Utgrunden Offshore Wind Farm: Results of 5 Years of Operation and Research

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Abstract
In December 2000, the Swedish offshore wind farm Utgrunden was commissioned with seven 1.5 MW wind turbines. The paper highlights some main findings in the technical and environmental parts of a comprehensive research project and some lessons learnt during the five years of operation. Important technical aspects include: the marinisation of a well-proven onshore wind turbine design, a soft-soft monopile foundation with a grouted joint between the pile and the transition piece, measurements of dynamic characteristics, loading due to wake effects, waves and floating sea ice, grid measurements, verification of meteorological wind resource models (MIUU, WA^{S}P) and evaluation of operation and maintenance as well as installation techniques. Environmental investigations focused on effects on migrating birds and showed very encouraging results.

1. Introduction

The offshore wind farm at Utgrunden, Sweden with seven 1.5 MW turbines has been operating since autumn 2000, i.e. for almost five years. The relatively long operational experience and a number of specific features are of large interest for the rapidly developing field of offshore wind energy utilisation in general.
Installed in autumn 2000, Utgrunden is one of the very first offshore wind energy projects based upon machines in the megawatt class. The plant consists of seven variable-speed, variable-pitch regulated 1.5 MW turbines of the type *GE1.5s offshore* and is situated 8 km offshore from the Swedish mainland near the island of Öland (Figure 1, Table I). It has been planned, designed and constructed as a turn-key project by GE Energy.
The machines are erected on driven, steel monopiles. The fundamental eigenfrequency of approximately 0.28 Hz lies in the operational range of the mean rotor speed but well below the rated value of 0.33 Hz. Depending on the actual eigenfrequency of each turbine, an individual operational window of the rotor speed is excluded from stationary operation. Table II compares the actually built soft-soft design with a considerably heavier soft-stiff concept,

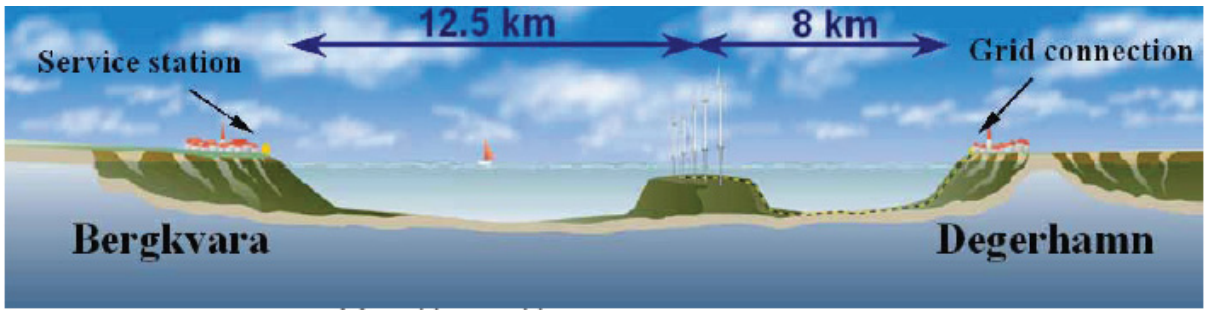

Fig. 1: Location of the Utgrunden wind farm on a subsea ride in the Kalmarsund between the Swedish mainland (left) and the island of Öland (right)

as used for all other offshore wind turbines so far. The relatively small pile diameter of 3 m enabled weight savings of one third of the total weight for the softer pile, and smaller reductions for the transition piece and tower. Furthermore, manufacturing and installation effort as well as the ice loads are reduced. Due to these soft characteristics the overall dynamic behaviour is more important and sensitivity with respect to the soil conditions and dynamic wave excitation, even at this sheltered location, needed attention.
The wind farm is connected by a 20 kV subsea cable to the relatively weak 55 kV grid on Öland. These electrical conditions apply some additional constraints on the turbine operation.
Observations of offshore winds over the Baltic Sea show complexity and inhomogeneity to a much larger extent than might be expected for offshore conditions. In particular the Utgrunden site in the entry of the Kalmarsund is interesting with respect to micro-siting and poses a challenging test case for wind resource models.
Another innovation at Utgrunden, which established to a standard solution in todays design practise, is the use of a grouted joint for the connection of the transition piece and monopile. With respect to load characteristics, this design feature differs considerably from grouted joints commonly used at offshore platforms in the oil & gas industry.
The location of this demonstration wind farm was carefully chosen within an environmentally sensitive region in order to gain important experience for later large-scale projects. The Kalmarsund is passed by about 1.5 million of migrating birds per annum and this was a major issue during the permitting procedure.

The above-mentioned particular aspects established the rationale for a comprehensive research project that was carried out between late 2000 and early 2005. This paper highlights the main findings in the technical and environmental parts of the project and the lessons learnt from a developer's and designer's point of view.

Table I: Main project data

Project size	10.5 MW
Turbines	7 x GE 1.5s offshore 1.5 MW, variable-speed, variable-pitch
Diameter	70.5 m
Rotor speed	11-20 rpm
Hub height	65 m above MSL
Distance from shore	12.5 km from mainland 8 km from Öland island
Water depth	7.1 – 9.9 m
Commissioning	21st December 2000
Estimated energy yield	31.400 MWh/a

Table II: Data of the monopile designs

	Soft-soft	Soft-stiff
Pile size	3 m x 45 mm x 31.4–33.7 m	3.65 m x 55 mm x 31.4–33.7 m
Pile weight	up to 110 t	up to 165 t
Transi-tion piece weight	18 t excl. platform	22 t excl. platform

2. Utgrunden research project

The research project funded by the Swedish National Energy Authority (STEM) is divided in a technical part with five work packages and an environmental part. The entire project was coordinated by GE Energy and different participants were in charge of the different work packages.

The technical part consists of five work packages:

- WP 1.1: Design Verification – Measurements IEC 61400-13 and Eigenfrequency Measurements (GE Energy, DE)

- WP 1.2: Design Verification – Performance and Loads (FOI - The Swedish Defence Research Agency)
- WP 2: Evaluation of the Electrical Performance and Connection of the Utgrunden 10 MW Wind Park (Chalmers University, SE)
- WP 3: Meteorology (Uppsala University, SE)
- WP 4: Operation and Maintenance (GE Energy)
- WP 5: Installation Technique (GE Energy)

For the scientific supervision of the technical part of the project a reference group was formed. The following institutions participated in the reference group: Energimyndigheten (STEM), Airicole AB, Teknikgruppen AB, the Endowed Chair of Wind Energy at the University of Stuttgart, Germanischer Lloyd Wind Energie GmbH and FOI, Department of Wind Energy Research.

The main emphasis of the environmental investigations was on the impact of the two offshore wind farms, the Utgrunden wind farm and the Yttre Stengrund wind farm on a million of migrating birds passing every season. Additional investigations, partly funded and carried out by other parties, include underwater noise measurements during pile driving and turbine operation at the Utgrunden wind farm.
Another reference group of environmental scientists with its principal centre at the Department of Animal Ecology, Lund University, Sweden was established for the supervision of the environmental investigation programme.

The results of the research project have been published in an executive summary [1] and several detailed reports [2-9], which are available at STEM. This paper presents summaries the different technical and environmental parts of the research project and some overall conclusions and recommendations for future projects.

3. Technical investigations

3.1 Work package 1.1: Design, Load and Eigenfrequency Measurements

The most southern turbine, facing the prevailing wind, was equipped with a large number of sensors for load measurements in accordance with IEC 61400-13. No wind met mast with hub height on a separate offshore foundation was available due to economic constraints. Therefore, the wind measurements were derived from a small met mast with 18 m height on a corner of the access platform. Furthermore, wave and current measurement devices were installed and strain gauges were placed inside the monopile.
The measurements were carried out in co-operation with Windtest Kaiser-Wilhelm-Koog GmbH between in January 2001 and summer 2003 with some interruptions. In addition, main operation data were recorded on all machines and meteorological measurements continued at the Utgrunden lighthouse approximately 2 km north of the wind farm.
Varying water depth and soil conditions at the site cause different eigenfrequencies at all Utgrunden machines. The first bending eigenfrequency of the support structure was measured on all machines in order to check whether the proposed soft-soft characteristics were met. Measurements of the first bending eigenfrequency of the support structure showed a very good agreement within the design envelope (Figure 2). Despite the complex geological conditions, the difference between the natural frequencies of the different turbines is relatively small. This is a result of the design philosophy of combining a relatively stiff foundation with a relatively soft tower. Due to this, the sensitivity with respect to soil uncertainties and the influence of dynamic wave excitation can be minimised.
Mechanical fatigue loads were measured at the blade root, tower base and monopile and extrapolated to 20 years design life. Although the first eigenfrequency of the tower is in the range of energy-rich frequencies of the sea states, no significant effect of wave excitation could be observed in the monopole and at the rotor-nacelle assembly. The tower shows some wave excitation. Measured response due to wind and waves has been compared with

load calculations with an integrated turbine model in the FLEX5 simulation code and all loads were found to be within the design envelope.

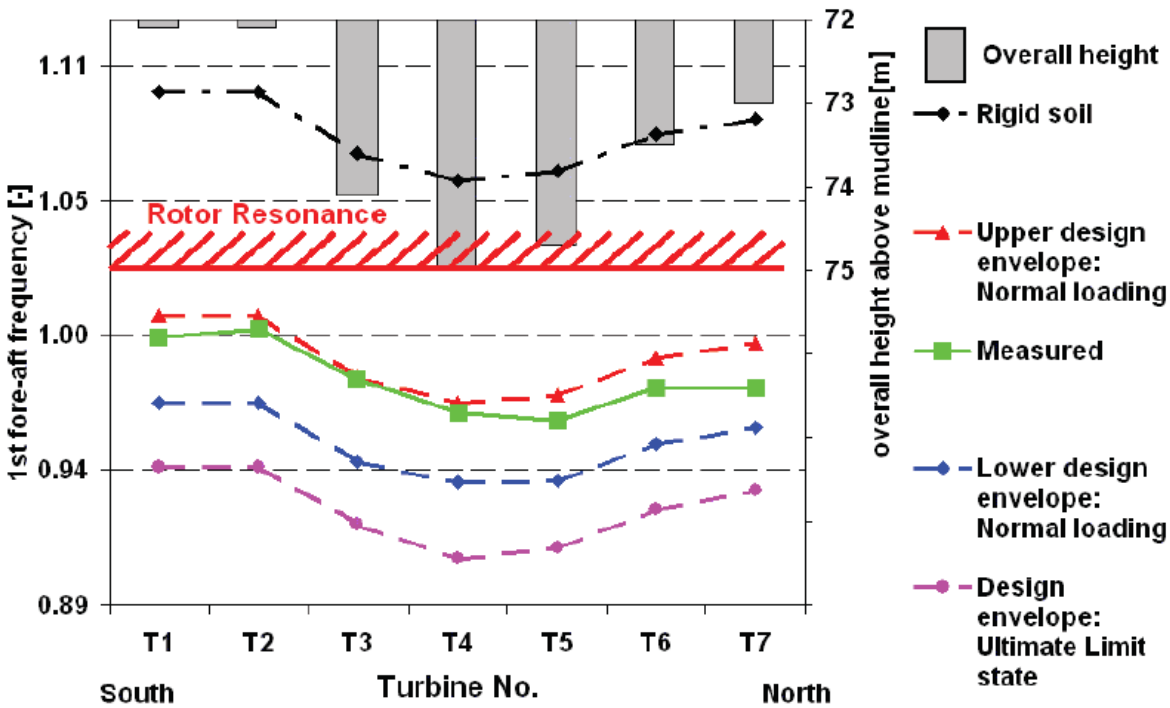

Fig. 2: Comparison of measured first fore-aft eigenfrequency (normalised by the value of turbine T1) with design calculations for different soil conditions [2]

3.2 Work package 1.2: Wake effects and other loads

The main subjects of this work package deal with the assessments of turbine loads due to wind and waves, and to a lesser extent sea ice. The power losses of the turbine due to wake effects are mapped using data from the SCADA and loads due to wakes from other turbines are also assessed.

Originally the project was also planned to investigate a novel concept of active wake control (AWC) to control the path of the wake behind turbines and thus to avoid shadowing effects on down-stream turbines. Recent findings from experiments with small wind turbine models have shown that the development of the wake can be controlled by controlling the operational modes e.g. yaw angle, pitch angle and rotational speed of the turbine. A series of measurements has been carried out to quantify turbine loads during yaw misalignment. However, the first measurement turned out to be unsuitable since the wind speed was above rated. Further evaluation with the complete measurement data to pick out load measurement with yaw misalignment was not successful either. In addition, simulation results with forced yaw angles showed considerable increases in loads during forced yaw operation. From the available data it was not possible to conclude that active wake control would not present a threat to the structural integrity of the turbine, for this reason active wake control was not pursued further.

The lack of an IEC compliant met mast and difficulties in correlating the measurements of the met mast on the platform, the lighthouse and the nacelle anemometry made the determination of the actual wind direction a difficult task. Typical results are presented in Figure 3 showing the relative power output as a function of the wind direction for turbine T1. The power deficits at single wake operation at 350^0 wind direction are very similar for all power levels, suggesting an efficient extraction of energy over all wind speeds below rated power. Investigation of power output for different yaw angles showed some asymmetry with

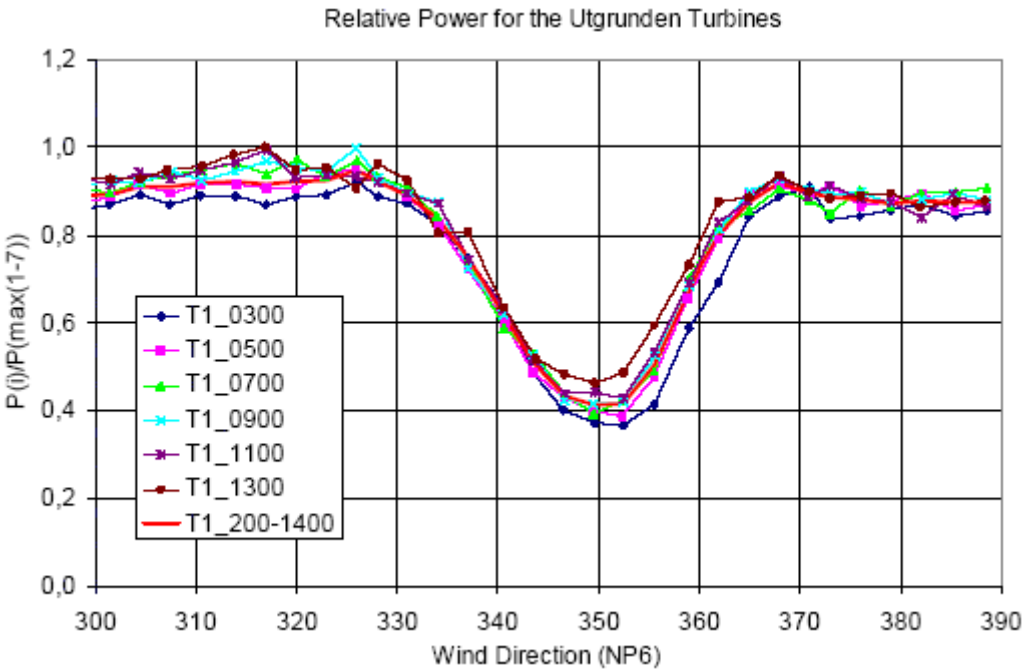

Fig. 3: Relative power output of the turbine number 1 as function of wind direction [3]

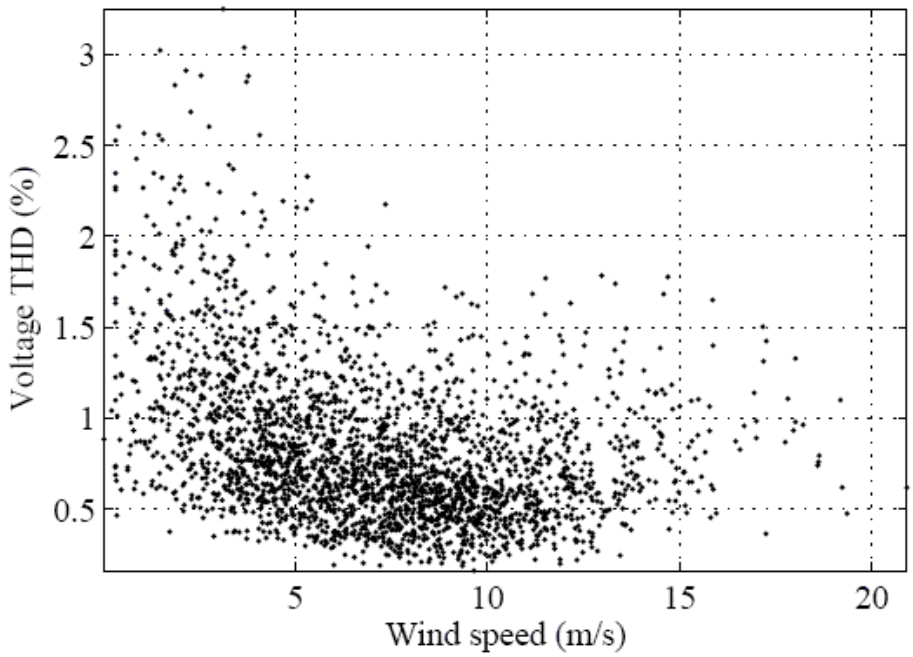

Fig. 4: Harmonics of the voltage at 20 kV level of onshore transformer station [4]

respect to the direction of yaw misalignment that is commonly not observed at other onshore turbines.

The service crew recorded one event of significant dynamic excitation due to impact of drifting sea ice of moderate thickness during one winter season. The load records for the monopile and the turbine were analysed in order to identify the ice impact events. From the recorded events no excessive bending load can be registered. Events such as stopping of the turbine actually do result in a higher load than the recorded ice impact event.

3.3 Work Package 2: Electrical Performance

The power quality of the Utgrunden wind park, reactive power exchange with the grid, flicker emissions, response to the voltage disturbance and harmonic emission were analysed. Measurements were carried out on the low voltage side of the transformer that connects the wind farm to the 55 kV grid on Öland.

The wind farm showed no negative effects on the grid and the power quality is well within the tolerance of the wind farm. Figure 4 presents the total harmonic distortion of the voltage as a function of the wind speed. Note that the harmonic distortion is at its highest during low wind speeds. One reason could be that at low wind speeds the fixed-speed turbines located onshore in the vicinity of the power station are starting and the soft starters of these turbines are functioning, which contribute to a higher harmonic distribution.

During the measurement period from March-September 2004 several voltage dips down to 60% remaining voltage occurred. About 15 of these events lead to the disconnection of at least one turbine. The disconnection limit is about 85% of the remaining voltage. Except for the loss of production, some higher current during the fault events, the response of the turbines to a voltage dip does not cause problems to the grid.

3.4 Work Package 3: Meteorology

A correct description of the offshore wind climate is crucial due to obvious reasons. Observations of offshore winds over the Baltic Sea show complex wind conditions and inhomogenity to a much larger extent than one might expect from offshore environmental conditions. The aim of this work package is to show that complex models based on the physics can deliver good estimates of the wind conditions in complex offshore environments in the Baltic Sea.

The study with the model of the Meteorological Institute of Uppsala University (MIUU) shows that with this type of model the complex and inhomogeneous wind fields is reproduced in the model results. At the same time it is obvious that simple models, like the commonly used WA^{s}P, do not include the physics needed to simulate the complex offshore winds.

To corroborate the model results, measurements from the metmast located on top of the lighthouse 38m above the sea level have been used. Attempts to derive wind speeds at larger heights by indirect methods using the wind turbine power and the nacelle anemometer have been applied with limited success. In a late stage of the project the wind farm developer Airicole AB replaced the old met mast on the lighthouse by a new tower of 90 m height to enable further meteorological investigations with much higher accuracy.

Modelling of the wind climate over the Southern Kalmarsund area was done using the higher-order closure MIUU-model, which has been developed at Uppsala University. The results showed good agreement with the observations made at Utgrunden lighthouse and at the lighthouse Öland Södra Grund. The modelled annual average wind speed at 70 m height was found to decrease from about 8.9 m/s at Öland Södra Grund to 8.0 m/s at Utgrunden.

The wind modelling of the Kalmar Sound is carried out with the more advanced meso-scale model and the WA^{s}P model. A direct comparison between the annual average wind speeds estimated with the two models was made, using wind data from Öland Södra Grund as input to the WA^{s}P model. The comparison showed that far offshore the two model results agreed quite well (see Figure 5), while in Kalmar Sound the MIUU-model results showed up to 1.2 m/s lower annual average wind speeds at 34 m height, a difference of up to 18%. This result is in general agreement with earlier findings when WA^{s}P was used to predict the wind climate at Utgrunden using wind measurements from four meteorological stations in the area, which gave very different results varying between 7.4 and 9.6 m/s in the annual average wind speed at 65 m height depending on the choice of reference input data.

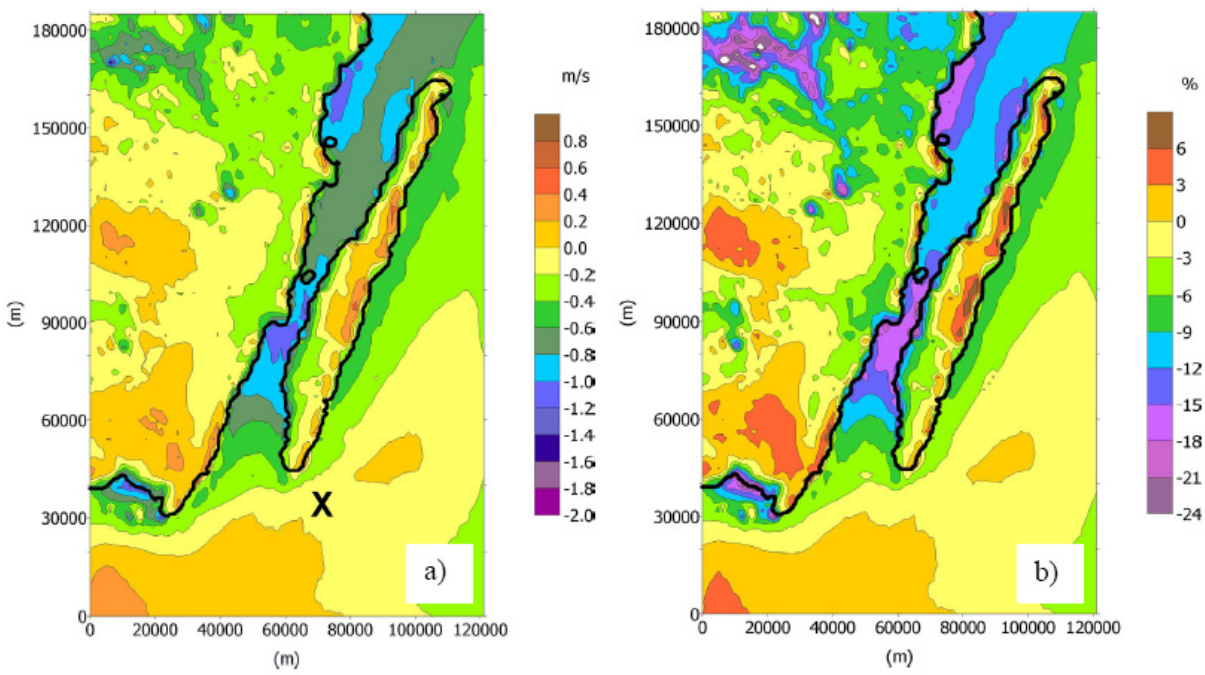

Fig. 5: Difference in annual average wind speed between estimates made with the MIUU model and the WA^{s}P model a) in m/s b) in % [5]

3.5 Package 4: Operation and Maintenance

The investigation of the operation and maintenance aspects of the projects focus on three crucial aspects:

- Statistics of wind turbine production, availability and reliability
- Evaluation of offshore design modifications and turbine reliability
- Evaluation of transport and access of service personnel

Operation

The energy produced from wind during the period 2001-2003 averaged 31.4 GWh per year, corresponding to a capacity factor of about 34%. The technical availability was over 95% in 2001. There has been a slight decrease over the 3-year period of the annual availability, as some turbines have experienced longer downtime due to corrective maintenance. After the corrective maintenance, the availability is bound to increase.

The evaluation of the capacity factors showed that the energy available from wind in fall and winter amounts to nearly twice of that available during spring and summer. The plant achieved an annual average specific mean power output of nearly 1150 kWh/m². This is considerably higher than the 750 kWh/m² for the turbines installed in the coastal state of Schleswig-Holstein, which has one of the best wind resources in Germany.

Four plants achieved availability levels in excess of 94% over the 3-year period. This is remarkable for the first generation of offshore wind turbines. The most productive turbine reached a capacity factor of 36.3% or almost ⅔ more than the reference turbines mentioned earlier for the onshore site.

Grid faults represent an external operating condition for wind turbines. Their examination for Utgrunden revealed that most were undervoltages and presented somewhat of a seasonal development. The higher frequency of grid faults during the summer months most likely originates from the smaller number of conventional power plants being used to balance the grid at that time of the year.

The impact of grid faults on downtime is indeed substantial. Most grid deviations are short-lived and the newer generation of turbines will be able to ride through the undervoltage or

automatically restart after such an error has occurred. Yet, in some occasions, under-voltage events at the wind farm extended over several hours. These faults do have a significant impact on service activities and operational costs. The service personnel estimates that approximately 20% of visits where forced by a grid undervoltage which required the turbine to be reset on-site.

Reliability

The probability of failures at wind speeds above the rated value is almost twice as high as in the partial load range. The frequency converter and pitch system produced a large part of the 'first faults' during the first three years of operation. Most components had a higher number of errors in the first year due to the start-up problems of the offshore operation. These were corrected through repair or adjustments of Programmable Logic Controller parameters.
The gearbox and braking system have experienced under-performance over the period as the gearbox experienced degradation of the sub-components. It could not be determined which was the main root cause for the failure as the failure modes are not the same even for identical design of the gearbox. The higher full load hours cannot be the main cause since they do not affect all the gearboxes. The large number of grid faults is a likely reason for the increasing brake problems as the corresponding braking procedure not only involves aerodynamic braking but also mechanical braking.
The considerable number of design modifications in the scope of the turbine marinisation was evaluated with respect to the operational experience of the five years.

Access

A simulation method has been applied to determine the availability of the turbine depending on the choice of the vessel. The simulation shows that using a purpose built catamaran docking by driving against the monopile would increase accessibility by fifteen to twenty percent. It also points out that the inclusion of an additional ladder/fender on the east side of the monopile could further increase access by up to ten percent.
One of the special constraints here at Utgrunden is the formation of sea ice. During a strong icy winter the turbine can only be accessed with an icebreaker. Currently an icebreaker is rented whenever it is needed. To increase the availability of the icebreaker, it may need to be rented for the winter months so it is on standby for ice conditions. This increases the cost considerably. Otherwise long delays in finding an icebreaker could have substantial effects on production.

3.6 Work Package 5: Installation Technique

The installation work package describes and evaluates the installation process for the Utgrunden wind farm. It consists of project planning, logistics of the wind turbine components and the number of tasks carried out during the installation and commissioning and evaluation of the grouted connection.
Due to the limited storage space at the port it is was not possible to have the components of all the turbines delivered to the port at the same time. A just in time delivery has maximized the space available for assembly of large components such as rotors.
It is essential to have a thorough knowledge of the site conditions before the installation work offshore starts as this imposes the operational window of the vessels contracted for that purpose. The installation of the monopiles was carried out without significant delay from the original schedule and the connection of the transition piece to the monopile using the grouted joint was a novel approach but proved to be reliable and the grouting process was carried out without difficulties.
In 2000 only general purpose offshore equipment was available on the market. The combination of two ordinary jack-up barges for the installation seems to have positive effects on the installation as the transportation task and the installation task can be carried

out in parallel which means that the available (sometimes short) weather window can be utilized fully and the standby time of the offshore equipment is significantly reduced.
The installation of the turbines proved to be straightforward given the right lifting equipment and weather conditions. Except for the weather dependency the commissioning process does not differ significantly from the onshore commissioning. An extended pre-commissioning of the components can further reduce the amount of the commissioning work that needs to be carried out offshore. The access system is a critical item for the commissioning process; a safe and proven access system should be in place when the commissioning work starts.
The use of a grouted joint for the connection of the transition piece and monopile was used at Utgrunden for the very first time at offshore wind energy applications. The transfer of loads from the transition piece to the monopile through the grout performs up to the expectation as no defects and cracks were found during the inspection. The grouted joint proved to be a large success and has been further developed to become a standard solution in this young industry.

4. Environmental investigation: Bird Study

The location of offshore wind farms in the southern Kalmar Sound was selected for its excellent wind conditions, but the area is also a migration path for waterfowl with a concentrated passage of about 1.5 million birds per annum (Figure 6). This provides very good conditions for the study of waterfowl reactions to wind turbines in their flight path.
The study covering four spring and four autumn seasons from 1999-2003 was carried out by Jan Pettersson at the request of the Swedish Energy Agency, GE Energy and Vindkompaniet AB. The study was carried out in collaboration with a reference group based at the Department of Animal Ecology, Lund University.

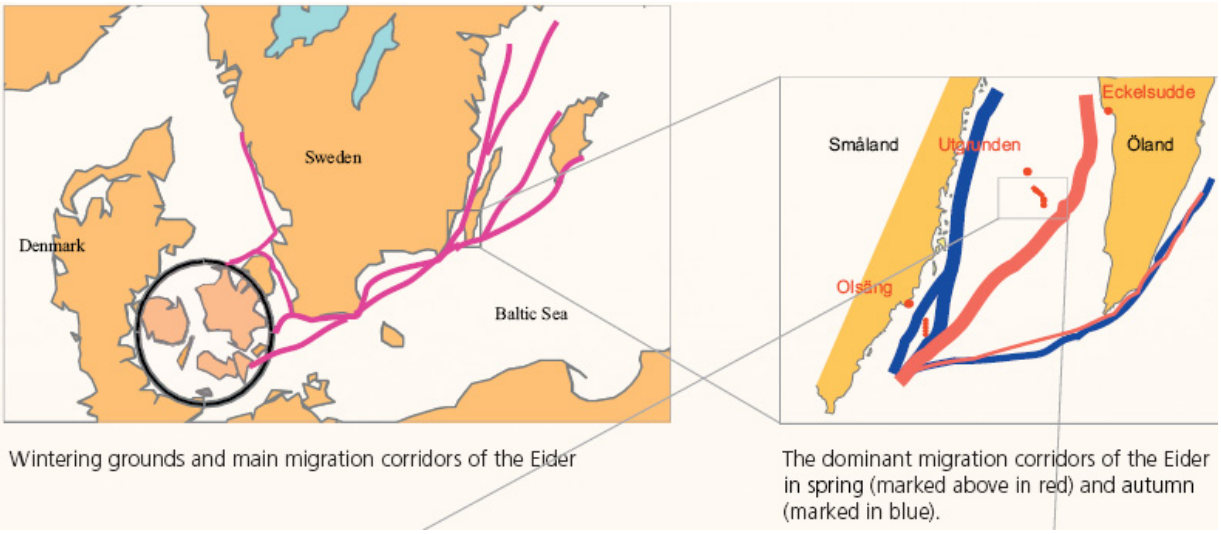

Fig 6: Main migration corridors of Eider through the Kalmarsund [8]

Data from Swedish military radar indicate that flocks of migrating waterfowl somehow detect the presence of the turbines in poor visibility and at night and change their flight paths to avoid them. The majority of Eider and other migrant waterfowl avoid the immediate vicinity of the wind farms. The birds generally start an evasion manoeuvre 1–2 km before the wind farms. The birds' behaviour is generally similar, irrespective of time and visibility – the majority of all waterfowl react to avoid the wind farms at night as well as at daytime, in poor visibility as well as in clear conditions. The waterfowl that make an evasion manoeuvre extend their migration distance and thus time by 0.2–0.5%. This entails only a marginal increase in energy expenditure for the whole migration. Very few waterfowl flocks fly so near the wind turbines (≤ 100m) that they risk a collision.

One collision of an Eider flock with one of the turbine blades was recorded and four out of the 310 Eider in the flock were hit or affected. A calculation of collision risk based on data collected from the Kalmar Sound studies shows that 1–4 flocks during the spring and about 10 flocks during the autumn (and only one bird in each flock) run the risk of colliding with existing wind turbines. This translates into one waterfowl killed per wind turbine per year.
The construction of the Utgrunden wind farm has a possible negative impact on the attractiveness of the area for staging and wintering waterfowl, indirectly through the activity of the service boat. Utgrunden is still used by the Long-tailed Duck, Eider and other staging and wintering waterfowl. The service boats that travel to and from the turbines are clearly a greater source of disturbance than the wind turbines themselves.

5. Conclusions

The offshore wind farm at Utgrunden, Sweden with seven 1.5 MW turbines has been operating since autumn 2000, i.e. for almost five years. The relatively long operational experience and a number of specific features are of great interest for the rapidly developing field of offshore wind energy utilisation in general. The project is a technological, commercial and political success. Marinisation of a well-proven wind turbine, the innovations of the soft-soft monopile and the grouted joint, are confirmed by the good experience during installation and operation. Eigenfrequency measurements proved the soft-soft design and the tailoring of the dynamics of the entire system. The large number of grid faults is a likely reason for some reliability problems in the mechanical drive train.
Results of a comprehensive investigation of migrating birds and the public acceptance are very positive and encourage further exploitation of the offshore wind energy potential.

Acknowledgement

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