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THE WORLD'S LARGEST OFF-SHORE WINDFARM, MIDDELGRUNDEN 40 MW

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ABSTRACT

The Middelgrunden project is an offshore wind farm with a rated power capacity of 40 MW. The project consisting of 20 wind turbines at each 2 MW, is situated just 2 km outside the Copenhagen harbor on shallow water (3-5 meters deep). 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: windturbine cooperative, economic, offshore, foundation, environment, public awareness, renewable. The author is one of the promoter of the project and has been responsible for the preinvestigations and is now the projectleader for the windturbine cooperative.

INTRODUCTION

Today more than 100,000 Danish families are members of wind energy cooperatives and such owners have installed 86% 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 Since then, single person ownership has by far superseded the importance of the cooperatives.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). Figure 1 Development in ownership of wind farms in Denmark MW installed power each year. (Nielsen, 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. An ongoing restructuring and liberalization of the Danish energy market including new regulation mechanisms for the renewable energy sector have complicated the realisation of the project.

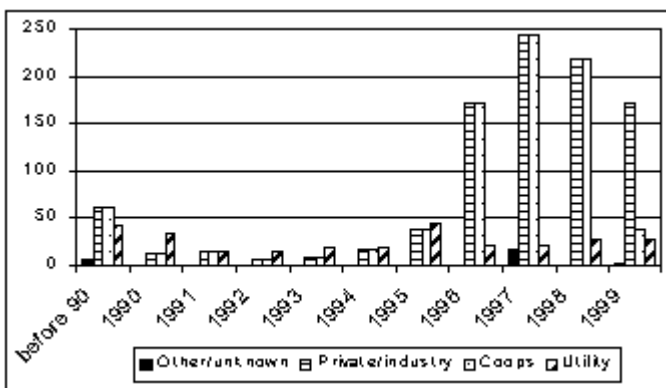


Figure 1. Development in ownership of wind farms in Denmark MW installed power each year. (Nielsen, 1999).

PRESENTATION OF THE PROJECT

The proximity of the site to Copenhagen has called for investigations concerning the visual and environmental impacts right from the beginning of the planning process in 1997. 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 possess any financial means at the early planning stages.



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

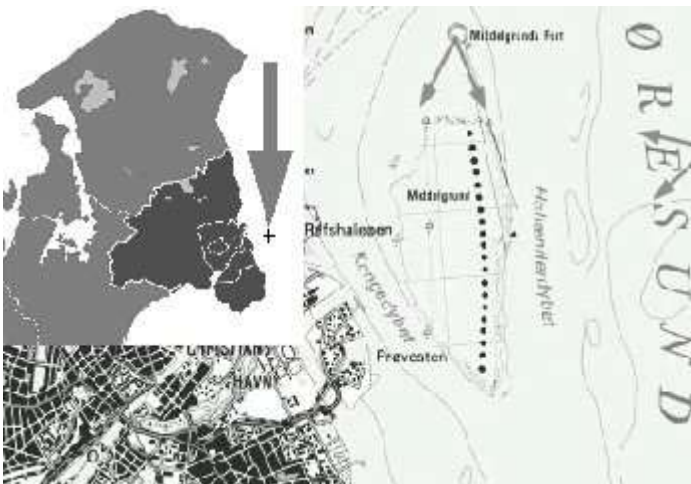


Figure 3. The location of the Middelgrunden wind farm

THE OWNERSHIP AND ORGANIZATION

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 WINDTURBINE COOPERATIVE

In 1996, the Copenhagen Environment and Energy Office (CEEEO) took the initiative to propose and organize the project. After mapping the wind potentials in the area of Copenhagen, the CEEEO organized a working group consisting primarily of citizens from the area who were interested in wind energy. Different personal and educational backgrounds were represented with a common belief that the project was going to be a success. CEEEO was a part of the working group in the beginning and now serves as a consultant for the wind energy co-operative. The wind farm has since been developed and now of the 20 wind turbines, 10 turbines are owned by the Co-operative and 10 turbines is owned by the local utility Copenhagen Energy. The hole project have been developed fifty/fifty by the Co-operative and the Copenhagen Energy. Who Could Buy Shares? In the beginning, only people from the municipal area could buy shares. In 1999, new regulation came into effect and all Danish people could buy shares. The newest development in year 2000 was that all people also outside Denmark could buy it within certain conditions.

THE UTILITY

Also in 1996 the Copenhagen Energy took the first step to investigate the feasibility of an offshore wind farm at Middelgrunden. The Municipality of Copenhagen owns the Copenhagen Energy. After 2 years of negotiations 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. It is my evaluation that both parties (Co-perative and Utility) have gained from the arrangement. CE possesses the big organization for questions about technique, contractor work, etc. The wind co-operative has the knowledge from the private wind sector, with enthusiasm and commitment as well as better contacts with the public and the press. The locally based commitment, along with co-operation between the co-operative, the local utilities, and the municipality of Copenhagen, constituted a significant precondition for the development of the project. This co-operation has provided credibility to the project in relation to politicians and the public.

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 8,500 people, primarily in the local area, have joined the cooperative. By October 2000, 100 % of the private shares were sold. The cooperative will be the world's largest wind turbine cooperative. The project will be the largest wind farm worldwide based on dual ownership and the largest offshore wind farm in the world.

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 resistance from authorities and interestgroups, 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.

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
Starting work on seabed	May - June 2000
Placement of gravity foundations including the first 30 m section of the tower	October-November
Placement of the sea cables between the turbines	November
Placement of the upper part of the turbine including rotor	November - December
Establishment of the erosion protection	January - February 2001

Table 1. Timetable for the establishment of Middelgrunden wind farm

THE PUBLIC AWARENESS

The public attitude towards wind power in Denmark is to some extent self-contradictory. 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 developed 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 the environmental impact study (Soerensen et. al., 1999). The conclusion regarding pollution from harbor sludge was that 3-4 sites were 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 Engineer-ing, 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 theoretical 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 50-m height	7.2 m/s
Weibull scale parameter at 50-m height	t 8.1 m/s
Weibull shape parameter at 50-m height	2.3
Energy density at 50-m height	380 W/m ²
Turbulence intensity at 50-m height	0,12

(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. turbines larger 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	89 GWh
Parkefficiency	93 %

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; Thøgersen and Larsen, 1999). It is evident that the construction of two big bridges in the Danish seas

during the last 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 had to be developed. Special considerations were 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 would be placed. There was up to several meters at the sites to the north in general more waste than to the south. The original subsurface consisted of limestone with large agglomerates of flint stone. The limestone was 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 other sites the deposits including glacial deposits had to be removed to obtain sufficient shear strength, 150 kPa.

THE FOUNDATION

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
- A monopile solution.

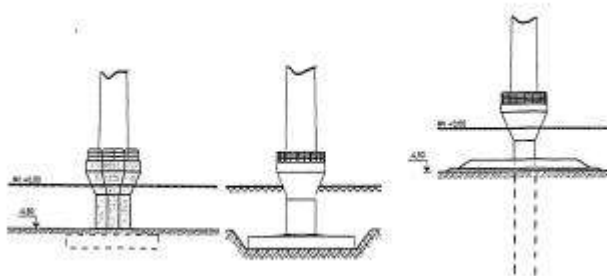


Figure 4. Two types of gravity foundations and a monopile solution were investigated. Ice protection percussion causes the shape of the upper part. (Carl Bro, 1998; Niras, 1998)

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.

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)

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.

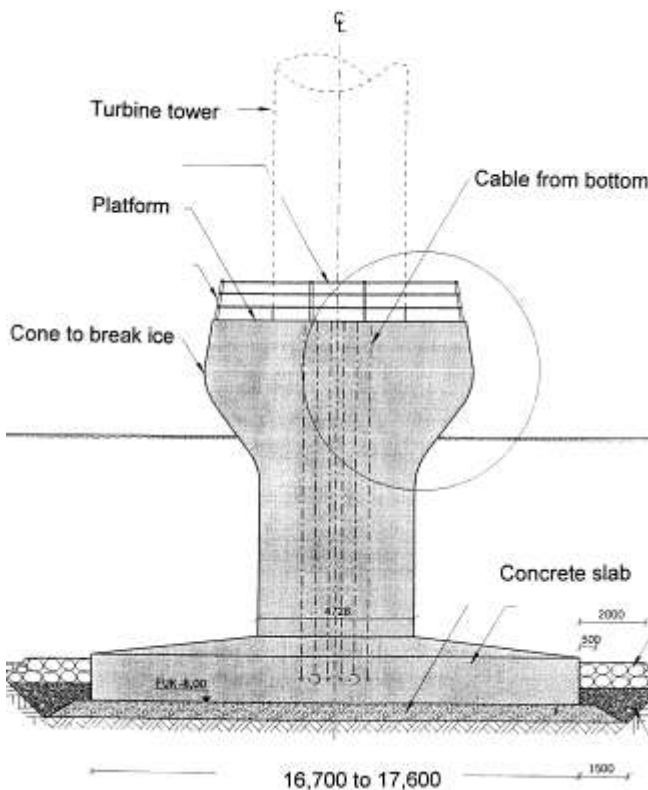


Figure 5. The actual design of the concrete gravity foundation. The height of the total foundation is between 11.3 and 8 m. Measures in mm. (Carl Bro, 1999)

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 20MVA 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 both 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	October-November
Placement of the sea cables between the turbines	November
Placement of the upper part of the turbine including rotor	November - December
Establishment of the erosion protection	January - February

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	

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 budget

Production price of electricity	0.34 DKK/kWh	0.046 EUR/kWh
Investment/kW	8.5 DKK/kW	1.14 EUR/kW
Yearly production	89,000,000 kWh	

(own calculations; Calculationrate = 5%, lifetime = 25 years, Service = 0,07 DKK/kWh, 1. EUR = 7,46 DKK)

Table 8. Budget of the wind farm

The total investment in the project	EUR (mill)	DKK (mill)
Wind turbines	26.11	200
Foundations including changes after the tender to reduce the time on sea	9.92	74
Grid connection, from land to farm	not included	not included
Grid connection, off-shore	4.56	34
Design, advice and planning	2.15	16

Wind turbine cooperative	0.54	4
Other costs	1.61	12
Total	44.89	340

(Middelgrundens Vindmoellelaug I/S, 1999)

ECONOMY FOR SHAREHOLDER

The Co-operative's part consists of 40,500 shares (10 x 2 MW turbines). The budget of the Co-operative is 172 mill. DKK (app. 50% of the budget in tabel 8). One share yields 1,000 kWh/year and is sold for 4250 DKK.

Jacobsen family bought 1 share	
Price of the share is 4250 DKK	
(172 M DKK/40500 shares = 4250 DKK)	
Yearly production is 1000 kWh for 1 share	
Selling price of electricity	330 DKK
RE certificate(*)	270 DKK
Income/year	600 DKK
Maintenance cost	-70 DKK
Net income/year	530 DKK
Rate 530/4250	12,5%
Simple pay back time	8 years
Calculated lifetime	20 years
5% yearly depreciation	212,5 DKK/year
Income after depreciation	317,5 DKK/year
Rate after depreciation 317,5 /4250	7,5%

(*) All Danish electricity consumers are obliged to buy renewable energy (RE) certificates. For this project, the price of the RE certificates is guaranteed for the first 6 years. The income is tax free up to buying 5 shares per person. If one owns more, then 40% of the income is still tax-free. Some Danish banks are offering loan to finance buying shares for those who do not have money right now to invest.

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 of Samsøe with a power of 22 MW is planned for 2001-2002 (www.samsøe.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 were 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 and transmission techniques 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 expect 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.

All in all, the next few years will bring the establishment of new large offshore projects. They will increase 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		

COPENHAGEN ENVIRONMENT AND ENERGY OFFICE (CEEEO)

We are a local association that provides free, impartial information and guidance on energy conservation, as well as on the utilization of renewable energy sources. We have more than 1500 enquiries about these subjects every year. We are a non-governmental member organization and are a part of a network with 22 offices in Denmark We have worked to promote ecologically sustainable development in Denmark for more than 20 years. Since 1987, we have initiated energy and environment activities and urban ecology projects in Greater Copenhagen. We receive financial assistance from the Danish Energy Agency based on the national programs on renewable energy.

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