capacity which is 1.7% of power generation capacity and in 2006 it accounted for 0.82% of electricity production. Offshore wind still only counts for a very small amount and development has only taken place in North European counties round the North Sea and the Baltic Sea, where around 1 GW has been installed over the last 15 years.

Offshore wind is still some 50% more expensive than onshore wind, but due to expected benefits of more wind and lesser visual impact from larger turbines several countries have very ambitious goals concerning offshore wind. Since the early 1990s, where the first small demonstration offshore installations of less than 5 MW were built in the Danish, Dutch and Swedish waters, offshore wind farms with a capacities of over 100 MW have been erected in both Denmark, the Netherlands, Sweden and in UK. Prospects are that the better wind resources offshore at the longer term will be able to compensate for the higher installations cost.

2 Overview of Status and Prospects

2.1 Deployment

Wind turbines are not only installed on land. By the close of 2006, more than 900 MW of capacity was located offshore in 4 countries: Denmark, Ireland, Netherlands, Sweden, and the United Kingdom (Table 2.1 and Table 2.2), and in 2007 110 MW at Lillgrunden Sweden has been installed. Most of the capacity has been installed on relatively low water dept and close to the coast to keep the extra cost to foundations and sea cable as low as possible. As can be seen from Table 2.2 sea dept is < 20 meter and within a distance to the coast of 20 km

The total capacity is still limited but growth rate has on average been 64% over the last 12 years. Offshore wind farms are installed in large units - often 100-200 MW and only two units installed a year will results in future growth rates between 20-40%. Higher costs and temporally capacity problems in the manufacturing stages and in availability of installation vessels causes some delays at present, but still several projects in both UK, Denmark will be finish with in the next 3 years.

Country	MW Installed in 2005	Accumulated MW end 2005	MW Installed in 2006	Accumulated MW end 2006
Denmark	0	423	0	423
Ireland	0	25	0	25
The Netherlands	0	18.2	108	126.8
Sweden	0	23.3	0	23.3
UK	90	214	90	304
Total in the world	90	703.5	198.0	902.1

Table 2.1: Installed offshore capacity in offshore wind countries. Source BTM Consult and Danish Energy Authority

	Turbines	Sea dept in m.	Distance to coast in km.	MW	Year
Vindeby (DK)	11 x 450 kW, Bonus	2.5-5.1	2.3	4.95	1991
Lely (Ijsselmeer) (NL)	4 x 500 kW, NEG Micon	5-10	<1	2	1994
Tuno Knob (DK)	10 x 500 kW, Vestas	2.5-7.5	5-6	5	1995
Dronton (Ijsselmeer) (NL)	28 x 600 kW, NEG Micon	5	<0.1	16.8	1996
Bockstigen (S)	5 x 550 kW, NEG Micon	6	3	2.75	1997
Blyth (UK)	7 x 1.5 MW, GE Wind	6-11	<1	4	2000
Utgrunden (Oland) (S)	2 x 2 MW, Vestas	7-10	8	10.5	2000
Middelgrunden (DK)	20 x 2 MW, Bonus	3-6	1.5-2.5	40	2000
Yttre Stengrund (S)	5 x 2 MW, NEG Micon	6-10	5	10	2001
Horns Rev (DK)	80 x 2 MW, Vestas	6-14	14-20	160	2002
Samsø (DK)	10 x 2.3 MW, Siemens	18-20	3-6	23	2002
Ronland (DK)	Mix of Vestas and Siemens	< 1	<1	17.2	2003
Frederikshavn (DK)	Mix of Vestas and Siemens	1-3	< 1	7.6	2003
North Hoyle (UK)	30 x 2 MW, Vestas	12	6-8	60	2003
Arklow Bank (Irl)	7 x 3.6 MW,GE Wind	2-5	10	25.2	2003
Nysted (DK)	72 x 2.3 MW, Siemens	6-9.5	10	166	2003
Scroby Sands (UK)	30 x 2 MW, Vestas	2-8	3	60	2004
Kentish Flat (UK)	30 x 3 MW, Vestas	5	8.5	90	2005
Barrow (UK)	30 x 3 MW, Vestas	21-23	7.5	90	2006
NSW (NL)	30 x 3 MW Vestas	19-22	10	108	2006
Lillgrunden (S)	48 x 2.3 MW, Siemens	3-6	7-10	110	2007
Burbo Bank (UK)	24 x 3.6 MW, Siemens	2-8	5-7	90	2007

Table 2.2: Installed offshore wind farms in the world (BTM Consult ref.1 and Risø)

2.2 Present cost of offshore wind energy

Most offshore wind farms are installed in British and Danish waters, but recently also Sweden has entered the large scale offshore arena establishing the Lillgrunden wind farm. Table 2.3 gives information on some of the recently established offshore wind farms.

Offshore costs are largely dependent on weather and wave conditions, water depth, and distance to the coast. The most detailed cost information on recent offshore installations comes from the UK where 90 MW was added in 2006. The present-day costs of installing wind energy in the UK are between 585 and 800 £/kW (868 and 1,187 €/kW) onshore, rising to 1,200 to 1,600 £/kW (1,781 to 2,375 €/kW) offshore. The higher capital costs of offshore are due to the larger structures and complex logistics of installing the towers. The costs of offshore foundations, construction, installations, and grid connection are significantly higher than for onshore. For example, typically, offshore turbines are 20% more expensive, and towers and foundations cost more than 2.5 times the price for a project of similar size onshore.

	In operation	Number of turbines	Turbine size	Capacity MW	Investment cost mill. €	Mio. €/MW
Middelgrunden (DK)	2001	20	2	40	47	1.2
Horns Rev I (DK)	2002	80	2	160	272	1.7
Samsø (DK)	2003	10	2.3	23	30	1.3
North Hoyle (UK)	2003	30	2	60	121	2.0
Nysted (DK)	2004	72	2.3	165	248	1.5
Scroby Sands (UK)	2004	30	2	60	121	2.0
Kentich Flat (UK)	2005	30	3	90	159	1.8
Barrows (UK)	2006	30	3	90	-	-
Burbo Bank (UK)	2007	24	3.6	90	181	2.0
Lillgrunden (S)	2007	48	2.3	110	197	1.8
Robin Rigg* (UK)	2008	60	3	180	492	2.7

Table 2.3: Key information on recent offshore wind farms. (Note that Robin Rigg is planned to be in operation in 2008

As shown in Table 2.3 the chosen turbine size for offshore wind farms ranges from 2 MW to 3.6 MW, the newer wind farms equipped with the larger turbines. Also the turbine farm sizes differ substantially from the fairly small Samsø wind farm of 23 MW to Robin Rigg with a rated capacity of 180 MW, which will be the worlds largest offshore wind farm. Investment costs per MW range from a low of 1.2 mill.€/MW (Middelgrunden) to almost the double of 2.7 mill.€/MW (Robin Rigg) to a certain extent covering differences in water depth and distance to shore (Figure 2.1)

In general the costs of offshore capacity have increased in recent years as seen for on land turbines and these increases are only partly reflected in the costs shown above in Figure 2.1. For that reason average cost of future offshore farms will expectedly be higher. On average investment costs for a new offshore wind farm are expected be in the range of 2.0 to 2.2 mill. €/MW for a near-shore shallow depth facility

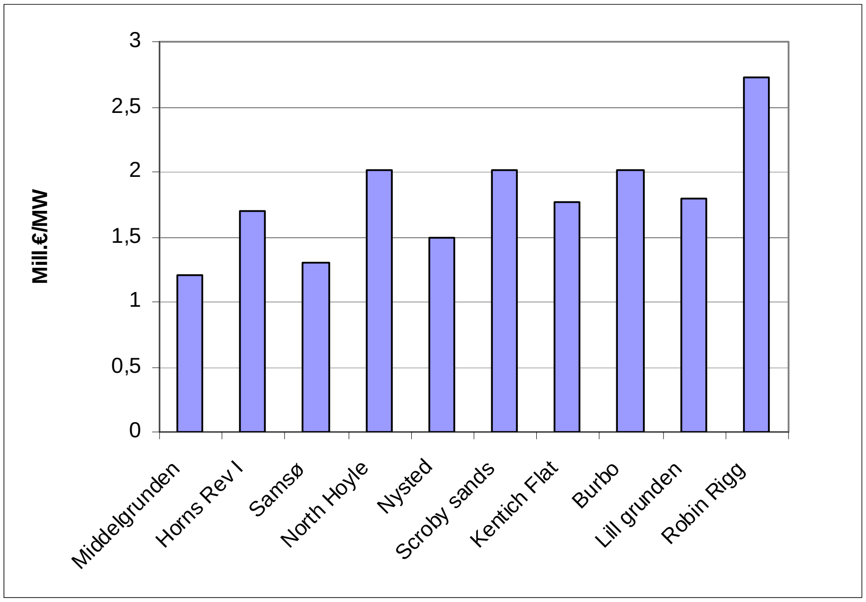


Figure 2.1: Investments in offshore wind farms, mill.€/MW (Current prices)

To illustrate more thoroughly the economics of offshore wind turbines, the two largest Danish offshore wind farms are chosen as examples. The Horns Rev project located approximately 15 km off the west coast of Jutland (west of Esbjerg) was finished in 2002. It is equipped with 80 2 MW machines and thus have a total capacity of 160 MW. The Nysted offshore wind farm is located south of the isle of Lolland. It consists of 72 2.3 MW turbines and have a total capacity of 165 MW. Both wind farms have their own transformer station located at the sites, which through transmission cables are connected to the high voltage grid at the coast. The farms are operated from onshore control stations and no staff is required at the sites. The average investment costs related to these two farms are shown in Table 2.4.

	Investments 1000 €/MW	Share %
Turbines ex work, including transport and erection	815	49
Transformer station and main cable to coast	270	16
Internal grid between turbines	85	5
Foundations	350	21
Design, project management	100	6
Environmental analysis etc.	50	3
Miscellaneous	10	<1
Total	1680	~100

Note: Exchange rate 1 € = 7.45 DKK.

Table 2.4: Average investment costs per MW related to offshore wind farms at Horns Rev and Nysted.

In Denmark all of the above costs components have to be born by the investors except the costs of the transformer station and the main transmission cable to the coast, which is born by the TSO's in the respective areas. The total cost of each of the two offshore farms is close to 260 mill. €.

Compared to land-based turbines the main differences in the cost structure are related to two issues (ref.9):

- Foundations are considerably more costly for offshore turbines. The costs depend on both the sea depth, and the chosen principle of construction[1]. For a conventional turbine sited on land, the share of the total cost for the foundation normally is approx. 4-6%. As an average of the two above mentioned projects this percentage is 21% (cf. Table 2.4), and thus considerably more expensive than for on-land sites. But it should be kept in mind that considerable experiences are gained in establishing these two wind farms and therefore a further optimization of foundation can be expected in future projects.

- Transformer station and sea transmission cables. Connections between the turbines and to the centrally located transformer station and from thereon to the coast generate additional costs compared with on-land sites. For Horns Rev and Nysted wind farms the average cost share for the transformer station and sea transmission cables is 21% (cf. Table 2.4), of this is a minor share of 5% to the internal grid between turbines.

Finally, in relation to the two projects a number of environmental analysis, including an environmental impact investigation and visualizing the wind farms, and also additional research and development were carried out. The average cost share for these analyses for the two wind farms account for approximately 6% of total costs, but part of these costs are related to the pilot character of these projects and is not expected to be repeated next time an offshore wind farm will be established.

Though the costs are considerable higher for offshore wind farms this is to a certain degree moderated by a higher total electricity production from the turbines due to higher offshore wind speeds. For an on-land installation utilization time is normally around 2000-2300 hours per year, while a typical offshore installation has an utilization time of 3000 hours per year or above. The investment and production assumptions used to calculate the costs per kWh are stated in Table 2.5.

	In operation	Capacity MW	Mill.€/MW	Full load hours per year
Middelgrunden	2001	40	1.2	2500
Horns Rev I	2002	160	1.7	4200
Samsø	2003	23	1.3	3100
North Hoyle	2003	60	2.0	3600
Nysted	2004	165	1.5	3700
Scroby sands	2004	60	2.0	3500
Kentich Flat	2005	90	1.8	3100

[1] At Horns Rev monopiles have been used, while the turbines at Nysted are erected on concrete foundations.

Burbo	2007	90	2.0	3550
Lillgrunden	2007	110	1.8	3000
Robin Rigg	2008	180	2.7	3600

Table 2.5: Assumption used for economic calculations. Note that Robin Rigg is expected to be in operation in 2008

In addition the following economic assumptions are used

- Over the lifetime of the wind farm annual operation and maintenance costs are assumed to 16 €/MWh, except for Middelgrunden where O&M costs based on existing accounts are assumed to be 12 €/MWh for the entire lifetime. These assumptions on O&M-costs are subject to high uncertainty.

- The number of full load hours is assumed for a normal wind year, corrected for shadow effects in the farm and for unavailability and losses in transmission to the coast.

- The balancing of the power production from the turbines is normally the responsibility of the farm owners. According to previous Danish experiences balancing requires an equivalent cost of approx. 3 €/MWh. Also balancing costs are subject to high uncertainty and might differ substantially between countries.

- The economic analyses are carried out as simple national economic ones, using a discount rate of 7.5% p.a. over the assumed lifetime of 20 years. No taxes, depreciation, risk premium etc are taken into account.

Figure 2.2 shows the total calculated costs per MWh for the wind farms stated in Table 2.5.

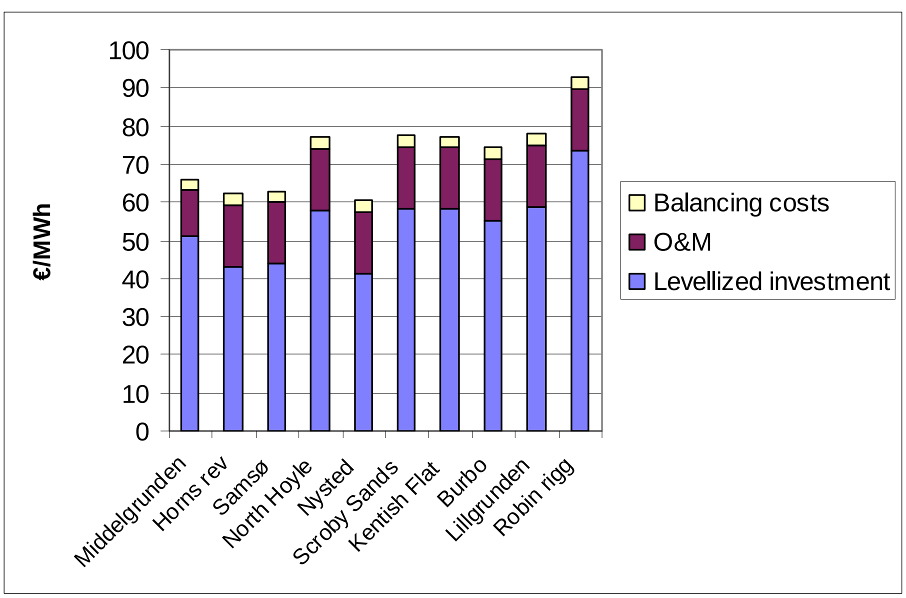


Figure 2.2: Calculated production cost for selected offshore wind farms, including balancing costs (2006-prices).

As shown in Figure 2.2 total production costs differ significantly between the illustrated wind farms, Horns Rev, Samsø and Nysted being among the cheapest, while especially Robin Rigg in UK appears to be expensive. Partly differences can be related to depth of sea and distance to shore, partly to increased investment costs. Observe that O&M-costs are assumed to be at the same level for all wind farms (except Middelgrunden) and are subject to considerable uncertainty.

Costs are calculated as simple national economic ones, thus these costs will not be those of a private investor, which will have higher financial costs, require a risk premium and a profit. How much a private investor will add on top of the simple costs will among other things depend on the perceived technological and political risk of establishing the offshore farm and, on the competition between manufacturers and developers.

3 Environmental factors for offshore projects

The shallow waters around the North European coasts of the North Sea, the Baltic Sea and the English Channel offers good conditions for offshore wind farms. These areas combine shallow water with a good wind resource. At the same time these areas host millions of breeding, migrating and wintering water birds, with large congregations occurring in specific areas. With present plans to develop more large offshore wind farms in especially Denmark, UK, Sweden, Germany and Holland, it is increasingly important to study how this development can be taken forward with minimum impact upon the environment.

3.1 The Danish experience

Like wind farms and other infrastructure projects on land it is obvious that offshore wind farm projects will have an impact on their natural surroundings. However, the Danish experience from the past 16 years shows that offshore wind farms, if placed right, can be engineered and operated without significant damage to the marine environment. Since 1991 a total of 8 offshore or near-shore wind farms have been commissioned with a total installed capacity of 423 MW from 213 wind turbines in the range from 450 kW to 2.3 MW – and one 3 MW.

3.1.1 The Danish Offshore Monitoring Programme 1999-2006

Before, during and after the construction of the two large wind farms Horns rev (160 MW) and Nysted (165 MW) an environmental monitoring programme was launched to investigate and document the impact of these two wind farms. The results were published on 27-28 November 2006 at an international conference in Ellsinore (ref.10).

The studies and analyses have dealt with:

- Benthic fauna and flora, with particular focus on the consequences of the introduction of a hard-bottom habitat, which is the turbine foundation and scour protection, this also included a survey of the in-fauna community in the wind farms.
- The distribution of fish around the wind turbines and the scour protection, and the effect of electromagnetic fields on fish.

- Studies of the numbers and distribution of feeding and resting birds, performed by aerial surveys, and of the food choice of scoters.
- Migrating birds, including study of the risks of collision between birds and wind turbines.
- The behaviour of marine mammals – porpoises and seals – and their reaction to wind farms.
- Sociological and environmental-economic studies.
- Coastal morphology.

Below the findings on benthic communities, fish, marine mammals, birds and people are summarised.

Benthic communities and fish

For both wind farms new artificial habitats developed quickly. At Horns Rev, the new habitats have increased diversity and biomass in the area, whilst in the Nysted offshore wind farm, monocultures of common mussels have developed due to the low salt content in the area and the absence of such predators as starfish. The artificial habitats are expected to have positive effects on fish populations, both with regard to the number of species and the quantity of fish, once the artificial reef is fully developed.

Marine mammals

During construction every effort was made to frighten seals and harbour porpoises away from the area before the extremely noisy work of inserting piles and sheet pile walls began, so as to avoid harm being done to them. After completion the seals have returned to both areas and have generally seemed unaffected by offshore wind farm operations both at sea and on land.

During the construction phase, the number of porpoises at the farms decreased immediately when noisy activities commenced, alleviating fears that marine mammals would remain in the area and so might be hurt by the intense pressure waves generated by pile driving. At Horns Rev the porpoise numbers very quickly returned to "normal" once construction was completed, although data on porpoises at Nysted are different and more difficult to interpret.

Birds

Potential hazards to birds include barriers to movement, habitat loss and collision risks. Radar, infrared video monitoring and visual observations confirmed that most of the more numerous species showed avoidance responses to both wind farms, although responses were highly species specific. Birds tended to avoid the vicinity of the turbines and there was considerable movement along the periphery of both wind farms.

The study confirmed that the sea birds and divers are good at avoiding the offshore wind farms either by flying around them or by flying low between the wind turbines, and therefore the risk of collisions is small. Of a total of 235,000 common eiders passing Nysted each autumn, predicted modelled collision rates were 0.02% (45 birds). The low figure was confirmed by the fact that no collisions were observed by infra-red monitoring.

Concerning loss of habitat post-construction studies initially showed almost complete absence of divers and scoters within the Horns Rev wind farm and significant reductions in long-tailed duck densities within the Nysted wind farm. Other species showed no significant change or occurred in too few numbers to permit statistical analysis.

The fact that no common scoters were observed inside the wind farm area lead to the perception that they had been forced out of their previous feeding grounds, even though this had only insignificant effects on the level of population. Then in late 2006 and early 2007 Vattenfall A/S maintenance crews and helicopter pilots reported increasing numbers of common scoters present within the wind farm site. On that background a series of four surveys of water bird distribution in the area was programmed during January to April 2007 (ref.11).

The results from these four aerial surveys carried out in 2007 show that, in contrast to the earlier years post construction, common scoter were present in significant numbers between the turbines at Horns Rev 1. It can therefore be conclude that Common Scoter may indeed occur in high densities between newly constructed wind turbines at sea, but this may only occur a number of years after initial construction.

Public acceptance

Public attitudes to offshore wind farms have also been examined. This part of the study consisted of a sociological survey with in-depth interviews with local residents both in the Horns Rev and Nysted areas and an environmental economy survey, in which local questionnaire surveys were supplemented by surveys among a national reference group.

The Horns Rev offshore wind farm is located 14 km west of Blåvandshuk in an area dominated by holiday homes with only 3,300 permanent residents. The offshore wind farm is only visible from just a few houses. The Nysted offshore wind farm is located 10 km from the coast and some of the approximate 4,300 permanent residents in the area can see the wind farm from their homes. The wind farm is also visible from Nysted harbour.

The environmental economy survey shows that more than 80% of the respondents are either positively or extremely positively disposed towards offshore wind farms. The greatest support is to be found in the area around Horns Rev, whilst there were most negative reactions in the Nysted area, though opposition here was restricted to a mere 10% of the respondents. The latter may relate to the fact that the township of Nysted is located close to the shore and thereby to a higher degree exposed to aviation warning lights placed on the nacelles of the turbines on the outer edges of the wind farm.

A clear willingness to pay (via electricity bills) to reduce visual impact was found. In the Horns Rev sample, respondents were willing to pay 261 DKK/household/year to have the distance from the shore extended from 8 to 12 km and 643 DKK/household/year to have the distance extended from 12 to 18 km. There was no extra willingness to pay to have wind farms moved from 18 to 50 km from the shore. In the Nysted area, respondents were willing to pay nearly twice as much as in the Horns Rev sample.

Furthermore the sociological survey showed that the original opposition in the Blåvandshuk area has gradually diminished after the Horns Rev offshore wind farm was commissioned, and by 2004 the general attitude was neutral or even slightly positive.

3.1.2 Summary of Danish environmental programme

The comprehensive environmental monitoring programmes of Horns Rev and Nysted wind farms confirm that, under the right conditions, even big wind farms pose low risks to birds, mammals and fish, even though there will be changes in the living conditions of some species by an increase in habitat heterogeneity.

The technological tools developed in the Nysted and Horns Rev studies, especially for the study of behavioral responses of marine mammals and birds, will be very useful for researchers working on new offshore wind farms in other locations. Among others these involve the so-called T-POD system, which measures the supersonic activities of harbour porpoises within the offshore wind farms and in the test areas, and TADS technology, which measures bird collisions. These technologies can readily be transferred to estuarine or open sea sites and applied for study of a wide range of focal species.

The results of the environmental monitoring programme in general show that it is possible to adapt offshore wind farms in a way which is environmentally sustainable and which causes no significant damage to the marine environment. Territorial planning, which identifies the most suitable locations, is crucial in this context. In the light of the programme, offshore wind farms now in many ways stand out as attractive options for the development of sustainable energy, as long as authorities and developers respect the marine environment.

3.2 UK, Sweden and Holland

The Swedish Energy Authority (Energimyndigheten) launched an environmental monitoring program (Vindval) in 2004 with a total budget of 35 mio. SEK. The program includes monitoring of effects on fish, mammals and birds as well as a sociological survey. The program is due at the end of 2007.

For the wind farm Utgrunden and Yttre Stengrund both located in Kalmar sound extensive monitoring of bird migration were carried out in 1999 to 2003. This is a very busy area for migration of sea birds. Each year approximately 1.3 million birds are passing by. A calculation of collision risk based on the observations shows that 1-4 birds in spring and about 10 birds in autumn run the risk of colliding with the existing 12 wind turbines. The waterfowl that make an evasive maneuver due to the wind turbines extend their total migrating distance and time by only 0,2 – 0,5 %.

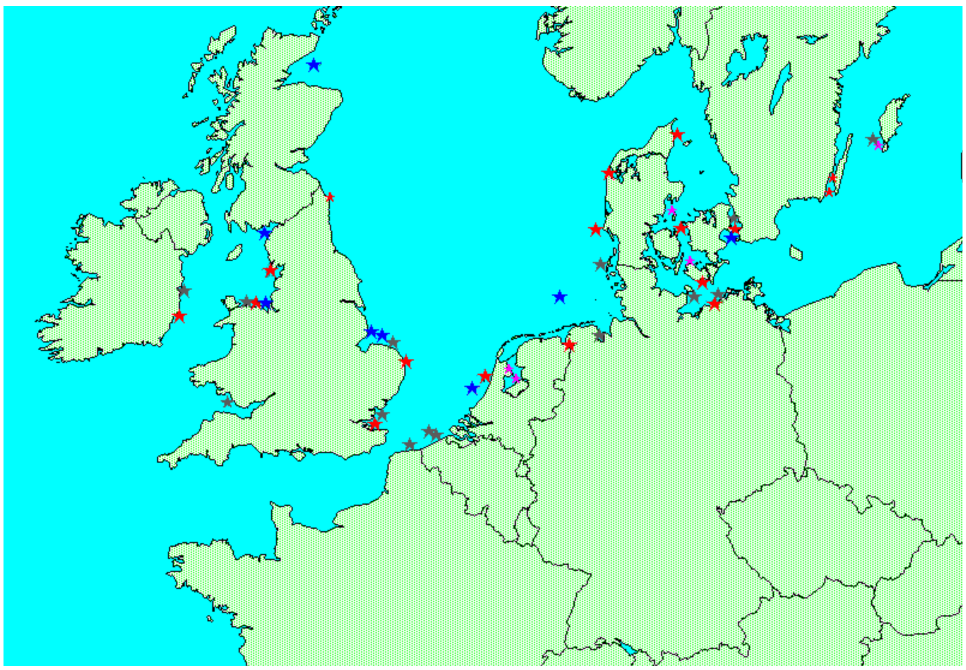
For the wind farm North Hoyle (60 MW) in the UK commissioned in November 2003 Jamie May PMSS Ltd, at the Copenhagen Offshore conference October 2005 ended his presentation on the environmental impact assessment with the conclusion that for a wind farm placed away from sensitive species and habitats basically no negative impact were found.

In the Netherlands a large monitoring program has been launched to monitor effects from the first Dutch offshore wind farm Egmond an Zee (108 MW) completed in April 2007. The first results are due in 2008.

4 Offshore wind power prospects in 2015, 2030 and 2050

4.1 Offshore wind farms under construction and in planning stage

At present several offshore wind farms are under construction in UK waters (Robin Rigg, Rhyl Flats, Inner Dowsing and Lynn) and in Dutch waters the second offshore farm Q7-WP consisting of 60 2 MW turbines will be operational in spring 2008. And much more offshore capacity is in the planning stages. In the United Kingdom, for example, London Array Limited received consent in December 2006 for the world's largest offshore wind farm to be built in the London Array. At 1,000 MW of capacity, it will be capable of powering one-quarter of the homes in London. In Denmark another 2 times 200 MW will be installed in 2009 and 2010.



© 2002 www.offshorewindenergy.org. "Stars": red = (built MW wind turbines), purple = (built small wind turbines), blue = (under construction), grey = (planned)

Figure 4.1. Map of existing and planned offshore wind farms in North-West Europe

4.2 Scenarios for the future development of wind power

In the last two decades wind power has developed rapidly. For 15 years annual growth rates in total accumulated capacity has ranged within 20 to 35%. At present the wind power market is characterized by a strong demand implying supply constraints within the turbine manufacturing industry and no signs indicate that demand will diminish within the coming years (BTM market world market updates ref.1). Turbine manufacturers and sub suppliers are expanding their manufacturing capacity and new companies are entering the arena. In the light of a growing concern for climate change and security of energy supply - increasing prices for fossil fuels, high crude oil prices - expectations are that the wind power industry also in coming years will witness a rapid growth.

Based on existing studies on future wind power development (ref.3 and ref.5) Risø has evaluated future opportunities in wind power and calculated a future scenario for wind power deployment. It should be strictly underlined that results shown in this chapter are subject to large uncertainties.

The following assumptions are used in the Risø wind power scenario:

- The present rapid growth within the overall wind power industry of approx. 25% increase in total accumulated capacity will continue until 2015, including both on- and offshore capacity. Up and downs will exist, but on average the growth rate will be 23% annually. The high demand will be driven by increasing demand for energy in developing regions (as China), increasing environmental concerns and by increasing fossil fuel prices.
- As the wind industry grows more mature capacity growth rates for on- and offshore wind power will decline, to 17% on average in the period 2015-20, to approx. 10% in 2020-30 and, to 2.4% in 2030-50.
- The capacity factor will on average be 25% for on land turbines (2200 full load hours) for the whole period until 2050, covering that new wind turbines will have a higher production being moderated by a lower availability of sites with high wind speeds.[2] Correspondingly, the capacity factor for offshore installations will on average be 37,5% (3300 full load hours) until 2050
- The global expected final electricity consumption will follow existing forecasts (ref.12 and ref.3); that is approx. 2.8% annual growth until 2030, followed by an assumed slower growth of 1.5% p.a. in the period 2030-50.

Based on the above-mentioned assumptions, the future scenario for wind power development is given in Table 4.1.

	Total installed Wind GW	Yearly growth rate of wind %	Production from wind total TWh	Expected electricity consumption TWh	Penetration of wind %
2006	74		163	15500	1.1
2015	486	23	1084	21300	5.1
2020	1066	17	2392	23800	10.1
2030	2633	9.5	6019	29750	20.4
2050	4200	2.4	10100	40100	25.2

Table 4.1: Scenario for global on and offshore wind power development.

As shown in Table 4.1 total wind power production (on land and offshore) is calculated to be 10,100 TWh in 2050, wind power supplying approx. 25% of global final electricity consumption. The assumed growth implies that the accumulated global wind power capacity will double each 3rd year until 2015, each 4th year from 2015-20, and, each 7th year from 2020-30. In the period 2030-50 growth will be much slower.

[2] Assumptions for offshore wind power development are stated below.

To some degree offshore development will follow the picture outline for the total wind power development, but a few exceptions do exist. The following specific assumptions are made for offshore wind power development:

- Mainly based on existing plans offshore wind power development is assumed to grow by approx. 34% p.a. until 2015. Growth rates are expected to fall after 2015 to approx. 27% in the period 2015-20, to 20% in 2020-30 and, to a little more than 5% in 2030-50.
- The capacity factor will on average be 37,5% for offshore turbines (3300 full load hours) for the whole period until 2050, covering that new wind turbines will have a higher production being moderated by a lower availability of sites with high wind speeds.

Based on the assumptions, the future scenario for offshore wind power development is given in Table 4.2.

	Offshore wind GW	Yearly growth offshore wind %	Offshore of total wind power, %	Production from offshore wind, TWh	Expected electricity consumption TWh	Penetration of offshore wind, %
2006	0.9		1.2	3	15500	0.0
2015	12.8	34	2.6	42	21300	0.2
2020	42.4	27	4.0	140	23800	0.6
2030	251.1	19.5	9.5	829	29750	2.8
2050	773.8	5.5	18.4	2559	40100	6.4

Table 4.2: Scenario for global offshore wind power development.

As shown in Table 4.2 total offshore wind power production is calculated to 2,559 TWh in 2050, offshore wind power supplying a little more than 6% of global final electricity consumption and constituting approx. 18.4% of total wind power capacity. The assumed growth implies that the accumulated global offshore wind power capacity will double each 2^{nd} to 3^{rd} year until 2015, each 3^{th} year from 2015-20, and, finally, each 5^{th} year from 2020-30.

4.3 Future technological development

In the long-term perspective the offshore technology development has to be been seen in relation to areas as aerodynamics, structural dynamics, structural design, machine elements, electrical design and grid integration. The development can be structured in:

- Incremental developments
- New main component concepts
- New Wind turbine concepts

Right from the start back in the 1970s the wind turbine industry has been characterized by *incremental development*. In the future this development is especially to be seen in the following areas:

- Development of more efficient methods to determine wind resources

- Development of more efficient methods do determine the external design conditions e.g. normal and extreme wind conditions, wave conditions, ice conditions etc.
- Development of more efficient methods to design and construct the wind turbines blades, transmission and conversion system, load carrying structure, control system and grid interconnection system. Condition monitoring can trough the introduction of new and more advanced sensor systems open up for the development of important improvements of the reliability of offshore wind turbines which can be crucial for the development of more cost efficient and competitive technology
- Innovations with more efficient designs, introduction of new control elements e.g. new sensor systems, more intelligent communication between wind turbines, and introduction of new more advanced materials.
- Innovations in the wind turbine production, transportation and installation methods.

The incremental development of the technology is where the main research and development priority is in the industry and in the research community. The learning (cost reduction) in the industry comes from a combination of incremental development in design and construction of wind turbines and cost reduction due to increased production volume.

Development of *new main components concepts* has also been seen from the mid 1970s and new component concepts competes with existing concepts and thereby is continuously a challenge for the existing main component concepts. The main areas for the competition today are:

- New wind turbine blade concepts with new materials, new structural designs and new aerodynamic features
- New transmission and conversion systems e.g. wind turbines with gearboxes versus wind turbines without gearboxes with multipole generators
- New electrical generator concepts
- New power electronic concepts
- New grid integration concepts
- New foundation concepts e.g. gravitation foundations, monopole foundations, tripod foundations and floating wind turbines

The development of new main component concepts is a very dynamic part of the technology development of the wind energy field and opens often up for new innovative components. This development is extremely dependent of a very reliable verification of the performance of the new component concepts through research and experimental verification.

The competition between *new wind turbine concepts* was intense from the late 1970s to mid 1990s. The most important concepts were:

- 3-bladed upwind wind turbines with a ridged rotor connected to the electrical grid through a gearbox and an induction generator
- 2-bladed downwind wind turbines with at theater rotor connected to the electrical grid through a gearbox and an induction generator

- 2- or 3 bladed Darrieus wind turbine (vertical axis wind turbine) connected to the electrical grid through a gearbox and an induction generator.

Also other concepts were on the market but in the end the 3-bladed upwind wind turbine until now has been the winner in the competition. But in general the technological development combined with a rapid offshore development might open op for new concepts. On the other hand is the experience with existing concepts so valuable that it is a big challenge for new concepts to compete with the existing ones.

In general the future technological development of offshore wind energy is expected to be mainly incremental and more fundamental research is very important to continue the innovation in the industry. In the future development it might prove to be important to distinguish offshore wind turbines from onshore ones. The onshore development is more mature than offshore wind technology and new innovative concepts are more likely for offshore applications.

The development offshore goes from shallow water to very deep water. The development until now is mainly seen in areas with shallow water. Technologies used offshore are expected to differ depending on the water depth and can be divided into:

- Shallow water
- Intermediate depth (50 m > depth > 20 m) bottom mounted
- Floating concepts

It should be mentioned that availability and reliability is crucial for the development of a competitive offshore wind energy technology and will in coming years be the dominating factor for the development.

4.4 Long-term cost perspectives for offshore turbines

Until 2004 the cost of wind turbines in general followed the development of a medium-term cost reduction curve (learning curve) showing a learning rate of approximately 10% that is each time wind power capacity was doubled the cost was reduced by approx. 10% per MW-installed. This decreasing cost-trend was interrupted in 2004-6 where the price of wind power in general increased by approx. 20%, mainly caused by increasing material costs and a strong demand for wind capacity implying scarcity of wind power manufacturing capacity.

A similar increase in price is witnessed for offshore wind power, although a fairly small number of realized projects in combination with a large spread in investment costs make it difficult exactly to identify the price level for offshore turbines. On average expected investment costs for a new offshore wind farm will today be in the range of 1.9 to 2.2 mill.€/MW.

In the following the long term cost development of offshore wind power will be estimated using the learning curve methodology. However, learning curves are not developed to be applied for that long a time period and for this reason the estimated figures are mainly to be seen as the results of a long term scenario development.

The long term cost perspectives for offshore wind power is shown in Table 4.3 given the following conditions:

- The total capacity development of wind power (Section 4.2, Table 4.1) is assumed to be the main driving factor also for the cost development of offshore turbines, because the major part of turbine costs are related to the general wind power industry development. However, a faster development of offshore capacity is expected and also a number of cost issues (foundation, transmission cables etc.) are specific for offshore, which by now are expected to have considerable cost reduction potentials. For that reason the total wind power capacity development is used in combination with higher learning rates for offshore development than seen for onshore.
- The existing manufacturing capacity constraints for the wind turbines will persist until 2010. Although we gradually will see an expanding industrial capacity for wind power, a continued increasing demand will also continue to strain the manufacturing capacity and not before 2011 increasing competition among wind turbine manufacturers and sub suppliers will again imply unit reduction costs in the industry.
- For the period 1985 to 2004 a learning rate of approx. 10% was estimated (ref.6). With the return of competition in the wind industry again in 2011 this learning rate is again expected to be realized by the industry. Because offshore wind power is a relatively young and immature area, this learning rate is assumed to persist until 2030, where after the learning rate is assumed to fall to 5% until 2050.

Given these assumptions minimum, average and maximum cost-scenarios are reported in Table 4.3.

	Investment costs, Mill. €/MW			O&M	Cap. factor
	Min	Average	Max	€/MWh	%
2006	1.8	2.1	2.4	16	37.5
2015	1.55	1.81	2.06	13	37.5
2020	1.37	1.60	1.83	12	37.5
2030	1.20	1.40	1.60	12	37.5
2050	1.16	1.35	1.54	12	37.5

Table 4.3: Scenarios for cost development of offshore wind turbines, constant 2006-€.

As shown in Table 4.3 average cost of offshore wind capacity is calculated to decrease from 2.1 mill.€/MW in 2006 to 1.35 mill€/MW in 2050 or by approx. 35%. A considerable spread of costs will still exist, from 1.16 mill. €/MW to 1.54 mill.€/MW. A capacity factor of constant 37.5% (corresponding to a number of full load hours of approx. 3300) is assumed for the whole period, covering an increasing production from newer and larger turbines moderated by sites with lower wind regimes and increasing distance to shore and thus increasing losses in transmission of power.

A study in UK (ref.2) has estimated the future costs of offshore wind generation and the potential for cost reductions. It identified the cost of raw materials—especially steel, which accounts for about 90% of the turbine and a primary cost driver. The report emphasized that major savings can be realized if turbines are made of lighter, more reliable materials and if major components are developed to be more fatigue resistant. A cost model based on 2006 costs predicted that costs will rise from approximately 1.6 million £/MW to approximately 1.75 million £ (2.37 to 2.6 million €/MW) in 2011 before falling by around 20% of the cost by 2020.

5 New offshore concepts

Although the offshore market is only 1.3% of the world market (installed MW in 2006) many new technology developments are first seen offshore. There are many reasons for this. The development offshore started much later than on-shore development and is not as mature. At the same time off-shore is the most challenging environment for application of wind power with a harsh environment and difficult access, which calls for autonomous designs with very high reliability. Furthermore the relatively high cost for foundations and grid connection drives the size of the wind turbines towards larger units in order to reduce generation costs. In some countries e.g. USA and Norway locations outside the visibility zone are considered in order to eliminate possible conflicts with people living near the coast. The water depth outside the visibility zone (> 25 km) in these waters is significant and leads to new challenges.

As offshore oil and gas runs low the production facilities are likely to be transformed from pure fossil fuel based towards hybrid/renewable energy facilities adding wind, wave and solar devices for generation of electricity and later also fuels for the transport sector. A first sign of this development is seen in the North Sea at the Beatrice oil field off the cost of Scotland. The prototype installation consist of two 5 MW wind turbines at water depths of 42 m and the power from the wind turbines can cover approximately one third of the needs of the nearby oil production platform (Figure 5.1).

Figure 5.1: The Beatrice wind farm consisting of two 5 MW wind turbines *in 42 m deep water. The wind farm is connected to an existing oil production facility. Source www.beatricewind.co.uk*

In the US in 2004, the Offshore Wind Energy Consortium financed by the US Department of Energy, General Electric and the Massachusetts Technology Collaborative announced a project to consider technology for water depths from 50 ft to 100ft (20-35 m). Same year a company called Atlantis Power LLC launched a financing scheme for $2 million for 3 x 2MW wind turbines to be operated in 120 m water depth. In March 2006, GE announced a $27 million partnership with the U.S. Department of Energy to develop 5 to 7 MW turbines by 2009, supplanting the company's current 3.6-megawatt turbines.

Japan has also been investigating offshore wind development (ref. 8). Japan has a national target of 3000 MW by 2010 (current status is 1500 MW total on and offshore) which will be the equivalent of 0.5% of national electricity consumption. There are several areas within wind speeds above 8 or 9 m/s at 60 m height but the contour of 20 m water depth is only about 2 km from the coastline. Ryukyu University has developed the ‘hexa-float’ system made of concrete with 10 m sides and a 10 kW prototype is planned. Also under consideration is a stable floating platform for two turbines in a diamond shape which has been tested in a water tank as has the spar type floating structure.

In Norway two competing projects, Hywind (Norwegian Hydro, Statoil) and Sway (Statoil, Statkraft, Lyse Energi, Shell) both are developing floating offshore wind farm concepts for deep water (200-300m). Both are based on wind turbines rated at 3-5 MW or larger and the sub-sea structure is made of concrete. The main difference between the two concepts is the mooring principle. Recently Hywind has received 59 mill NOK financial support from the Norwegian Government for their prototype off the cost of Norway to be installed in 2009 while the companies behind Sway have managed to raise the necessary funds for the prototype from private investors.

Figure 5.2: The floating wind turbine *concept Hywind. Source: Norwegian Hydro and Solberg production*

5.1 Offshore wind and wave

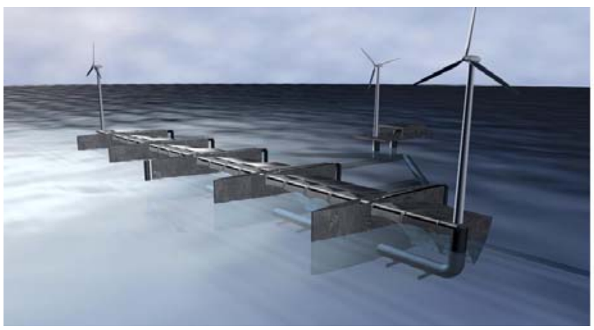
Poseidon's Organ is a hybrid power plant transforming waves and wind into electricity – a floating offshore wave power plant which also serve as foundation for wind turbines. The concept has been tested in wave tanks in scales up to 1:25. Late in 2007 a 1:6 scale model rated at 80 kW wave power and measuring 25 by 37 m will be launched off the coast of Lolland, Denmark in connection with the first offshore wind farm in Denmark at Vindeby. The full size plant (Figure 5.3) is designed to be 230 m by 150 m and is expected to be placed off the cost of Portugal, and will be characterized by:

- 35 percent of the energy in the waves is transformed to electricity

- 30 MW generation capacity including three 2 MW wind turbines

- 28GWh annual generation if located in the Atlantic Ocean off the Portuguese west coast

- 22GWh annual generation from the three wind turbines



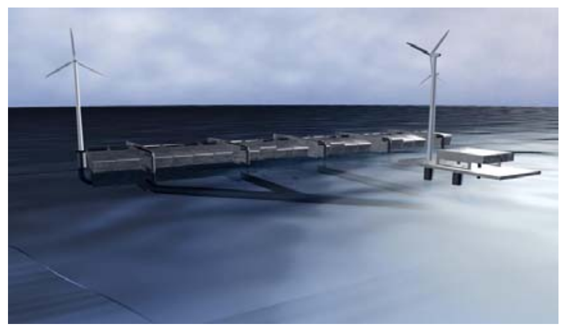


Figure 5.3: Computer image of Poseidon's Organ. The front of the full size wave power plant is 230 metres wide and consists of 10 floats. The floats absorb the energy inherent in the waves. A double functioning pump transforms the wave energy into a water flow driving a turbine producing electricity. Source www.poseidonorgan.com

6 RD&D Offshore wind within IEA

The International Energy Agency (IEA) Wind agreement Task 11 is a vehicle for member countries to exchange information on the planning and execution of national large-scale wind system projects. Common research tasks which are in progress at present under IEA Wind are:

- Base technology information exchange (Task 11)
- Wind Energy in Cold Climates (Task 19)
- Horizontal axis wind turbine aerodynamics (HAWT) and models from wind tunnel measurements (Task 20)
- Dynamic models of wind farms for power system studies (Task 21)
- Offshore Wind Energy Technology Development (Task 23)
- Integration of Wind and Hydropower (Task 24)
- Power System Operation with Large Amounts of Wind Power (Task 25)

Based on an expert meeting on long term research needs arranged in 2001 within Task 11 IEA Wind developed a long term strategy for 2000 to 2020 (ref.4), and it is now due time to arrange a new meeting on the same subject in order to sum up progress and identify future research needs. Future R&D must support incremental improvements in e.g. understanding extreme wind situations, aero-dynamics and electrical machines. But, the challenge is to try to find those evolutionary steps that can be taken to further improve wind turbine technology including offshore technologies, for example in large scale integration incorporating wind forecasting and grid interaction with other energy sources.

As a follow up the Task 11 will arrange a topical expert meeting 6-7 Dec. on long term R,D&D needs in conjunction with the European offshore wind conference & exhibition in Berlin, 4-6 Dec. One of the goals of the meeting will be to gather the existing knowledge on the subject and come up with suggestions / recommendations on how to proceed.

This will result in definition of necessary research activities and "Recommendations" to the IEA Wind Agreement and the governments involved on key wind issues including offshore technologies.

Within the ongoing IEA Wind Implementing Agreement's Task 23 Offshore Wind Technology Developments work is ongoing in 2 Subtasks – one on Experience with critical deployment issues and one on Technical research for deeper water.

Within *Subtask 1* focus is set on 3 issues:

- Ecological Issues and Regulations
- Electric System Integration of Offshore Wind Farms
- External Conditions, Layouts and Design of Offshore Wind Farms.

A number of workshops have been held and based on the conclusions special work will be continued within several areas e.g. grid issues like "Offshore wind meteorology and impact on power fluctuations and wind forecasting", "Technical architecture of offshore grid systems and enabling technologies, and within external conditions "Benchmarking of models for wakes from offshore win farms."

With *Subtask 2* participants have formed a working group named Offshore Code Comparison Collaboration (OC^3) to focus on coupled turbine/substructure dynamic modeling. The OC^3 participants developed dynamics models for an offshore wind turbine with a monopole foundation support structure. They made basic model-to-model comparisons of the wind-inflow, wave kinematics, and wind turbine response. They are currently focusing on comparisons of the monopile geotechnical response and are defining a tripod support structure to be used in the next phase of the project. The code comparison work has established a procedure and database that can be used for future code verification activities and analyst training exercises. In addition, the EU-integrated UpWind research program has adopted the NREL[3] offshore 5-MW baseline wind turbine model, which is used in the OC^3 project as its reference wind turbine. The model will be used as a reference by all UpWind Work Package teams to quantify the benefits of advanced wind energy technology.

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