Middelgrunden 40 MW offshore wind farm near Copenhagen, Denmark, installed year 2000

Per Vølund and Jens Hansen, Department of Wind Energy, SEAS DENMARK.

Abstract
By the end of year 2000 a 40 MW wind farm will be operating three kilometres offshore the Port of Copenhagen. The wind farm will consist of one slightly curved line of 20 turbines with a rotordiameter of 76 m and a generator-size of 2 MW. The offshore wind farm will by then be the largest anywhere in the world.

The background is the two successful small wind farms at Vindeby and Tunø, which initiated a wide examination of the possibilities for offshore wind energy in Denmark. Before this examination had come to an end a group of private individuals had initiated the project at Middelgrunden, which is equally owned by the local utility and a local co-operative of around 10,000 private individuals.

The turbines are of the so-called "Danish Concept" with three blades, upwind rotor, fixed speed and asynchronous generator directly coupled to the grid, but with active stall control. Foundations are of stiff solid concrete plates with central steel cylinders to support the tower. Serious ice loads at the site are overcome by means of an ice-cone mounted at sea level to break approaching ice-flakes. Wave loads are also significant, but were found to have limited correlation with the extreme wind load. Grid connection is on 30 kV level with separate transformerstations in each turbine.

The wind resource is limited, but due to the near-shore siting capital cost is as low as 1.2 million EURO per MW including grid connection. Cost of electricity is 5.3 EURO-cents per kWh including operation and maintenance.

Keywords:
Wind Farm, Offshore, Economics, Implementation, Wind Turbines, Foundation, Grid Connection.

1. History

The Vindeby and Tunø 5 MW offshore projects installed in Denmark in 1991 and 1995 indicated good possibilities of more cost effective wind energy from the vast Danish offshore potential than earlier expected. On this background a wide examination of the possibilities for offshore wind farms in Denmark was carried out in the years 1995-97 and reported in "Action plan for offshore wind farms in Danish Waters", SEAS 1997. The examination finished up concluding that the resources in Denmark potentially can cover at least 50% of the Danish need for electricity at surprisingly low cost compared to earlier forecasts.

A working group of private individuals in Copenhagen picked up the idea at an early stage, and they began in 1996 planning an offshore wind farm at Middelgrunden 3 kilometres outside the Port of Copenhagen. From the very beginning they invited the local utility of Copenhagen to participate. They also started uncovering possible serious problems of the project by means of help from dozens of experts, who unpaid helped to point out problems and good solutions. In 1997 the parliament then dedicated money to support initiation of offshore wind co-operatives, and the working group was granted 0.5 million EURO to document the potential environmental problems of installing a wind farm at Middelgrunden.

The investigation pointed to the "visual impact" as being the environmental problem of most concern as the wind farm is to be looked at every day by hundreds of thousands of people in the centre of Copenhagen. After a first public hearing the project was changed from three lines of turbines to one line, and the change was welcomed as an important visual improvement on the following public hearings. Most people supported the idea and the municipality of Copenhagen decided to co-operate with the working group to carry through the project. After 3 public hearings with few serious comments apart from the visual impact the project was eventually approved on 15 December 1999, and it will be in operation by December 2000.

The Danish model of introducing wind energy through locally based co-operatives and wide public support is successfully clearing the way for offshore development as it has earlier done on-shore.

2. Organization

Half of the turbines will be owned by a private co-operative "Middelgrunden Wind Co-operative", and half will be owned by the local utility "Copenhagen Energy". The non-profit monopoly company "EK Energy" (part of the former "Elkraft") will own the grid connection from the wind farm to the shore.

The co-operative has 10,000 members, who are primarily local citizens, each investing relatively small amounts of money. More than 95% of the members have invested 500-3,000 EURO. Parliament has made this amount a soft threshold for investors by making income from this investment in wind turbine shares tax free, and has in return gained the wide local support, that is an important reason for the success of the project.

The utility is fully owned by the municipality, and the majority of local politicians has from the very beginning supported the involvement of the utility. This support from the top has meant that staff of the utility have received the necessary support to solve many difficult problems in the project. Confidence in the financial and professional capabilities of the utility helped to create acceptance of the project-organisation on the side of public authorities as well as in the public in general.

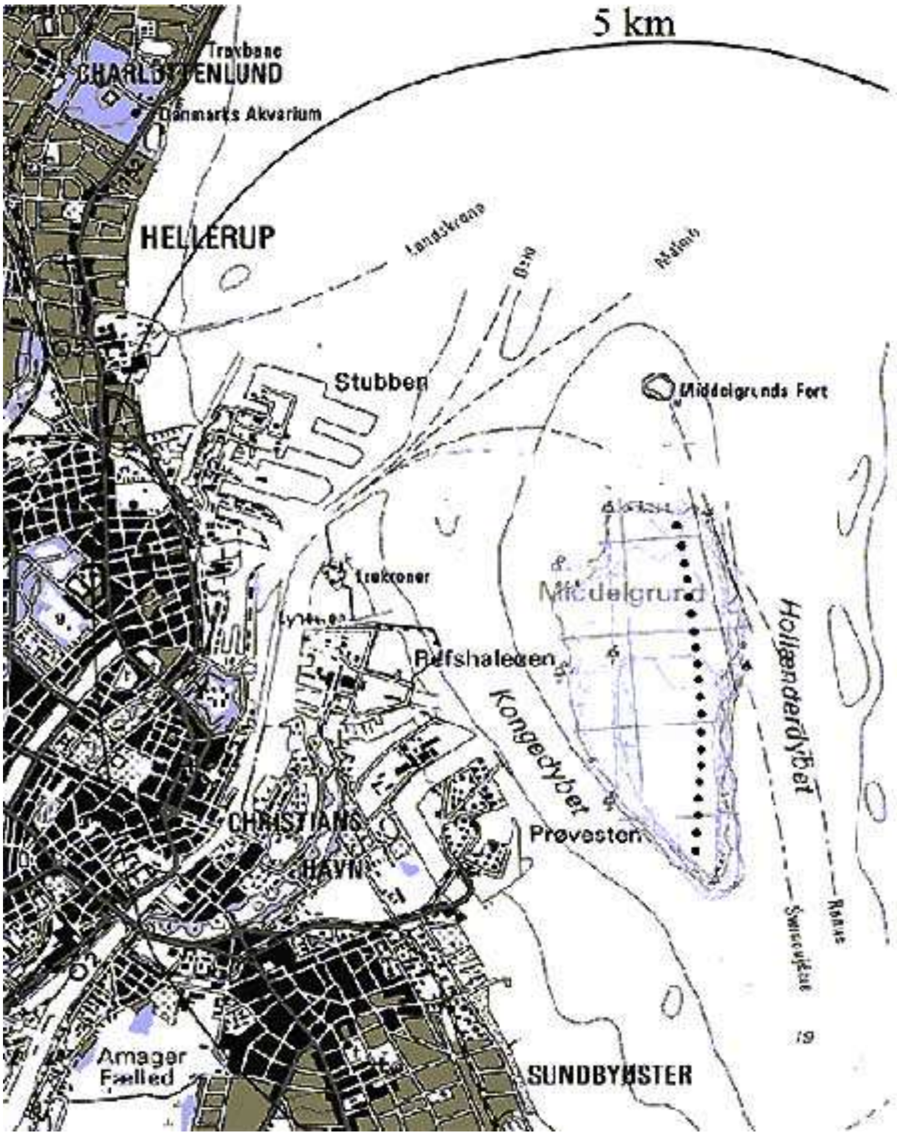
Late in 1999 the Energy Agency decided that the grid connection of the wind farm is to be financed and owned by the responsible of the overall system of the regional grid.

In the project SEAS (on behalf of Elkraft) is working as project manager for all three project owners.

3. Project

The site of installation is found 3 kilometres outside the Port of Copenhagen at a shoal, which was used as a dumpsite until 1980. Pretty few birds and no mammals are found at the site, and only very little fishing takes place. Some pollution - especially heavy metals - from the time when the shoal was used as dumpsite is present in the upper layers of the ground, but apparently the sea has dispersed most of the pollution. Busy traffic is found around the shoal and the potential risk of collision with ships is of some concern, even though fewer ships are expected to run aground when turbines clearly indicate the shoal.

20 turbines each of 2 MW are to be installed in a slightly curved line 182 meters apart. This corresponds to only 2.4 rotordiameters and is much closer than initially planned. In the first public hearing the original proposal of 27 turbines of each 1.5 MW sited in three parallel lines was much criticised for being visually unpleasant. It was proposed to place all turbines in one line, as eventually is to be the case. Space proved to be just as much a problem as we are used to on shore in Denmark. The limited spacing brings unusually large fatigue loads and wake-induced power losses, and has been a design challenge for turbine designers and foundations designers.



Layout of Middelgrunden 40 MW Offshore Wind Farm – 3 kilometres outside Port of Copenhagen.

4. Wind ressouce
A wind measuring mast was installed on the site in the autumn of 1997. Consequently the wind resource is fairly well documented, even though the measuring equipment has been sampling with some disruptions for different reasons. Measurements show poorer wind resource than was predicted with Wasp on the basis of measurements with nearby onshore met-masts and prediction models used on shore.

Annual mean wind speed at hub height of 64 m is 7.1 m/s.

The reason for the poor wind resource is the unfortunate proximity of Copenhagen to the west. For comparison, it can be mentioned that the best on shore sites on the West Coast in the area have a better wind resource than Middelgrunden. And that the next offshore wind farm, Rødsand, which will be installed by SEAS 200 kilometres south of Middelgrunden in 2002, will have a 50% higher production per turbine of the same size. But good onshore sites are scarce, and offshore costs of Middelgrunden are limited compared to projects far offshore.

5. Turbine

The turbine chosen for the project is a Bonus 2 MW with a rotordiameter of 76 m and hub height of 64 m.

The type of the turbine is the so-called "Danish Concept", meaning three bladed stall controlled upwind rotor and asynchronous generator directly coupled to the grid at fixed speed. The machine is equipped with a two-speed generator with nominal output of 400 kW at low wind speed and 2MW at high wind speed. The active stall control is based on three individual blade pitching mechanisms and combines the stall-advantage of fast passive power control with the possibility of precise adjustment of the mean power at high wind speed independent of air density, rain, dirty blade surface etc.

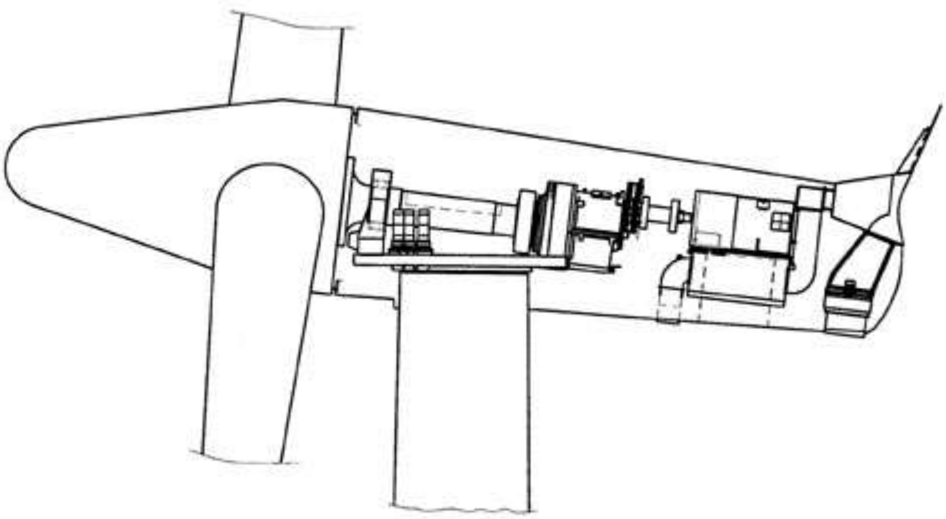
When stopped all blades are pitched 90 degrees, and thus act as aerodynamic brakes over the full blade length. The turbine is also equipped with a mechanical brake at the high speed shaft, which at normal operation is only delivering a limited braking torque leaving most of the braking to the blades. At emergency situations the mechanical brake is able to stop the turbine. Lightening catchers are mounted in the blade tips and on the middle of the blades, which reduces damages in case of direct lightening strokes. Blades are manufactured in fibre glass reinforced polyester by LM Glasfiber and have a length of 37 m.

The three-stage gearbox is equipped with an extended supervision of temperatures of oil-sump and bearings, and the temperatures are kept lower than what is usual for wind turbines. The internal climate of tower and nacelle is to be carefully controlled by heating and dehumidification, and special corrosion-protection and high quality painting are used. Special service cranes, for offshore use, are built in.

64 m of hub height was found to be cost effective compared to 74 m, which was an option in the tender. Extra costs for tower and foundation proved to more than counterweight the extra production available at the higher hub height.

The rotor has a weight of 50 ton, the nacelle weight is 75 ton and the tower weight is 85 ton.

Bonus 2MW prototype Offshore Wind Turbine at test site in Germany (photo by Bonus).



Sketch of the nacelle (by Bonus).

6. Foundations

6.1 Geotechnics

Depth of the sea at Middelgrunden is 3-6 meters. Limestone is found at depths of 2 to 10 meters below seabed. The limestone is covered by till of varying thickness, and at the top of this a layer of polluted material from the time the site was used as dumpsite is found. A layer of 2-5 meter thickness has to be removed to have fair support for gravity foundations.

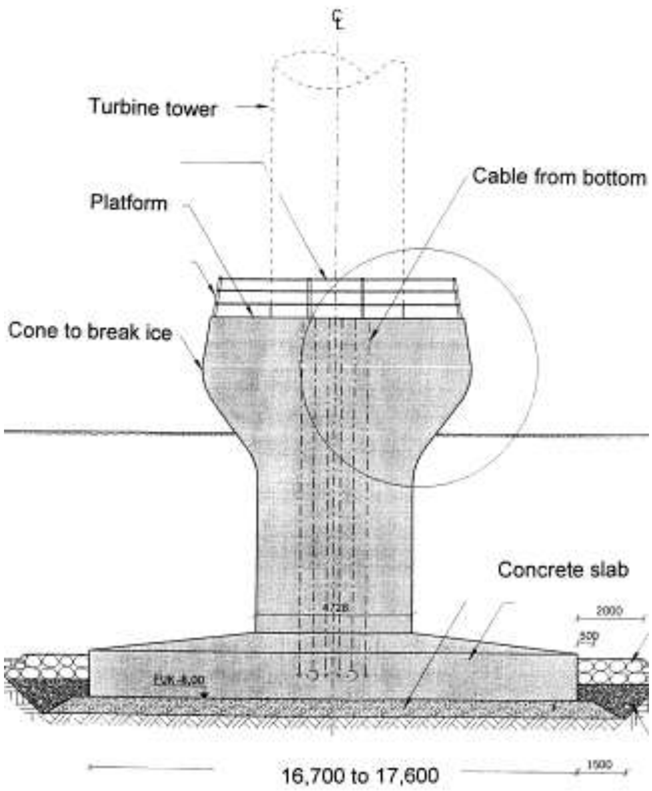
6.2 Ice and Waves

At Middelgrunden ice can be very serious. A working group of experts concluded, that foundations have to be designed for a 60 cm thick drifting ice-flake of 2 by 2 kilometres, which is moving with a speed of 0.65 m/s. The solution chosen to this challenge is an ice-cone mounted at the level of sea surface. The ice-cone will brake an ice-flake pressing against the foundation, and reduce ice-loads by a factor of 5-10, meaning that ice-loads are not a design driver any more.

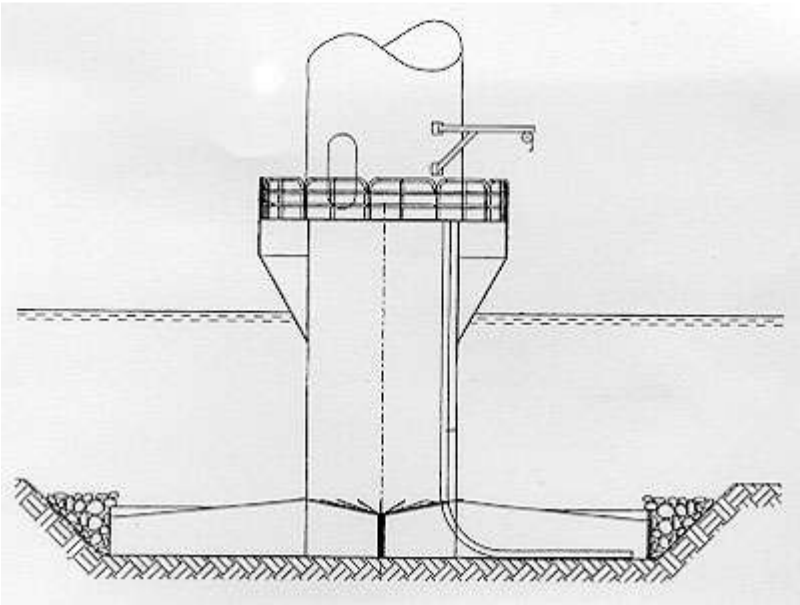
Waves at Middelgrunden may not be very serious in comparison to other offshore sites, but from the north the free build up distance for waves is 40 kilometres and the limiting factor for the height of the breaking waves is the depths. Maximum design wave height is 3.8 m, and wave loads are significant. Correlation between extreme wind load and extreme wave load do exist, but simply adding extreme wind load to extreme wave load would be very conservative, because correlation for the bending moment at sea bed is limited. For this reason combined wave and wind loads were predicted in the time domain in a simple way, but even so this load combination proved to be the design giving extreme load.

6.3 Choice of foundation concept

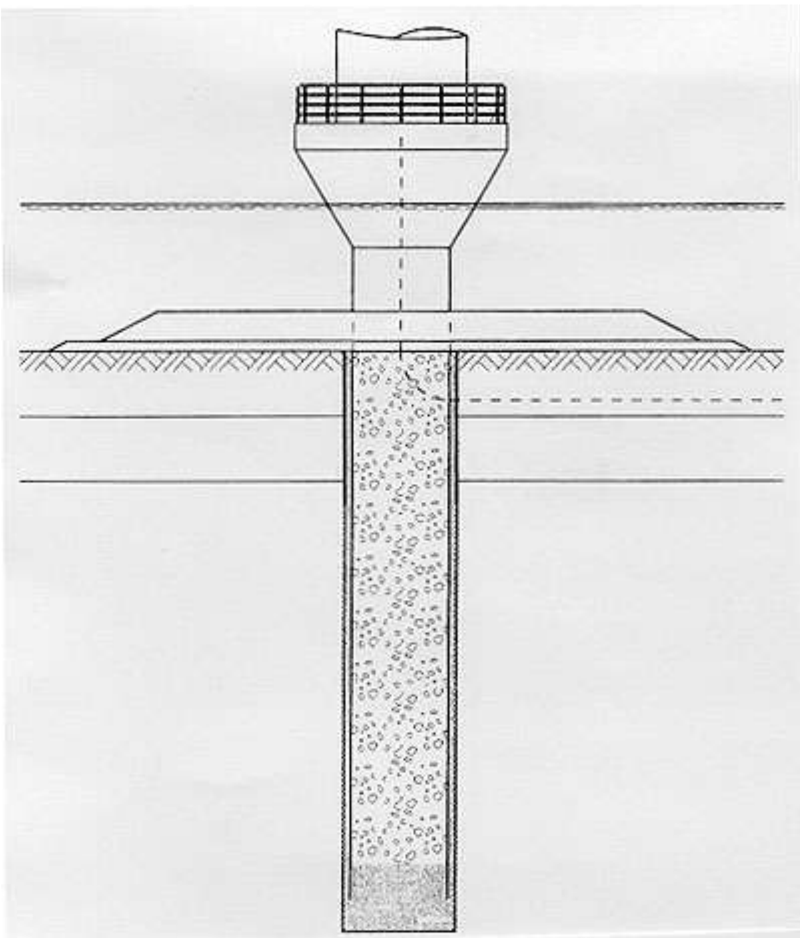
Three foundation concepts were seriously considered: A solid concrete plate, a ballasted steel-caisson and a monopile.



Sketch of Solid Concrete Plate Foundation used at Middelgrunden (designed by Carl Bro as).



Sketch of Ballasted Steel-Caisson Foundation for Middelgrunden (designed by Niras).



Sketch of Monopile Foundation for Middelgrunden (designed by Carl Bro as).

Expected high start-up costs for monopile-foundations and difficult geotechnics made SEAS decide not to aim specifically for the monopile concept. Actually no drilling was carried out in the limestone during the geotechnical investigations, but some tending companies carried out their own drilling in the limestone.

The ballasted steel-caisson has the advantage of a much lighter transport weight than the solid concrete plate. It was hoped that this would result in reduced transport and installation costs, which would make the design the cheapest choice.

Basically the concrete plate is the same as is used for most megawatt turbines onshore in Denmark, even though one important difference is that no ballast on the concrete plate is used for Middelgrunden. Thus it is a relatively well proven cheap choice. But the concept is very heavy, and it was feared that transport and installation might prove to make the concept an expensive choice.

The result of the tendering was clear: The concrete plate was cheapest, the ballasted steel-caisson was around 10-20% more expensive and the monopiles around 20-40% more expensive.

6.4 The Solid Concrete Foundation of Middelgrunden
The chosen concept of foundation is based on a heavy round concrete plate. The plate is solid and wide, and provides a stiff base for the wind turbines. In the centre of the concrete plate a steel cylinder is anchored in the concrete. Basically the steel cylinder works as an extension of the steel tower, and has the same diameter as the base of the tower. For corrosion protection the cylinder is covered with a 35 cm thick layer of concrete, which at sea surface level is widened out to become the ice cone. In addition an offer anode provides passive corrosion protection. On top of the ice cone 2 meters of solid concrete provides weight and acts as working platform below the tower, but above the highest significant level of waves. After installation at the site the centre of the steel-cylinder is filled with around 100 m^3 of sand.

The mass of the un-ballasted foundations is around 1500 tons. The outer diameter of the concrete plate is around 17 m, and the thickness of the plate at the periphery is 1.5 m. Carl Bro as carries out design.

Monberg & Thorsen manufactures the foundations in a dock in the harbour of Copenhagen. All 20 foundations are manufactured at one time. Eventually the dock will be flooded, and a heavy crane will pick up the foundations one by one and transport them directly to the site without reloading on the way.

7. Grid connection
Internal grid in the wind farm consists of 30 kV pex-cables dug into the ground. The idea of using oil-isolated cables was carefully considered, but the tenders showed that the pex-cable solution was by far the cheapest. Eventually authorities decided due to environmental concern not to allow oil-cables anyway.

A central transformer station in the wind farm is not used. Instead each turbine contains a 690V/30 kV transformer in the bottom of the tower.

From the central turbine of the wind farm two 3 kilometre long parallel 30 kV pex-cables connects 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.

NKT Cables delivers the grid connection.

8. ECONOMIC RESULT
Main contracts of turbines, foundations and grid connection were signed in December 99, and the budget is very close to the final result.

Million EURO	
Turbines	27.0

Foundations	9.5
Internal Grid	4.6
External Grid	4.1
Various	4.1
TOTAL	**49.2**

Budget for Middelgrunden 40 MW wind farm, based on signed main contracts.

Bonus guarantees 95% availability and a production of 89 GWh per year.

Based on the guaranteed production capital cost including grid connection is as low as 4.4 EURO-cent per kWh at 5% interest rate over 20 years. O&M costs of 0.9 EURO-cent per kWh are expected. Total cost of electricity is thus as low as 5.3 EURO-cent per kWh.

9. CONCLUSION

The commercial 40 MW offshore wind farm at Middelgrunden will be installed in 2000 using 2 MW turbines.

The Danish model of introducing wind energy through locally based co-operatives and wide public support is with the Middelgrunden project successfully helping to clear the way for offshore development, as it has earlier done on-shore.

Capital cost for the wind farm is 1.2 million EURO per MW - including grid connection.

Annual mean wind speed at hub height of 64 m is as low as 7.1 m/s, but the wind farm will produce electricity at a total cost of 5.3 EURO-cent per kWh including O&M and grid connection.

The tenders pointed to the largest available turbine of 76 m rotordiameter and 2 MW generator as the most cost effective. The tenders also pointed out the concrete foundation known from most recent megawatt turbines onshore as being the most cost effective. Grid connection with 690V/30 kV-transformers in each turbine, 30 kV pex-cables between turbines and to regional grid on shore were chosen - without central transformer in the wind farm.

Middelgrunden will become the largest wind farm in Denmark, and the largest offshore wind