

COST OPTIMIZING OF LARGE-SCALE OFFSHORE WIND FARMS

**SK Power Company i/s
by ELKRAFT A.m.b.A./SEAS A.m.b.A.**

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Associated partners:

National Wind Power Ltd. United Kingdom
Risø National Laboratory. Denmark
Nellemann, Nielsen & Rauschenberger A/S. Denmark
Stadtwerke Rostock AG. Germany
Universidad Politécnica de Madrid. Spain

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JOULE III

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1. INTRODUCTION

1.1 Background

In the scope of the framework of the Non Nuclear Energy Programme JOULE III the European Commission has in 1996 engaged SK Power Company i/s of Denmark together with 5 European partners and institutes to carry out the project “Cost Optimising of Large-Scale Offshore Wind Farms Project” (JOR3-CT95-0089). The project comprises investigation and development of large offshore wind farms within the European community.

1.2 Development of Offshore Wind Energy

1.2.1 General

In the late 1980s locations for new sites in Europe for construction of wind farms were examined as an alternative to the onshore wind farms. The wind conditions along most of the coast lines of Europe are excellent with large potential use of the wind energy especially in Denmark, United Kingdom and Spain. In these countries the wind flow is reasonable steady for commercial exploitation of the wind energy. Investigations of offshore wind farms were conducted with financial support from EU and the above countries.

1.2.2 Denmark

In the 1990s development of offshore wind farms started. In 1991 the first offshore wind farm was built by ELKRAFT at Vindeby north/west of the island of Lolland. The wind farm comprises 11 wind turbines each of 450 kW. In 1995 a second offshore wind farm was constructed by ELSAM at Tunø Knob located in Århus Bay between the island of Samsø and Jutland. This wind farm is erected on 3-5 m water and consists of 10 wind turbines each of 500 kW.

A comprehensive investigation of possible sites for location of large offshore wind farms has taken place in “The Offshore Committee of the Ministry of the Environment and Energy and the Danish utilities”. The Committee published their report in 1995, identifying 5 possible “positive-areas” for location of offshore wind farms in the Danish waters, where there were no significant conflicts with other interests and the water depths was maximum 10 meters. Three of the five sites are located in the Eastern Danish waters (*Gedser Rev, Omø and Rødsand*) and has formed basis for this study.

In 1996 a Work Group was established to investigate the possibilities for implementation of the Danish Governments goal of installation of a total of 4,000 MW of offshore wind turbines in large-scale projects before year 2030 (*Energy 21*). This offshore capacity would correspond to around 40% of the anticipated total Danish electricity consumption by year 2030 in addition to the 10-15 % from the land based wind turbines. The report from the Work Group support that this goal is technically feasible, however the technical and environmental effects should be investigated further. The report recommends the implementation of a “first-phase” large-scale demonstration project on each of the proposed sites (*Gedser Rev, Omø and Rødsand* in the Eastern waters, and *Horns Rev and Læsø* in the Western waters).

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In February 1998 the Minister of Environment and Energy enforced the power companies in Denmark, in accordance with the recommendation of the “Action Plan” to establish 5 large-scale offshore wind farms of 150 MW each (totally 750 MW) at Rødsand, Gedser Rev and Omø Stålgrunde in the East of Denmark and 2 at Horns Rev (West coast of Jutland and south of the island of Læsø in the Kattegat Sea).

The capacity of the 3 wind farms at Rødsand, Gedser Rev and Omø Stålgrunde is around 450 MW and the investments will be around 5 Billion DKK. The first 2 wind farms (Rødsand 1 and Horns Rev 1) will be producing power from year 2002.

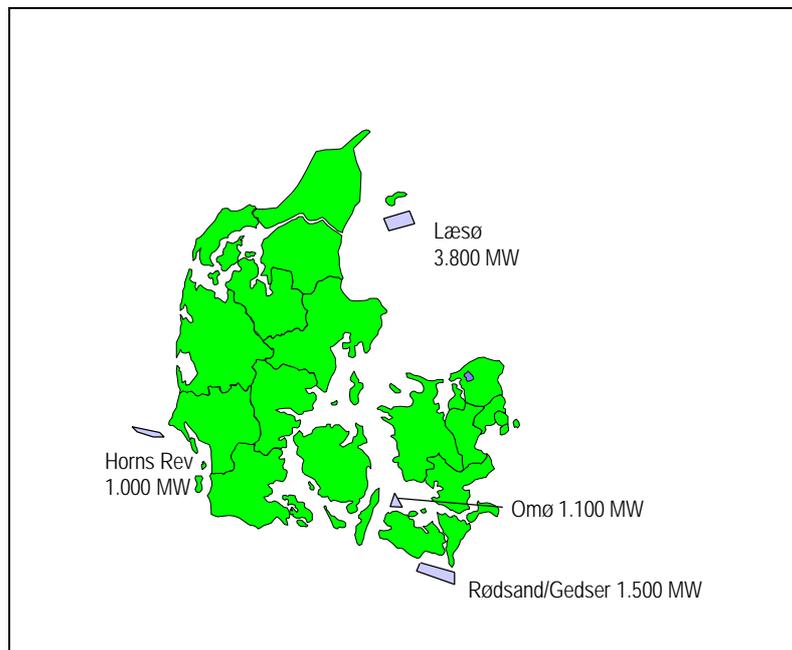


Figure 1.2.2 Possible areas for large-scale offshore wind farms

1.2.3 Europe

A study of the offshore wind power potential in Europe was performed in 1995 under the contract JOUR-0072 (Study of Offshore Wind Energy in the EC).

The offshore wind resource is known to be vast. Production figures of approximately 50% above similar land based projects are possible, however only a few projects have yet been developed.

Location	Units	Made/size	Capacity MW	Year	Country
Nogersund	1	Wind World 220 kW	0.22	1990	Sweden
Vindeby	11	Bonus 450 kW	4.95	1991	Denmark
Lely (Ijsselmeer)	4	Ned Wind 40-500 kW	2.0	1994	Netherlands
Tunø Knob	10	Vestas V39-500 kW	5.0	1995	Denmark
Dronten I (Ijsselmeer)	19	Nordtank 600 kW	11.4	1996	Netherlands
Bockstigen	5	Wind World 550 kW	2.75	1997	Sweden
Total	50		26.3		

Source: BTM Consult Aps 1999

Table 1.2.3 Global installed Offshore Capacity by end of 1998

Several proposed offshore wind farms in the European waters have been announced (off the German Baltic coast, in the UK waters, off the North Sea coast of the Netherlands, off the Southern coast of Sweden). However, uncertainties concerning authority approvals, costs of the implementation of the projects, grid connection and sales price for the electricity has put constraints on the implementation of several projects.

1.3 Scope of the Project

The EU project comprises investigation of the technical and economical possibilities of large-scale offshore wind farms at 3 locations in the eastern Danish waters: Rødsand and Gedser Rev located south of the islands of Falster and Lolland and Omø Stågrunde located south-west of the island of Zealand plus experiences obtained from British and German offshore wind energy projects.

The project has been performed by SK Power Company i/s, represented by SEAS A.m.b.A., Wind Power Department, together with 5 European partners.

The project included wind and wave measurements at the above 3 locations, data collection, data processing, meteorological analysis, modelling of wind turbine structure, studies of grid connection, design and optimisation of foundations plus estimates of investments and operation and maintenance costs.

Prior to the commencement of the project, the investigations, research and related works have been divided between the involved partners, which are all specialised within various technical engineering disciplines such as: Wind energy and measurements, offshore and wind turbine technology, analyse of data, grid connection and geotechnic including design of wind turbines and foundations.

The 6 partners have worked closely together in order to optimise the technical quality of the result of the project, so that the experiences achieved during the last 2-3 years can be used for future offshore projects within the European community.

1.4 Work Programme

1.4.1 Work Content

The work content of the project includes investigations of the technical and economical possibilities of large scale wind farms within the range of 200 to 500 MW in the Baltic Sea and the Langeland Belt. Furthermore, experiences from a British offshore demonstration project and works carried out by Stadtwerke Rostock AG are included in the project together with meteorological measurements performed by Risø, geotechnical investigations and engineering performed by Nellemann, Nielsen & Rauschenberger A/S and finally research performed by Universidad Politécnica de Madrid.

The project has been divided into 2 phases:

- Phase 1 - Initial Activity
- Phase 2 - Field Investigations and Technical/Economical Study

Phase 1 comprises review of potential areas, geotechnical review, grid connection, priority of sites for 100 MW wind farms plus authority approvals and environmental investigations.

Phase 2 comprises investigation areas, production capacity and turbine size, wind and wave measurements, assessment of attainable power production, park lay-out, geotechnical investigations, establishment of design basis (wind, wave and ice loads), conceptual design and optimisation of foundations, functional requirements and optimisation of wind turbines, operation and maintenance systems, grid connection and communication systems, time and activity schedules, possible environmental investigations, estimate of investments and O&M costs, outline description of demonstration projects and preparation of final report.

2. PARTNERSHIP

2.1 Partnership of the Project

The project has been prepared by an international co-operation of leading engineers and researchers within the field of wind energy, offshore technology, wind measurements, wind turbine technology, geotechnic and power management.

The group of participants in the project comprise:

Contract holder and co-ordinator of the project:

- SK Power Company i/s represented by SEAS Distribution A.m.b.A. Wind Energy Department (short name in the report: SEAS)

SK Power Company is a Danish utility in the Eastern part of Denmark and producer of power for the ELKRAFT-area. The company has built wind farms onshore and offshore for the ELKRAFT-group since the mid 1980s.

SEAS has carried out the overall co-ordination of the project, preparation of the major parts of the technical reports and has been in charge of installation of the meteorological measuring equipment. Furthermore, the company has provided the offshore measuring masts, performed the overall studies of the grid connection plus the wind farm design and operation.

Associated partners:

- National Wind Power Ltd. (short name in the report: NWP)

National Wind Power Ltd. is a wind power subsidiary owned by National Power PLC with several years experiences from working within the wind energy sector in United Kingdom.

The company has contributed to the project with investigations of British offshore wind farm projects including design basis relation to wind, wave and bed connections.

- Risø National Laboratory (short name in the report: RISØ)

Risø is a government owned energy research institute within the fields of wind, solar, nuclear and renewable energy. The institute was established in 1960s by the Danish Ministry of Environment and Energy.

Risø, the Department of Meteorology and Wind Energy has contributed to the project with operation and monitoring of the meteorological measuring system, data collection, pre-processing of the data base system, modelling of wind turbine structure and has specified the load cases for the offshore wind turbines.

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- Nellemann, Nielsen & Rauschenberger A/S (short name in the report: NNR)

Nellemann, Nielsen & Rauschenberger A/S (NNR) is a private Danish consulting engineering firm with more than 25 years experiences within the energy and environmental sectors including geotechnic.

For this project NNR has carried out the geotechnical and foundation design including determination of design loads, preparation of conceptual design and optimisation of foundations for the various types of wind turbines based on the result of the geotechnical investigations and laboratory tests performed by NNR's sub-contractor the Danish Geotechnical Institute (DGI).

- Stadtwerke Rostock AG (short name in the report: SR)

Stadtwerke Rostock AG is a public utility located in Rostock, Germany, and a distributor of power and district heating for the city of Rostock and vicinity.

The company has contributed to the project with experiences from offshore wind farms from the German part of the Baltic Sea including authority regulations, evaluation of wind data, foundation design, grid connection and geotechnical conditions.

- Universidad Politécnica de Madrid (short name in the report: UPM)

The Department of Energy and Fluid Mechanic of the Spanish university has worked within the field of wind energy for several years.

The university has contributed with modelling of the flow in offshore wind farms and interpretation of measurements.

3. OBJECTIVES OF THE PROJECT

3.1 General

The overall objectives of the project are:

- To supplement the existing offshore wind data base, by setting up offshore meteorological measurements significantly further away from the coast than was done previously and thereby developing a base of necessary wind data for large scale offshore wind farms at potential sites in Danish waters.
- To use the achieved data base for comparison and improvement of existing models to provide a more accurate description of the offshore wind conditions (less than 10 % uncertainty on cost estimates).
- To optimise the foundation design with respect to the design loads and geotechnical conditions and large-scale production, and to minimise the construction costs.
- To investigate the options for optimising the use of materials, and thus the cost, for offshore wind turbines with respect to the reduced turbulence level and remoteness of the sites.
- To optimise the design of large wind turbines (>1MW) in large wind farms (more than 100 wind turbines) in respect to serviceability, thereby minimising the power production costs.
- To optimise the grid connection design with respect to the design loads, geotechnical conditions and large-scale production, and to minimise the construction costs.
- To contribute to the existing base of know how concerning offshore wind farms by dissemination of results within the European Community.

3.2 Fulfilment of Objectives

The investigations performed by SK Power Company, represented by SEAS, and partners have resulted in fulfilment of the major objectives specified in the Contract Document:

- The existing offshore wind data base has been supplemented with data from potential offshore sites in Danish waters.
- The existing models has been compared and improved to provide a more accurate description of the offshore wind conditions.
- The foundation design has been optimised with respect to the design loads, geotechnical conditions and large-scale production.
- Optimisation of the use of materials for offshore wind turbines has been investigated.
- Optimisation of the design of large wind turbines in large offshore wind farms in respect to serviceability has been reviewed.

- Optimisation of the grid connection design has been investigated.
- The results have been disseminated within the European Community.

The target of less than 10% uncertainty on the cost estimates has not been reached during the project, as the uncertainty on the energy density estimate alone vary from $\pm 8\%$ at Rødsand and $\pm 15\%$ at Omø and Gedser Rev. With the addition of a 5% uncertainty on the price estimates, the total uncertainty on the cost estimate is $\pm 13\%$ for Rødsand and $\pm 20\%$ for Omø and Gedser Rev.

A better accuracy on the cost estimates require primarily a lower uncertainty (in the range 4-6%) on the energy density estimate.

An accuracy of 4-6% on the energy density estimate is achievable with a minimum of one full year of wind measurements. This will be reached in short time as a results of the continued measuring programmes and investigations which are part of the preparations of the first large scale offshore wind farms in the Danish waters.

4. TECHNICAL DESCRIPTION OF THE PROJECT

4.1 General

The project has investigated the technical and economical possibilities of large scale offshore wind farms in the range of 200 to 500 MW in the Baltic Sea and the Langeland Belt.

In amendment to the experience from the British offshore demonstration project of National Wind Power including bigger height of the waves and tidal water was included in the general part of the study. Experience from the work carried out was transferred currently to the new federal states of Germany through the co-operation with Stadtwerke Rostock AG.

The project was divided in two phases. Phase 1 has identified potential sites which were subject to further investigations in Phase 2.

Phase 1 was conducted as studies, while phase 2 included studies, investigations, measurements at the proposed sites, laboratory tests and preparation of technical reports.

The project initially had a planned duration of 24 months. However, due to technical problems with the attainment of a continuous wind data set of around one year, an extension of the project up to 36 months was granted, without implying additional costs for the project.

Activities which required an input from the wind- and wave measurements were subsequently postponed and performed later in the project.

4.2 Technical Description of the Project

4.2.1 Wind- and wave measurements

Sites for erection of measuring mast were selected, where optimum and representative wind, wave- and current data were to be expected in the potential investigation.

Three new 48 m offshore masts were installed in the areas. One 48 m mast on the shoreline was installed on the southernmost tip of Falster. Two existing masts (at *Vindeby*) were renewed.

The basis instrumentation of the masts consists of fast response cup-anemometers at three levels, on wind-direction sensor, temperature sensors for ambient temperature and atmospheric stability, acoustic wave height sensor for water level and wave height measurements (at one mast only). The instrumentation was supplemented with sonic anemometers for fast, high resolution 3-D measurements of the wind vector for selected periods.

The data acquisition system is capable of logging mean values and turbulence statistics, together with fast sampled timeseries for pre-selected conditions. Data were transmitted from the offshore stations to Risø via GSM.

The solution for power supply for the offshore instrumentation and data acquisition was 2 very small wind turbines and a battery-pack installed on each mast.

4.2.2 Turbulence and wake analysis

An existing model to calculate the effects of wakes in wind farms, UPMPARK, has been adapted to deal with very large wind farms located offshore. The fundamental changes that have been introduced in the model are:

- The surface roughness of the sea is no longer an independent data, but it is a function of the calculated characteristics of the flow.
- The wind farms are so large that they can even modify the whole planetary boundary layer, consequently, in order to apply the boundary conditions of UPMPARK in a realistic and feasible way it had to be considered that they are not known a priori.

4.2.3 Geotechnical investigations and foundations

The geotechnical investigation activities comprised:

- Boring at specified positions from a jack up platform with a near continuum of D=100 mm undisturbed samples, borehole-logging and in situ tests (pressure-meter as well as SPT's and ordinary vane tests). A number of 5 deep (more than 20 m) and 18 shallow (approximately 10 m) borings, performed from a jack-up rig, to illustrate to a sufficient degree the variability of the subsoil and its impact on the foundation and the economy.
- Geological description, photography and classification tests in the laboratory at Danish Geotechnical Institute, including advanced testing and cyclic tri-axial testing.
- Conceptual design and optimisation of foundations.

4.2.4 Wind farm related investigations

The investigations related to the wind farm design were:

- Power system analysis for the transmission grid capacity on the Southern part of Zealand was conducted within this study and comprises load flow calculations as follows:
 - Assessment of necessary power system reinforcement, new lines and cables needed to transfer power from farm sites to central Zealand.
 - Voltage stability studies to assess necessary capacitor banks and dynamic compensation.

The analysis was combined with preliminary park layouts and cost estimates for the proposed solutions were elaborated.

- Optimisation of the wind farm layout was performed by a combined calculation of wind farm production with a *Reference wind turbine* and cost estimates. A maximum rated power of 150 MW per offshore wind farm project was assumed, corresponding to approximately

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100 wind turbines of each approx. 1.5 MW. The wind farm production figures were calculated using general onshore wind data and a special version of the *Park (EMD)* windfarm production programme. The obtained production figures were processed further in a cost-optimising programme including the major cost parameters (developed by SEAS).

- Optimisation of the wind turbine design was performed by RISØ using an aeroelastical calculation programme (based on *Flex4*) including cost parameters for the major wind turbine components.
- Visualisations of the proposed projects were performed by two architect companies (*Møller & Grønberg* and *Hasløv & Kjærgaard*) with comprehensive experience in computer-aided visualisation of wind turbine projects (including *WinPro* by *EMD*). For this purpose a number of photographs were taken from the coastlines around, and the air above, the proposed projects.

4.3 Major Achievements of the Project

The major achievements of the project are related to following areas:

- The wind regime in offshore and coastal areas.
- Calculation of the production offshore from individual turbines and large wind farms.
- Models for wake and turbulence in large offshore wind farms.
- Design basis for and optimisation of offshore wind turbines.
- Optimisation of different foundation designs with respect to different water depths, soils, tidal water etc.
- Optimisation of grid connection designs, design basis and technical solutions.
- Optimisation of operation and maintenance systems, including access and transportation systems, and service intervals.
- Visual impact of the proposed projects
- Offshore wind projects for more severe conditions off the UK coast lines.

5. RESULTS AND CONCLUSIONS

5.1 Results of Investigations

The main results of the wind measurements are in the table below:

Data for 48 m above sea level	Uncertainty on energy estimate (%)	Average wind speed (m/s)	Energy density (W/m ²)	Yearly production (GWh) ²⁾	Weibull A	Weibull K
Omø	±15	8.3	590	5.0	9.4	2.3
Stålgrunde						
Rødsand	±8	8.8	700	5.6	9.9	2.3
Gedser Rev	±15	8.8	700	5.6	9.9	2.3
Vindeby ¹⁾	±4	8.1	540	4.8	9.1	2.3

1). Data from the existing "Vindeby offshore wind farm" (5 MW) for reference

2). Based on one 1.5 MW wind turbine

Table 5.1.1 Meteorological measurements. Main results.

The main results of the optimisation of a 1.5 MW wind turbine for offshore installation is shown in the table below:

Selected parameters	Reference offshore	Optimised LM29.2m	Optimised new blade
Rotor diameter (m)	60	71	74
Rated power (MW)	1.5	2.0	2.0
Production increase	-	28 %	32 %
Cost increase	-	16 %	16 %
Reduction of production costs	-	11 %	13 %

Table 5.1.2 Cost optimising of 1.5 MW wind turbine

The main results of the production calculation for the proposed projects is shown in the table below:

	Rødsand	Omø	Gedser
Gross yearly production (MWh/y)	516,008	434,762	518,827
Park efficiency (%)	89.8	84.0	90.2

Availability and transmission losses are not included.

Table 5.1.3 Calculated production based on park layouts with 96 V66/1.65 MW and actual wind data.

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The cost estimate for the foundations shows only little sensibility to the water depth and to the tower height.

Water level	5 m	8 m	11 m
Structure	265	289	318
Installation	21	23	27
Access platform	33	33	33
Dismantling	11	13	17
Total	331	359	395

Table 5.1.4 Total cost of foundation in 1000 ECU for Rødsand.

The result of the cost estimate for the proposed projects is shown in the table below:

		Rødsand	Omø	Gedser
Foundations	Mill ECU	36	36	36
Wind turbines	Mill ECU	113	113	113
Grid connection	Mill ECU	55	45	73
O&M facilities	Mill ECU	3	3	3
Project design	Mill ECU	8	8	8
Miscellaneous	Mill ECU	5	5	5
Total investment	Mill ECU	221	211	239
Investment per MW	Mill ECU	1.53	1.47	1.66
Capital costs/kWh	ECU	0.037	0.038	0.040
O&M costs/kWh	ECU	0.011	0.011	0.011
Total costs/kWh	ECU	0.048	0.049	0.051
Total uncertainty¹⁾	%	±13	±20	±20

1) Uncertainty on production cost estimate (uncertainty on energy estimate plus uncertainty on price estimate).

Table 5.1.5 Investment and cost estimates in 1997 prices

5.2 Main Conclusions

The overall conclusions of the project include:

- Areas are available for large scale offshore wind farms in the Danish waters.
- A large wind potential is found on the sites.
- Park layouts for projects consisting of around 100 wind turbines each has been developed.
- Design of the foundations has been optimised radically compared to previous designs.
- A large potential for optimising of the wind turbine design and operation has been found.
- Grid connection of the first proposed large wind farms is possible with only minor reinforcement of the transmission system.
- The visual impact is not prohibitive for the projects.
- A production cost of 4-5 ECUcent/kWh is competitive with current onshore projects.
- The planned accuracy of $\pm 10\%$ on cost estimates during the project was not achieved. This accuracy would have required a continuous data-set from all offshore masts for at least one year. However, the planned accuracy is expected to be achieved in short time after the finalisation of the project.
- The environmental issues were initially not planned to be studied in details, however, especially the possible visual impacts of the proposed projects proved to be of major importance for the local acceptance of the projects.

6. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

6.1 General

The project has contributed to the preparation of the Danish “Action Plan for Offshore Wind Farms in Danish Waters” which was presented to the Danish Government in July 1997.

The “Action Plan for Offshore Wind Farms in Danish Waters” was prepared by a work group with representatives from the Danish Energy Agency, the National Forest and Nature Agency and the utilities from the Western part of Denmark (Elsam) and the Eastern part (Elkraft represented by SEAS).

The “Action Plan” has formed the basis for development of the Danish “750 MW Plan” for installation of 5 demonstration offshore wind farms in the Danish waters of each 150 MW before year 2008.

6.2 Exploitations Plans

The results of the project will be utilised and further developed as part of the preparations for the first large-scale offshore demonstration wind farm projects in the Eastern Danish waters:

- *Rødsand 1*. 150 MW. Planned start of operation in autumn 2002.
- *Omø 1*. 150 MW. Planned start of operation in autumn 2005.
- *Gedser 1*. 150 MW. Planned start of operation in autumn 2008.

The results will also provide valuable knowledge for the development of a minor offshore project near the port of Copenhagen:

- *Middelgrunden*. 40 MW. Planned start of operation in autumn 2000.

6.3 Benefits of the Project

The results of the project will be useful for all developers of offshore wind farm projects, including wind turbine manufacturers, utilities, private companies and other developers of wind farm projects.

All in all, the results from this project have proven to be very useful for the future development of large-scale offshore wind farms in the Danish waters, and thereby also an inspiration for similar projects in other (European) countries.

7. VISUAL ILLUSTRATION OF THE PROJECT

Computer aided visualisations of selected views of all 3 first phase projects:



Figure 7.1 Omø. Seen from the air above Langeland. Distance approx. 13 km.



Figure 7.2 Gedser Rev. Seen from the air above Gedser. Distance approx. 7 km.



Figure 7.3 Rødsand, Seen from the air above Nysted. Distance approx. 12 km.

