Middelgrunden 40 MW offshore wind farm, a prestudy for the danish offshore 750 mw wind program

International Society of Offshore and Polar Engineers.

ISOPE 2000 Conference Seattle 2000.

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Abstract
The Middelgrunden project is an offshore wind farm with a rated power capacity of 40 MW. The contracts have been signed December 1999, and the park will be operational in the autumn 2000. The project consisting of 20 wind turbines at each 2 MW, will be situated just 2 km outside the Copenhagen harbor on shallow water (3-5 meter depth). The use of the area is restricted due to its former use as a dumpsite for harbor sludge. The wind farm is owned fifty/fifty by a wind energy cooperative and the Copenhagen Utility. This article summarizes the experiences from the planning of the project, and draws the perspectives for the future development of offshore wind power in Europe.

Key words: wind, energy, offshore, foundation, renewable, Danish, cooperation.

Introduction
Today more than 100,000 Danish families are members of wind energy cooperatives and such owners have installed 80% of all Danish wind turbines. Until recently, the cooperatives were a very important and dominant factor in the development of the Danish wind energy sector (see figure 1). Since then, single person ownership has by far superseded the importance of the cooperatives. In the coming years the utilities are expected to play an increasing role in the establishment of large-scale offshore wind farms. The program of the Danish utilities alone has a total power of 750 MW within the next 8 years (The Offshore Wind-farm Working Group, 1997; Svenson et. al., 1999).

The Middelgrunden project has obtained planning permissions in May 1999 and formal political approval from the Danish Energy Agency in December 1999. Contracts with the turbine manufacturer and the foundations and grid contractors have been signed in December 1999.

A long-term contract governing the wholesale price of the energy production of the farm, as well as grid connection costs are currently being negotiated with the Danish Energy Agency. An ongoing restructuring and liberalization of the Danish energy market including new regulation mechanisms for the renewable energy sector have complicated the negotiations.

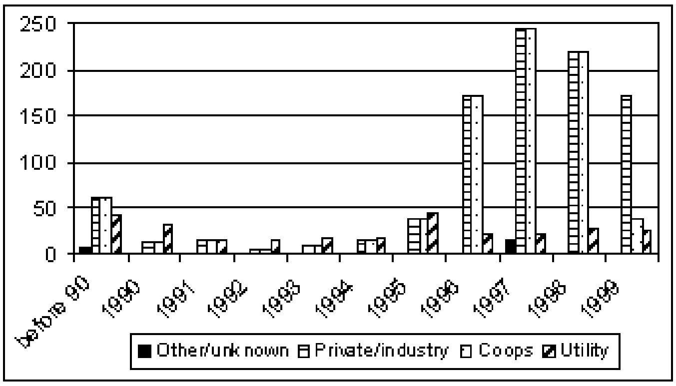

Figure 1. Development in ownership of wind farms in Denmark MW installed power each year. (Nielsen, 1999)

Presentation of the project
The proximity of the site to Copenhagen has right from the beginning of the planning process in 1997 called for investigations concerning the visual and environmental impacts.

In order to initiate such investigations 5.1 million DKK (680,000 EUR) from the Danish Energy Agency was granted. The purpose of the grant was to investigate the technical and environmental aspects of offshore wind power, on the specific site near Copenhagen. Furthermore, the grant covered an analysis of the organizational and economic aspects of the cooperatively owned part of the project, since cooperatives by nature do not posses any financial means at the early planning stages.

The ownership and organisation
In Denmark (particularly in the Copenhagen area) it is necessary to look for alternative sites for wind farms, if the policy goal of concerning future utilization of renewable energy sources in Denmark, is to be fulfilled. The involvement of large-scale cooperatives in this process is essential to legitimate the process and gain public support with a site located this close to a city.

The Cooperative
In 1996, the Copenhagen Environment and Energy Office and the Copenhagen Utility, each with their own background, took the initiative to propose the project. It was agreed that the project was to be owned fifty-fifty by the utility and a cooperative founded for the purpose.

At the Copenhagen Environment and Energy Office, a working group on a grass roots level was formed. It consisted of citizens from the Copenhagen area with all kinds of personal and educational backgrounds, sharing a common interest in wind power.

This grass root initiative resulted in the establishment of the wind energy cooperative Middelgrundens Vindmoellelaug I/S, hosted by the Copenhagen Environment and Energy Office, with the consultant EMU serving as secretary for the cooperative.

The utility

Figure 2. Visualization of the layout of the wind farm east of Copenhagen Harbor (Moeller & Groenborg, 1998)

Also in 1996 the Copenhagen Utility toke the first step to investigate the feasibility of an offshore wind farm at Middelgrunden.

The Municipality of Copenhagen owns[1] the Copenhagen Utility. After 2 years of negotiation and overcoming political differences, a contract between the cooperative and utility was established.

The department of wind power at the utility SEAS, acts as consultant for the Copenhagen Utility, and is heading the project organization for the establishment of the wind farm.

The financing of the cooperative

The cooperative's part will consist of 40,500 shares. One share represents a production of 1,000 kWh/year, and is sold for 4,250 DKK (567 EUR).

All shares have to be paid up front in order to follow the constitution of the cooperative.

By now, more than 8,000 persons, primarily in the local area, have joined the cooperative. The cooperative will be the worlds' largest wind energy cooperative, and the project will be the largest wind farm worldwide based on dual ownership, and the largest offshore wind farm in the world.

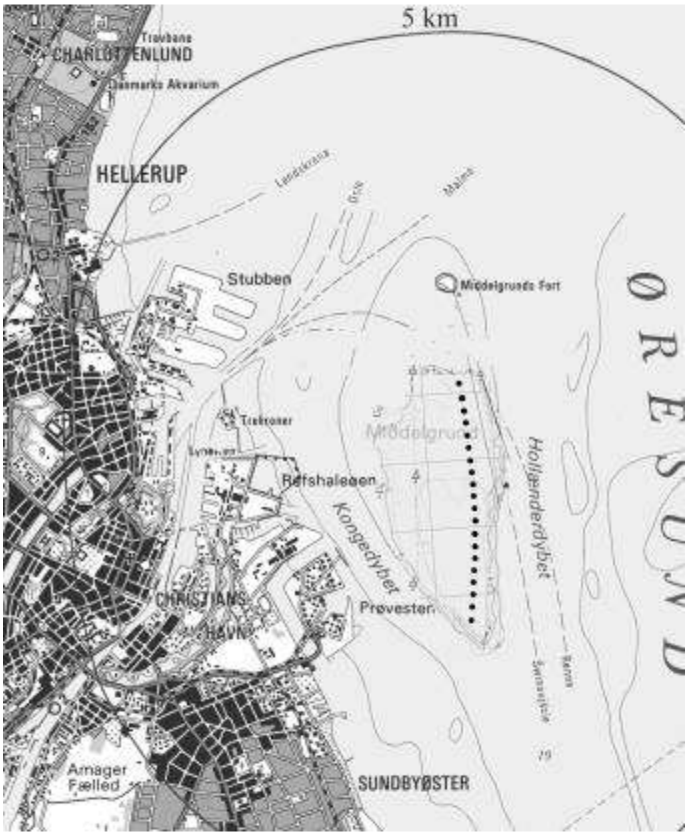

Figure 3. The location of the Middelgrunden wind farm (Soerensen et. al., 1999 p.23)

The time schedule
The restructuring of the electricity sector and the introduction of a new regulation mechanism governing the wholesale price of renewable energy resulted in a very narrow timetable for the decisions connected to the project. The new regulations meant, that the contracts with the turbine manufacturer and the foundations and grid contractors had to be signed before the end of 1999, to allow optimal grants from the Renewable Energy Scheme.

To achieve this was not an easy task, due to the three public hearings the project had to pass, before it could be realized.

First, the project had to pass a public hearing in 1997. Because of general public resistance, especially regarding the visual impression of the project, the size of the farm had to be downgraded from the originally proposed 27 turbines, to 20.

Secondly, this new modified project was exposed to a new mandatory hearing, focusing on the visual impression, which it passed.

Thirdly, the project had to pass a public hearing based on the careful environmental impact analyses carried out during the summer of 1999. In accordance with the ESPOO Convention, hearings were held in Denmark as well as in Sweden.

After this procedure, an official permission could not be expected before the end of November. The limited time from the final decision to the upstart has asked for large flexibility and cooperation from all partners involved in the project.

The contractors could not start working at sea before in April 2000, because of risk of ice on the sea, and the wind turbines have to be put in place before the usual autumn storms are expected in October - November 2000.

First by the end of the project we will know about potential savings which could have been obtained without this strict timetable.

Table 1. Timetable for the establishment of Middelgrunden wind farm

First public hearing (visual impact)	June - September 1997
Second public hearing (visual impact)	June - September 1998
Third public hearing (environment)	July - October 1999
EU pre-qualification	February - August 1999
Public tender turbines, foundations and grid incl. transformer etc.	October 1999
Signing of contract	December 1999
Casting concrete	April - July 2000
Work on seabed	May - June 2000
Placing caissons	August - September 2000
Placing turbines	September - October 2000
Placing grid connection	September - October 2000
Start of production	November 2000

The public awareness
The public attitude towards wind power in Denmark is to some extent self-contradictionary. In general there is a very positive attitude, but there are signs that people are unwilling to accept wind turbines in their own neighborhood. In realizing this project it has therefore been of utmost importance to establish a fruitful dialogue with individuals and NGOs, sharing this attitude. Especially it has been a challenge to convince them that a large-scale exploitation of wind power necessarily implies changes in the landscape.

In depth analyses have been undertaken in order to visualize the impact of 20 turbines (Jessien & Larsen, 1999). This has been important due to the controversial site selected for the project. Furthermore, the visualizations have been widely used as comprehensive illustrations to be used in the public hearings, which have been organized throughout the planning period. Several reports and brochures about the visual impact have been published (Moeller & Groenborg & Ramboell, 1997; Moeller & Groenborg, 1998; Jessien & Larsen, 1999; Soerensen et. al., 1999).

The original project dating back to 1997 consisted of 27 turbines (each 1.5 MW) placed in three rows. After the public hearing in 1997 the layout of the park was changed to a slightly curved line chosen in accordance with the historically development of the Copenhagen defense system around the City. At the same time, the number of turbines had to be decreased to 20. But as the technological development of wind turbines in the mean time had produced new larger turbines, the reduction in the number of turbines could be fully compensated by using larger turbines. The changes could therefore be implemented without decreasing the installed power of the park.

The environmental considerations

With respect to the environmental impact, independent consultants have analyzed the following subjects:

- The risk of leaking debris and heavy metal contamination from the former dumpsite
- Noise propagation
- Influence on the free flow of water in Oeresund
- Risk of collisions with vessels
- Impact on flora and fauna

- Risk of finding shipwrecks and deposits from the Stone Age of archaeological interest

In accordance with the EU directive governing environmental impact assessment (EU, 1997), such investigations have to be completed before a project of this type can be started. The results have been published in several reports, and are summarized in an environmental impact study (Soerensen et. al., 1999).

The conclusion regarding pollution from harbor sludge was, that 3-4 sites was contaminated by heavy metals (mercury and copper) (Soerensen & Naef, 1999; Miljoekontrollen, 1997). The most environmentally friendly method to overcome this problem is to treat the sediment as little as possible during the dredging work. Computer simulations have been carried out in order to optimize the working condition regarding dispersion of sediment to the sea.

The establishment of the wind farm will only reduce the water flow in the belt between Denmark and Sweden with 0.0012% (LIC Engineering, 1999). It has been necessary to investigate this matter, as the change in flow can influence the breeding of codfish in the Baltic Sea. In order to compensate the decrease of water flow in the Belt caused by the foundations it has been discussed to remove some 4,000 m3 of deposits from an optimal place on the ocean floor. The accuracy of the theoretically calculation of a reduction of the water flow does however not justify compensation treatment when talking about this small amount of deposits to be removed.

Noise propagation has been calculated, but it is not supposed to yield any problems, as the distance to populated areas is more than 2 km (Soerensen et. al., 1999).

In order to establish the influence on fauna and flora, video inspection has been performed before the upstart (Hedeselskabet, 2000). Similar inspections will be carried out just after the finalizing of the project and 3 years the establishment of the wind farm.

The wind parameters

Meteorological measurements have been collected on a 45-meter mast at Middelgrunden from October 1997 to the end of 1999. The characteristics of these data, including wind speed profiles, turbulence intensity, directional variability and stability, have been described (Barthelmie, 1999).

The data has been extrapolated to the turbine height of 64 meter, by comparison to wind data obtained at a height of 77 meters from the Risoe mast, using an amended version of the Weibull correction method and correlation/linear regression. WASP has also been employed with standardized wind climatology for Denmark and with the actual measurements at the site.

Using these techniques, 'best' estimates of the average wind parameters at the mast location can be calculated (see table 2).

Table 2. Wind parameters at Middelgrunden

Wind speed at 48-m height	7.2 - 7.4 m/s
Weibull scale parameter at 48-m height	8.2 - 8.3 m/s
Weibull shape parameter at 48-m height	2.2 - 2.5
Energy density at 48-m height	370-420 W/m²
Turbulence intensity at 48-m height	0.10-0.12
Estimated power output (64-m hub-height)	4.1-4.5 GWh/year

(Barthelmie, 1999)

The wind turbines

The turbines installed on Middelgrunden will be the first 2 MW turbines to be demonstrated offshore. The turbines will set new standards in terms of economic performance for wind energy technology. Larger turbines than 2 MW could have been chosen, but a decision, that the turbines had to have at least some months proven track record, limited the maximum size to 2 MW.

The turbine manufacturer chosen after the tender was Bonus Energy. The turbine data is shown in table 3.

To avoid very high maintenance costs, the turbines are constructed in a way that the main components can be changed without using an external crane.

Table 3. Key data for the 2 MW wind turbine from Bonus Energy

Hub height	64 meter
Rotor diameter	76 meter
Total height	102 meter
Estimated power output	88 GWh

The load assumption
Only little experience is available about how to establish the load combination with respect to wind, waves and ice loads.

Parallel to the design of the foundations several working groups have been active in order to establish a future norm for load assumption for offshore wind turbines (Carl Bro et. al., 2000; Thoegersen and Larsen, 1999).

It is evident that the construction of two big bridges in the Danish seas during the lasts 5 years has given a good basis for establishing a discussion about the load conditions. But as the combinations of wind and wave loads to be taken into account are of significantly different importance for bridges and wind turbines, a new set of construction norms has to be developed.

Special considerations have been given to:

- The fatigue strength
- The combination of waves and wind
- The turbulence caused by the relatively short distance (2.5 times the rotor diameter) between the wind turbines
- The ice load combined with the maximum wind load

50 years has been chosen as live length of the construction. Even the life span of the turbines itself usually is assumed to be 20 years.

The extreme wind velocity is assumed to be 55 m/sec and the mean wind velocity under service is 25 m/sec at the hub-height.

The extreme wave parameters are significant wave height 3,8 m, period 6.0 sec, and length 40 m.

The design moment is about 60 MNm from the wind and the 12 MNm from the waves.

The horizontal maximal force from ice is 1.2 MN.

The relatively bad soil on 13 sites causes that the horizontal forces from waves and twisting of the tower at some of the sites have been deciding for the dimension of the concrete slab.

The soil
The seabed is situated between 2.5 and 5 meter under sea level.

The deposit was situated almost randomly on the 3.4-km long line where the turbine will be placed. There was at the sites to the north in general more waste - up to several meters - than to the south.

The original subsurface consists of limestone with large agglomerates of flint stone. The surface is destroyed in the upper surface by the passages of the glaciers 10-15,000 years ago. At some sites the thickness of glacial sand and clay was up to 4 meters. At other places there was only 20 cm of sand.

At 7 sites the foundation could be placed directly on the glacial deposits with shear strength of 300 kPa. At 13 sites the deposits including glacial deposits have to be removed to obtain sufficient shear strength, 150 kPa.

The fundation
One very important technical issue has been to develop the most appropriate foundations. Through optimization it has been possible to gain substantial savings.

From the pre-investigations made by the independent consultant engineers Carl Bro and Niras, two types of foundations were initially analyzed:

A standard gravity caisson foundation used for wind turbines on land based on steel or concrete

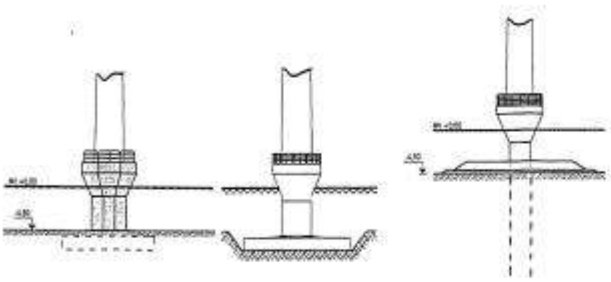

Figure 4. Two types of gravity foundations and a monopile solution were investigated. Ice protection percussion causes the shape of the upper part. (Carl Bro, 1998; Niras, 1998)

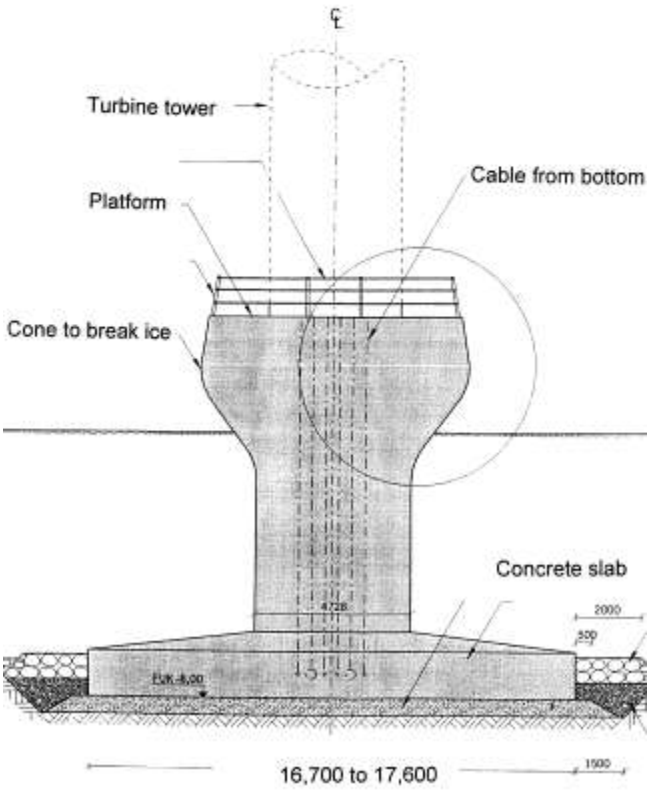

Figure 5. The actual design of the concrete gravity foundation. The height of the total foundation is between 11.3 and 8 m. Measures in mm. (Carl Bro, 1999)

To find the most cost-effective solution the international tender included both concrete and steel design of the gravity foundation. Possibilities were left open to bids based on alternative solutions e.g. a monopile. The results for the different options are shown in table 4.

The tender was won by the internationally well know contractor Monberg & Thorsen.

During the evaluation of the bids for the foundations, it was concluded that:

- The monopile was not feasible for the actual site, due to the presence of a special type of limestone. The shallow water and the relatively protected sea (waves and current) favored a gravity type of foundation
- The steel caisson type can not compete in shallow water with concrete, even with very low prices of steelwork. At a larger water depth (>10 m) other types of steel foundation will be more competitive than the standard gravity solution (Elsamprojekt et. al., 1997; and personal communication with the bidders)
- At larger wind farms (in number of turbines) located in shallow waters (<10 meters depth), rationalization can be expected especially with respect to the placement of the foundation, but concrete is still expected to be the cheapest solution

Table 4. Price comparison for different types of foundations (price a piece)

Concrete	Steel	Monopile
2.35 mill DDK	2.83 mill DDK	3.11 mill DDK
0.315 mill EUR	0.38 mill EUR	0.42 mill EUR

(Based on the tender result)

A foundation hanging between sheet piling has been developed in order to avoid possible difficulties posed by the polluted deposits. In the end the pollution turned out to be less than expected, why the solution will not be actualized.

The grid connection

The wind park is connected from its center to the shore with two 20 MVA cables at a distance of 15 meters. The distance to the 30/132/400 kV transformer at the Copenhagen Utility (Amagervaerket) on shore is 3.5 km. Between the turbines 20MWA cables are used. The transformer on the bottom of the tower at the wind turbine is a 30 kV dry transformer produced by Siemens. NKT Cables won the contract on the grid connection.

The logistic

During the contract negotiation and the following period, considerable efforts have been used to reduce the period of work at the sea. In order to minimize the necessary time at the sea it has been agreed to change the originally foreseen sequence of operations as shown in table 5.

The mentioned sequence of operations demands a larger barge and crane than originally foreseen to enable the transport out of the dry dock. The advantage is that also the transformer and the control equipment can be placed on shore. The total lifting capacity is 1,700 to 1,800 tons dry weight.

Table 5. Sequence of operations at the sea

Placement of gravity foundations including the first 30 m section of the tower	September
Placement of the sea cables between the turbines	End of September
Placement of the upper part of the turbine including rotor	September - October
Filling of the steel shaft in the concrete foundation with up to 300 tons of heavy sand at sea	September
Establishment of the erosion protection	In between

(Based on the discussion after the contracts was signed)

Special precautions have been made in order to allow regulation in the inclination of the combined tower and foundation if it turns out that the maximum tolerances (±½º) not have been met, after placement at the sea bottom. Inspiration of the practical solution (two coned shaped rings) came from Monberg & Thorsen from their work with establishment of light towers.

Combined tender for foundation and turbines
A result of the tender which deserves considerations in future projects is, whether further savings can be obtained by making a combined tender for turbines and foundations.

The actual tender procedure showed that a rationalization in some situations could be expected, especially if common use of crane equipment could be established.

The possibility of using this opportunity is strongly dependent on the access to lifting capacity, and thereby on the way the gravity foundation is produced (lever arm of the crane to move the caissons from a quay), and on the water depth at the site.

The basic crane requirement for the gravity foundation is a lifting capacity of about 1,200-1,500 dry tons. The lift requirement for placing the turbines is only 200 tons.

In the actual project a combined tender was possible, but the cheapest solution was a combination of two separate tenders.

At the coming large wind farms this combined tender solution has to be considered further, especially if the time schedule for the work on sea is of importance.

The economy

The Danish Renewable Energy Scheme yields the following prices for electricity delivered to the grid:

Table 6. Sales price of electricity delivered to the grid from the wind farm

Year	**Fixed**		**Added price for ren. energy**	
	DKK/kWh	EUR/kWh	DKK/kWh	EUR/kWh
0-6	0.33	0.044	0.27	0.036
6-10	0.33	0.044	0.10 to 0.27	0.013 to 0.036
10-25	Market price		Green label certificate to be traded	

(**www.ens.dk**)

The green label certificates have to be sold on the free market, where consumers have to buy a certain (typically 20%) amount of their electricity as green labeled certificate electricity.

The total investment in the project is as shown in table 7 and 8.

Table 7. Key figures after the tender

Production price of electricity	0.34 DKK/kWh	0.045 EUR/kWh
Investment/kW	8.8 DKK/kW	1.18 EUR/kW
Yearly production	88,000,000 kWh (own calculations)	

Table 8. Budget of the wind farm after the tender

The total investment in the project	EUR (mill)	DKK (mill)
Wind turbines	24.13	181
Foundations including changes after the tender to reduce the time on sea	7.87	59
Grid connection, installation	0.27	2
Grid connection, investment	11.20	84
Design	1.07	8
Legal advice	0.27	2
Marketing including cooperative	0.67	5
Other costs	1.20	9
Total	**46.95**	**352**

(Middelgrundens Vindmoellelaug I/S, 1999)

In the original budget, a production price of 0.4 DKK/kWh was anticipated. As it can be seen in table 7, this figure has decreased tremendously, primarily because of the unexpectedly low prices of wind turbines and foundations obtained at the tender.

Perspectives for the danish offshore wind program
Together with Vindeby (established 1991) and Tunoe (established 1995) the Middelgrunden offshore wind farm represents the first step in a planned large-scale extension of the electricity production from offshore wind turbines in Denmark. Within the next 5-8 years, 5 even larger offshore wind farms will be established. The total power of each of these farms will be 150 MW. A smaller offshore wind farm outside the island Samsoe with a power of 22 MW is planed for 2001-2002 (www.samsoe.com).

For this purpose studies on foundations in water depths of up to 10-15 meters have been performed (Elsamprojekt, 1997).

The potential for offshore wind farms in Danish waters have been estimated to 2,250 MW in the period 2000-2015, and additional 1,750 MW for the proceeding 15 years (The Offshore Wind-farm Working Group, 1997). These estimates are based on the wind power technologies, which was known a few years ago.

In 1997 the estimated average production price for electricity (including maintenance costs) was 0.35 DKK/kWh (0.04-0.05 EUR/kWh) (The Offshore Wind-farm Working Group, 1997). But the continuing development of wind turbines, foundation techniques, and transmission techniques, has meant that even lower production prices can be expected, as shown by the Middelgrunden project.

The production of wind energy already exceeds the targets in the present Danish Energy Plan (Danish Ministry of Environment and Energy, 1996). The power to be established offshore during the coming years will result in 50% of the Danish electricity consumption being produced by offshore wind power parks by 2030 (Danish Ministry of Environment and Energy, 1996; The offshore Wind-farm Working Group, 1997).

In this sense the Middelgrunden project has been a pilot project, from which great many experiences can be of considerable value, in the coming large-scale extension of the Danish offshore wind power production.

Other offshore wind programs -Perspectives
Until now offshore wind farms have only been a negligible part of the wind power sector, which can be seen from table 9. But several independent institutions expects that the market for offshore wind power will experience a major growth in the coming years (BTM Consult, 1999a; EU, 1998; Greenpeace International, 1998; Kühn et. al., 1998).

Presently the Danish development plan is by far the most prestigious, but in several other European countries large scale offshore parks are underway.

Difficult planing procedures are limiting the public information on all projects within the EU, but the following plans outside Denmark are known: Sweden 180 MW, Germany 100 MW, The Netherlands 100 MW and UK 150 MW.

In all, the next few years will bring the establishment of new large offshore projects increasing the installed power in Europe with several hundreds of MW. This poses tremendous challenges to consulting engineers, contractors, turbine manufactures, and future owners. To those parties the lessons from the Middelgrunden project, might be valuable.

Table 9. The Global installed offshore capacity by the end of 1998

Location	**Units**	**Size kW**	**MW**	**Year**	**Country**
Nogersund	1	220	0.22	1990	SE
Vindeby	11	450	4.95	1991	DK
Lely	4	40-500	2.0	1994	NL
Tunoe	10	500	5.0	1995	DK
Dronten	19	600	11.4	1996	NL
Bockstigen	5	550	2.75	1997	SE
Total	**50**		**26.3**		

(Svenson et. al., 1999)

Acknowledgment
The extensive pre-study of the Middelgrunden wind farm project has only been possible because of support from the Danish Energy Agency under the special scheme supporting private cooperatives to participate in the development of offshore wind farms.

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Internet addresses:

The cooperative Middelgrunden: **www.middelgrunden.dk**

The Utilities: **www.ke.kk.dk** and **www.seas.dk**

The Danish wind industry: **www.windpower.dk**

The Danish Energy Agency: **www.ens.dk**

The Samsoe offshore wind farm: **www.samsoe.com** or **www.emu-consult.dk/wind**

The turbine manufacturer: **www.bonus.dk**

The foundation contractor: **www.monthor.dk**

The grid connection: contractor. **www.nkt.dk**

[1] Recently the Copenhagen Utility has merged with SK-Energi covering most of the energy production in the eastern part of Denmark.