# Study of the Fish Communities at Lillgrund Wind Farm

Final Report from the Monitoring Programme for Fish and Fisheries 2002–2010


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# Study of the Fish Communities at Lillgrund Wind Farm

## Final Report from the Monitoring Programme for Fish and Fisheries 2002–2010

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# *Foreword*

Wind power is a renewable source of energy and its development can contribute to the achievement of several environmental targets. Consideration must also however, be taken regarding the location, design and impact on human health and the environment.

An EU Directive to promote the use of renewable energy (2009/28/EG) has been in place since the beginning of 2009. In Sweden, this Directive in practice means that the amount of renewable energy used, should increase by 49 % by 2020. Sweden has set a target of 50 percent (Prop. 2008/09:163).

In 2009, the Swedish Parliament established a planning framework for wind power, which means that by 2020, there should be plans in place to build wind farms with an annual production of 30 TWh per year, of which 20 TWh should be on land and 10 TWh offshore (Prop 2001/02:143, NU 2001/02:17, rskr 2001/02:117). Wind power has increased significantly in recent years from 0.05 TWh in 1993 to 7.2 TWh in 2012.

The development of wind power requires planning, consultation, monitoring and supervision, but also new knowledge. The responsibility for this is shared between a number of different government agencies, including the Swedish Agency for Marine and Water Management.

Lillgrund Wind Farm began operation in 2008, and it is currently the largest offshore wind farm in operation in Sweden.

The monitoring programme at Lillgrund has made a valuable contribution to the increase in the understanding of the impact of offshore wind farms on fish communities. The programme has also put focus on the need for studies over a longer period of time, as well as on the cumulative impact on for example migratory fish such as silver eel.

The Swedish Agency for Marine and Water Management hopes that the report will provide an important source of information for environmental impact assessments as well as for the planning and licensing processes for wind power. The Swedish Agency for Marine and Water Management would like to thank all of those who have contributed during the long period, which this project has been undertaken.

Göteborg November 2013, Björn Sjöberg

Director, Department for Marine and Water Management

# Summary

In 2001, the Swedish Government authorised the construction of an offshore wind farm at Lillgrund in the Öresund Strait between Denmark and Sweden. In 2002, the Environmental Court defined the final terms and conditions for the wind farm development and the extent of the monitoring programme required.

Lillgrund wind farm came into full operation in 2008, and is currently the largest offshore wind farm in operation in Sweden.

The Swedish National Board of Fisheries conducted a monitoring programme, in the area, in the years before (2002–2005) and after (2008–2010) the construction of the wind farm; a base line study and a study when the wind farm was operational, respectively. No investigation was conducted during the construction phase. The aim was to investigate the impact of the wind farm during the operational phase on the benthic and pelagic fish as well as on fish migration. These studies have partly been integrated into work conducted as a part of the Vindval Research Programme, funded by the Swedish Energy Agency.

## Acoustics (sound)

- The overall sound energy from the wind farm under water is mainly generated by vibration from the gearbox.
- An analysis of the sound pressure level for the wind farm area, showed a correlation between noise level and the number of turbines in the wind farm (the so called park effect), where each individual turbine helps to increase the overall noise level in the area.
- Sound measurements from Lillgrund wind farm showed that noise levels within a distance of 100 metres from a turbine at high wind speeds are high enough to be a risk for some species of fish to be negatively affected, e.g. in the form of direct escape behaviour, or masking of vocal communication between individuals.
- Stress reactions can also occur at distances of more than 100 metres from a turbine. This is due to the fact that the noise from the turbines is continuous and louder than the ambient noise levels within some frequencies.

Measurements of the underwater noise levels were carried out at varying distances from individual turbines, from longer distances away from the entire wind farm as well as within a reference site (Sjollen) 10 km north of the wind farm. The results show that the wind farm produces a broadband noise below 1 kHz as well as one or two tones where the 127 Hz tone is the most powerful (vibrations from the first stage in the gear box). The majority of the overall underwater sound energy from the wind farm lies around the tone of 127 Hz.

The maximum noise levels, generated by the wind turbine, working at full production (12 m/s), at 1 m were 136 dB re 1µPa$_{(RMS)}$ for the dominant tone of the turbine which was 127 Hz (integrated across 123–132 Hz) and 138 dB re 1µPa$_{(RMS)}$ at the full spectrum (integrated across 52–343 Hz). At a distance of

100 m from the turbine, the noise levels are reduced to 104–106 dB re 1µPa$_{(RMS)}$ across the full spectrum, which is close to the locally measured ambient noise in the Öresund Strait, but the noise level was still around 23 dB above the background level for the 127 Hz tone.

An analysis of the sound pressure level for the wind farm area showed a correlation between noise level and the number of turbines in the wind farm (called the park effect). Close to the wind farm (<80 m), the noise environment was dominated by the individual wind turbine with a calculated sound propagation loss of 17•log (distance). At greater distances (80 m to 7000 m) the sound propagation loss was non-linear and less than 17•log (distance). This is explained by the fact that the other turbines in the wind farm contributed to the total noise level. At even greater distances (>7 km) the entire wind farm functioned as a point source and the sound propagation loss was once again measured as 17•log (distance).

The noise levels equivalent to those recorded and calculated from Lillgrund wind farm have not been shown to cause any physical injury to fish according to the current published scientific literature. It was only within some 100 metres from a turbine at high wind speeds that the noise levels were high enough to result in the risk of negative effects on some species of fish in the form of direct escape behaviour or possible masking of communication. The response depends upon the individual species' sensitivity to sound. Fish have been shown to become stressed when they find themselves in a consistently noisy environment, which in turn can result in for example, lower growth rates or can have an impact on reproduction. Stress in general can also, in combination with other negative factors, make them more susceptible to disease etc., due to an impaired immune system. Animals can choose however, to remain in an area despite the disturbance, if the area is sufficiently important for their survival or reproduction.

Based on the calculated sound propagation around the wind farm, salmon and eel could theoretically detect the 127 Hz tone at 250 m and 1 km distances respectively at a productivity rate of 60 and 100 %, which is equivalent to a wind speed of approximately 6 and 12 m/s. The calculated distances would be limited by the hearing ability of both fish species and not the background noise levels in the Öresund Strait. For herring and cod, the theoretical detection distance was calculated to be between 13 and 16 km respectively for a production rate of 60 and 100 %. This distance should have been greater, but is limited for these species due to the ambient noise levels in the area. These calculations indicate that fish can potentially detect sound from the wind farm at relatively long distances. Local variations with regard to depth and physical barriers such as peninsulas, e.g. Falsterbonäset in the southern end of the Öresund Strait, can however, have a large impact on the actual sound propagation.

## Benthic Fish

- The temporal development of the fish community in Lillgrund was similar to that observed in the reference areas during the study period. For the wind farm as a whole, no effect was observed on species richness, species composition or on the abundance of fish.

- Several species of fish however, showed an increase in abundance close to the wind turbines compared with further away, especially eel (yellow eel) (*Anguilla anguilla*), cod (*Gadus morhua*), goldsinny wrasse (*Ctenolabrus rupestris*) and shorthorn sculpin (*Myoxocephalus scorpius*). The results reflect a redistribution of fish within the wind farm, rather than a change in productivity or migration from surrounding areas. The increase in abundance is probably due to the wind turbine foundations providing an opportunity for protection and improved foraging. The distance within which an increased abundance could be observed was estimated, for different species, to be between 50–160 metres from a wind turbine.
- Fish distribution may to some extent have been influenced by the local acoustic environment, as a lower degree of aggregation close to the wind turbines at higher noise levels. The effect was most obvious for eelpout and eel (yellow eel). No response was seen for cod in relation to sound levels.

Changes in the species composition of the fish communities over time were studied in comparison with two reference areas. Of these, the northerly reference area (Sjollen) had a larger marine component than the southern reference area (Bredgrund). The species composition at Lillgrund had similarities with both of the reference areas.

The results from fish sampling with fyke nets and gill net series indicate that there have been no significant changes in the number of species, the species composition or the fish abundance after the wind farm was built, looking at the wind farm as a whole. Some changes have however been noted in relation to individual species. An increased catch of shore crab and eel (yellow eel) was observed during the first two years of production, but not in the third year. The catch of eelpout increased in all areas during the period studied, but to a slightly lesser extent at Lillgrund when compared to the reference areas. For the other species, the changes observed at Lillgrund were similar to at least one of the reference areas. These results suggest that the fish communities within the wind farm were primarily affected by the same general environmental conditions as the fish communities within the reference areas, rather than by the effects of the wind farm.

An analysis of the distribution patterns of fish close to the turbines showed an increased abundance in the immediate vicinity of the wind turbines in four of the eight species of fish studied: specifically shorthorn sculpin, goldsinny wrasse, cod and eel (yellow eel). The effects were seen already after the first year and were similar over all three years studied. An effect was also identified for eelpout, but only in 2010. The aggregation effect was seen within a distance of 50–160 metres from the wind turbines, different for the different species.

A comparison of the relative effect of different factors, based on the data from an extended survey in 2010, showed that the observed distribution pattern could be explained to a larger extent by the presence of the turbines rather than the underwater topography of the area. The analysis also indicated weak effects of the local acoustic environment on fish distribution patterns, with a reduced presence of fish at higher noise levels. The response was strongest for eelpout and eel. No response in relation to noise level was seen for cod. For shorthorn scuplin and common shore crab a response was seen only during the autumn. The magnitude of the effect of noise was, however, lower than the aggregation effect. Hence, fish aggregated close to the wind turbines in all conditions, but the effect was weaker when the noise levels were higher.

It is recommended that the the wind farm area is reinvestigated after a number of years to follow the long-term development of the fish populations, and to see if the aggregation effect observed continues and potentially also increases over time. A prerequisite for a long term positive development of fish abundance is that the removal of fish, such as from fishing or predation by marine mammals and fish-eating birds, does not increase in the area.

# Pelagic Fish

- There was a dramatic increase in commercial fishing for herring north of the Öresund Link (close to the north of the wind farm) in the first years of operation of the wind farm, in contrast to south of the bridge that forms a part of the Öresund Link, where it virtually completely stopped. This change may imply that the Rügen herring migration was affected by the Lillgrund Wind Farm. Due to the fact that there were other factors in addition to the wind farm contributing to the herring movements, it proved difficult to identify any correlation.

The evaluation was based on catch statistics from the commercial fisheries in the Öresund Strait (ICEs subdivision SD 23) and fisheries independent statistics from ICES for adult herring (Rügen herring) (ICES subdivision SD 21–23, western Baltic Sea and southern Kattegatt) and density of juvenile fish (ICES subdivision SD 24).

There was a dramatic increase in commercial fishing for herring north of the Öresund Link in the first years of operation of the wind farm, in contrast to south of the bridge where it virtually completely stopped. The reason may be largely explained by the regulations banning drift-net fishing and a favourable market for herring, but potentially also because of the Öresund Link which was completed in 2000.The potential impacts of the wind farm are therefore difficult to distinguish from the impacts of these other factors because detailed resolution in the catch statistics are missing from the years before 1995 prior to the start of the building work on the Öresund Link.

The statistics independent of commercial fishing from ICES showed no significant correlation between the density of herring juveniles in the western Baltic Sea and the number of adult herring (3 years old or more) in the following years in the Öresund Strait (ICES SD 21–24). There was however a weak tendency towards a negative development of the fish population over the period 1993 – 2010. The presence of Rügen herring and their migration through the Öresund Strait is likely strongly influenced by the fact that the population shows large fluctuations between the years. In addition, there is a possible overlapping effect on the soundscape from the wind farm and the Öresund Link, which has been in use since 2000.

Overall, the variety of factors together mean that it is difficult to identify any clear results with regard to if the migration of Rűgen herring is influenced by Lillgrund wind farm.

## Fish Migration

- According to the results from this work, the wind farm at Lillgrund is not a barrier for the migration of the eels that come into contact with it. An equally large proportion of the tagged and released silver eels (approximately one third) passed the transect line with receivers, at Lillgrund both before the wind farm was constructed (baseline study) and after it was in operation.
- There was no statistically significant difference indicating any alteration in the migration speed of eels, but there were occasional longer migration times when the wind farm was working at higher levels of production (>20 % of maximum) which may indicate that some eels are affected by the wind farm. The fact that the eels also showed a tendency towards being noted on fewer occasions than expected within the wind farm at low productivity (<20 %) and on slightly more occasions than expected at higher productivity (>20 %), could indicate that they have greater difficulty in navigating past the wind farm at higher levels of productivity than lower.

The impact of the wind farm on migration was studied via tagging of migrating silver eels. In total, 300 acoustically individually tagged eels were included in the study and of these, 100 contributed with useable information. The baseline study period started on a small scale in 2001 and ended in 2005. The majority of the eels were tagged and monitored during the production period (2008–2010). All tagged silver eels were released south of the wind farm.

The results showed that an equally large proportion of the tagged and released silver eels; approximately one third, passed a transect with receivers at Lillgrund wind farm, both during the baseline period 2001–2005, and when it was in production 2008–2009. The greatest proportion of eels passed through the deeper part of the transect by the navigation channel Flintrännan close to the Danish border at Drogden during the production phase (31 %) and baseline period (43 %). A somewhat larger proportion of the eels were registered passing the most easterly part of the transect, close to Klagshamn, during the production phase (14 %) compared with the baseline period (5 %). A behaviour which occurred during the production phase, was that some individuals moved back to the release site, after being in the vicinity of wind farm. The most commonly observed behaviour during the study in 2010 was that an eel was registered moving south of the wind farm in a more or less northerly direction, but without being registered to the north of the wind farm.

The range in the time taken for the movement of the eels from the release site to the transect running through the wind farm was very great, from four to more than 1000 hours. There was no statistically significant difference in the time taken to travel, between periods with low production (<20 % of maximum) and periods with high production (>20 %) or for individuals which passed through or outside of the wind farm.

Even if the eels did not show any statistically significant behaviour, changes in movement patterns may occur for some individuals. The fact that there was a tendency towards longer periods of time taken for movement at higher production levels (not statistically significant) (>20 %) could indicate that some individual eels are influenced by the wind farm. The proportion of eels that took more than a week (168 hours) to make the journey was 48 % during the period with higher production (>20 %) compared with 28 % at lower production. No significant difference in the proportion of passes within or outside of the wind farm respectively could be shown. The eels showed however, – a tendency of being recorded on fewer occasions than expected inside the wind farm at low production levels (<20 %) and on more occasions than expected at higher production levels (>20 %). The irregularities in the proportions, compared with the expected result, could indicate that individual eels stayed longer in the wind farm when it was functioning at higher productivity. If the eels discover the wind turbine only when they are very close and do not change course, then other factors such as the speed of the current across the shallow marine areas become significant and can mean that the time spent in the area is shorter and records fewer. At high productivity, the eels may hesitate and/or divert their course and be recorded from close to or within the area, to then be recorded on the transect outside of the wind farm.

The mechanisms that lie behind the possible impact from the electromagnetic field or the noise pattern are difficult to distinguish, as both can have an impact on the same areas. Travelling speed showed no linear relationship with the level of production in the wind farm.

# Conclusions

The study at Lillgrund has resulted in an increase in the understanding of how offshore wind farms can affect fish, which is very valuable. Even within an international context, there are currently very few experience-based studies of offshore wind farms in operation.

The results from three years of monitoring during the operational phase show that the effects of the wind farm on fish populations and fishing were limited. One of the clearest results showed that some benthic fish species were attracted to the foundations of the wind turbines with their associated scour protection (reef effect). In addition, the effect on the local noise environment in the form of increased noise in the Öresund Strait was documented. The results of the eel tracking study may indicate that some eels are influenced by the wind farm on their migration. Some care should be taken however, when applying the results of these studies in other offshore environments and on a larger scale. The monitoring has only been carried out for three years and thus reflects only a short-term perspective. Lillgrund wind farm is also one of the first large-scale wind farms and is situated in an area with regular and noisy shipping traffic and both frequent and large variations in environmental factors such as salinity and currents.

A key knowledge gap that remains after the completion of this work is the lack of studies over a longer period of time, to help identify the long term ecological effects of, for example, the reef effect. Ideally, the wind farm should be re-visited after a number of years to see how the fish populations have developed over the longer term, and see if the observed aggregation of certain fish species close to the wind turbines continues, and to possibly see if any quantitative effects have taken place. Studies are also required in relation to how stress may affect fish species/individuals which choose the reef-like foundations and their noisier environment. Additional studies, primarily for the Baltic Sea, are also required to establish if there are any cumulative effects on migratory fish such as silver eels.

# Introduction

In 2001, the Swedish Government authorised the construction of a wind farm at Lillgrund in the Öresund Strait. (Department of the Environment, reference no.r. M1998/2620/Na). In 2002, the Environmental Court defined the final terms and conditions for the development (Växjö Court, case no. M 416-01). In the planning conditions (condition no.5) the Government stated that a monitoring programme on the impact of the wind farm on the fish populations and fishing within the development area should be undertaken. The studies that have been undertaken within the monitoring programme to identify potential impacts on fish populations and fishing include both a period before the development of the wind farm and after the wind farm was in production.

The programme began with a baseline study over the period 2002–2005 (Lagenfelt *et al.* 2006). Lillgrund wind farm came into full operation at the beginning of 2008. This report is a compilation of the results from the studies that have been carried out during the wind farm's first three years of operation 2008–2010, as well as how these relate back to the period before the wind farm was established.

## Offshore Wind Power in Sweden

Both on and offshore wind power is planned to contribute a significant part when the increased requirement for renewable energy sources are to be met, both nationally and internationally. The majority of the wind farms in Sweden are currently based on land, because offshore wind farms are more expensive to build and run. At the end of 2010 there were in total, 71 offshore wind farms with an operating capacity of of 163.4 MW (of which Lillgrund wind farm contributes 48 turbines and just over 110 MW) (The Swedish Energy Agency, Wind Power Statistics, 2010).

There are however, a large number of wind farms that have planning permission, but have not yet been built (September 2011, a total of 349 turbines with 1715 MW, divided over seven wind farms). Five of these wind farms are situated along the Swedish coast in the Baltic Sea proper. In the Baltic Sea proper, there are also plans for an additional three very large wind farms, including a total of up to 1200 turbines, with an operating capacity of approximately 3 800 MW and a production of approximately 12 TWh (two in the Bight of Hanö, Taggen and Blekinge Offshore, and one in the Södra Midsjöbanken).

## The Impact of Wind Power on Fish and Fishing

The National Board of Fisheries has previously, as a part of a government initiative in 2006, published a review of the current knowledge of the impact of offshore wind farms on fish populations and fishing (Bergström *et. al.* 2007).

An offshore wind farm goes through three separate phases during its lifetime which vary in the character and extent of impact.

1. Construction phase, this is calculated to take from one to several years for larger wind farms.
2. Production phase, which is expected to last at least 20–30 years.
3. Decommissioning phase.

The impact from the construction phase is to a large extent similar to other types of building work offshore, with noise (the most intensive noise occurs when the piles for the turbine foundations are being driven down into the sea bed) and the dispersion of sediment in the water column. The knowledge regarding the impacts of building in water is quite extensive with a relatively large quantity of peer reviewed scientific publications. The impact during the decommissioning stage is considered to result in similar sorts of disruption as under the construction phase.

Experience-based studies from offshore wind farms in operation are, in contrast, few (see Wilhelmsson *et al.* 2010, for a summary). Lillgrund is the largest offshore wind farm in operation in Sweden.

Compilations of the environmental impacts of offshore wind power are continually being published on an international basis and in relation to environmental impact assessments. The latest knowledge needs however to be updated based on recent experience, due to the fact that the last large review was published around 2006–2007 (Zucco *et al.* 2006, Åslund *et al.* 2006, Bergström *et al.* 2007). Several wind farm projects from several countries can be followed in current reports, e.g.

- Belgian (http://www.mumm.ac.be/EN/Management/Sea-based/windmills.php),
- British COWRIE-project (www.offshorewind.co.uk),
- Danish (http://www.ens.dk/da-DK/UndergrundOgForsyning/VedvarendeEnergi/Vindkraft/Havvindmoeller/Sider/Forside.aspx),
- Dutch Nordzeewind (www.noordzeewind.nl), and
- German wind farm project (www.bsh.de/de/Meeresnutzung/Wirtschaft/Windparks/index.jsp).

During the production phase, the primary potential impact is related to aspects of changes in habitat, partly as a consequence of the *creation of new habitat* consisting of the wind turbine foundations and scour protection, partly as a consequence of *loss of habitat* due to a change in the *noise environment* (an increased noise level) or *electromagnetic environment (alteration in electromagnetic fields from cables on the sea bed*). In some circumstances the potential risk of the impact of a change may be in terms of the *light environment* (*shade and reflections from the turbines and rotor blades*) as well as changes in *currents* (*by hindering and redirecting existing water currents*), but these impacts are likely to be very low on fish.

Changes, primarily in relation to the noise environment and electromagnetism could reduce the quality of the habitat for fish, but also be negative for fish species that use noise and the earth's magnetic field for navigation. The creation of new physical structures may result in an increase in the aggregation of fish in the area, because the structures provide improved opportunities for protection and foraging. The wind farm may also come with *fishing restrictions* of varying magnitude, in the form of the equipment that may be used and possibly even limitations in access, which can have direct economic consequences for those fishermen that are affected, as well as potentially on the fish population development. New restrictions on the fisheries are however, not planned in the Lillgrund Wind Farm area. In addition to these effects, changes in other parts of the ecosystem may lead to indirect ecological effects on fish, and the fish may, in turn, affect other components of the ecosystem. There is also a risk that new structures on the sea bed can provide habitat for invasive (non-native) species.

Overall, the cumulative effects may arise when larger and larger parts of the marine environment are exploited for wind power etc., even if the effects are not significant from the individual cases. (Berkenhagen *et al.* 2010).

# Study Design

The monitoring programme has been designed to evaluate the impact of the wind farm, when in production, on the fish fauna, by comparing the situation in the years before and after construction. The studies have been carried out for at least three years before and after construction respectively, in order to be able to usefully establish the magnitude of the natural variations. In order to see if any observed differences are dependent on the proximity of the wind farm or on other external factors, equivalent studies have also been undertaken on reference areas; Bredgrund, south of Lillgrund and Sjollen north of Lillgrund and the Öresund Link with its bridge.

The basic proposal for the monitoring programme included a range of different elements. In table 1, the sampling schedule is presented for the entire study period (2002–2005 and 2008–2010 respectively). No studies were undertaken during the construction phase. The programme has to some extent been modified over time, in order to incorporate experience developed over the course of the project. The potential impact of the wind farm, in the longer term, is not covered by the monitoring programme, which only covers the first three years of production.

During the production phase, studies of the underwater sound (acoustic studies) were undertaken, fish sampling directed at bottom-living fish and studies of the migration patterns of eel (studies using telemetry). Studies of the pelagic fish have been included by analysing commercial fishing catch statistics for the Öresund Strait as well as analysis of the more independent ICES fishing data for a larger sea area.

Table 1. Overview of the studies carried out within the monitoring programme for Lillgrund wind farm (L). The studies have in some cases been integrated with studies within the framework of the Vindval – Research Programme (V). *In Italics: Baseline only*

| | | Baseline | | | | | **Constr.** | | **Operational phase** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
| **Noise** | Acoustic Measurements | | | | | | | | L | V | V |
| **Benthic Fish** | Fish Sampling, Spring (Fyke Nets) | | L | L | L | L | | | LV | LV | LV |
| | Fish Sampling, Autumn (Fyke Nets) | | | | | | | | | | L |
| | Fish Sampling, Autumn (Gill Nets) | | L | L | L | L | | | L | L | |
| | *Fish Sampling Targeting Spawning Grounds* | | *L* | *L* | *L* | | | | | | |
| | *Habitat Mapping* | | | | *L* | | | | | | |
| **Pelagic Fish** | Commercial Fishing Catch Statistics | | | L | L | L | L | L | L | L | L |
| | *Acoustic Survey* | | | *L* | *L* | *L* | | | | | |
| **Fish Migration** | Eel Telemetry | L | L | L | L | L | | | V | LV | L |

The number of fish sampling stations using fyke nets increased from 24 to 36 in 2005. In 2010, fish sampling with fyke nets was also undertaken in the autumn, and the fish sampling with gill net series was not continued. The number of fyke net sampling stations was increased from 36 to 76. The aim with the changes was to obtain a better picture of the distribution of the fish in the vicinity of the turbine, and complement the studies of the distribution effects undertaken within the Vindval Research Programme. As a consequence of using the same equipment for fish sampling in the spring and the autumn, it was also possible to compare the presence of different fish species between the two seasons. This was particularly interesting in relation to the presence of common shore crab, which has become more common in the Öresund Strait over the last decade or so.

Fish sampling using gill net series in the autumn was significantly disturbed by the heavy presence of shore crab, which may partly have influenced the results. It was however assessed, that it was appropriate to continue to carry out this sampling technique up to and including 2009.

The planned vegetation mapping was abandoned, because it was deemed as not being feasible to undertake this in a technically equivalent manner across the entire area.

Targeted fish sampling for specific species that may have used Lillgrund as spawning grounds was previously included as a part of the baseline studies. Sampling targeting spawning populations of turbot was carried out between 2002 and 2004 and of lumpfish in 2003–2004. The fishing was severely disrupted however by drifting algae in all years, primarily at Lillgrund and Bredgrund. This disturbance continued despite attempts to alter the time of the fish sampling period. Due to the level of disturbance, it has not been possible to obtain reliable baseline data for a study to see whether the wind farm at Lillgrund has had an impact on the spawning of turbot and lumpfish. This fish sampling was thus abandoned after 2004. A description of the results available from the fish sampling targeting spawning populations which was carried out, is available in the report from the baseline studies (Lagenfelt *et al.* 2006).

The impact of the construction of the wind farm at Lillgrund on pelagic fish was studied during the baseline studies with hydroacoustics (Lagenfelt et. al. 2006). The studies were primarily aimed at quantifying the pelagic fish within the open water and were partly intended to be associated with the Rügen herring migration between spawning and nursery grounds. An analysis of the statistical strength of the studies showed however, that the likelihood of identifying even large changes in the quantity of pelagic fish after the wind farm was in production was low.

The activity involving hydroacoustics was replaced with an analysis of commercial fishing catches of herring in the Öresund Strait (catch area SD 23), as well as an analysis of ICES studies of herring juveniles and reproductively mature herring in the western Baltic Sea and southern Kattegatt (catch area SD 21–24).

# Wind Farm

Lillgrund wind farm is situated approximately seven kilometres out from the Swedish coast and seven kilometres southeast of the Öresund Link with the Öresund Bridge. The wind farm consists of 48 wind turbines, a substation with transformer building as well as cables between the turbines (in total 22 km 33 kW cables divided across five sections), the substation and to the shore (a 130 kW cable). The wind turbines are placed in straight rows with a distance which is slightly below optimum for the 2.3 MW generators that are used (Dahlberg 2009). The distance between the rows of wind turbines is 300m and the distance between each turbine in a row is 400m. The wind turbines cover an area of 4.6 km$^2$.

The wind turbines stand on gravity based foundations, hexagonal concrete pedestals which are 19 metres at their widest, on a bed of macadam on the sea bed. Around the base of each tower, there is ballast and a one to 1.2 m thick scour protection layer. The depth of the water in the area varied from between four and nine metres before construction and was dredged to be between seven and eleven metres before the installation of the foundations.

The wind turbines have a total height of approximately 115 metres up to the end of the blades, a rotor diameter of 93 metres and the tower a height of 68.5 metres. The blades rotate with a speed of 6–16 revolutions per minute. In total, the wind farm has a maximum production capacity of 110 MW and an annual production of approximately 330 000 MWh. Maximum electricity production is reached at a wind speed of 12–13 m/s (Jeppsson *et al*. 2008).

Figure 1. Lillgrund wind farm – an overview.).

The wind farm was available for production for 99% of the time during the years 2008 to 2010, when the studies on the fish populations were primarily carried out (May up to and including November). In the remaining periods, there was no production, or the wind farm even used small amounts of energy. Figure 2 is an illustration of the production over time. The soundscape under the surface of the water around the wind farm reflects the wind farm's production up to capacity.

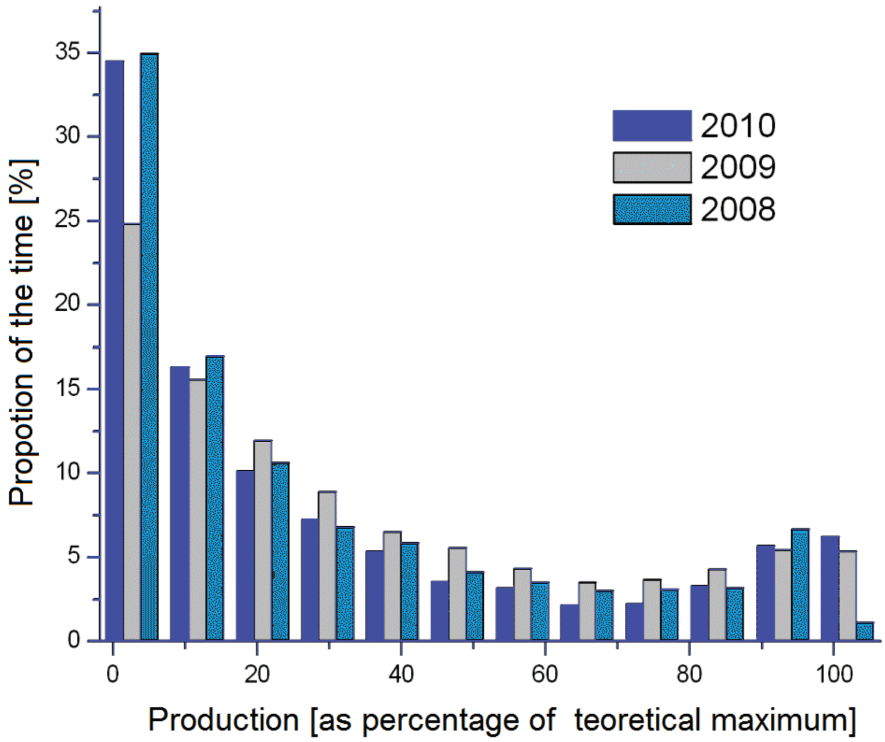


Figure 2. Production (% of the maximum) from the whole wind farm at Lillgrund, during the months of May to November (7 months), i.e. the main period when fish studies were carried out in the area, for the years 2008–2010 (from productivity data from Vattenfall for the wind farm).

# Final Report

The studies in this project have partly been integrated with the studies undertaken as a part of the research programme Vindval, which is financed by the Swedish Energy Agency. The final report has been coordinated with equivalent studies within the Vindval Research Programme, by including summarised results from the Vindval Research Programme in this report (bottom-dwelling fish), or by analysing all the data from both studies together (acoustics, fish migration).

The first chapter of the report covers the soundscape in the Öresund Strait and how fish perceive and react to noise. This is followed by a presentation of the results for benthic, bottom-dwelling fish species, which to a large extent are stationary and are thus more greatly affected than pelagic, open-water living fish species as a consequence of the altered sea bed structure. After the chapter on pelagic fish species, there is a chapter that discusses the effects of the wind farm on the migrating eels, silver eels. Eels that spawn in the Sargasso Sea have a very long migration route from the Swedish coast/Baltic Sea, which is why any disturbance of this migration can be of great significance in terms of whether the fish arrive or not. The report finishes with an overarching discussion where the different studies are weaved together and discussed within a wider context.

# Acoustics

## Introduction

Fish use sound for several biological functions such as to find food, for advanced warning of approaching predators or to find partners (Hawkins 1993). Many fish can create sound with the help of muscles, by vibrating their swim bladder or by grinding their teeth or rubbing their fin rays together. This has the aim of driving away rivals or attracting partners (Bass & Ladich 2008; Kasuman 2008). Sound in the sea can also provide fish with spatial perception, which eases orientation when breaking waves and biological noise created by marine organisms provide information on the coastline and reef or current wind direction. (Lagardère *et al.* 1994; Simpson *et al.* 2005; Fay 2009). The increase in industrial activities e.g. shipping traffic, seismic studies, construction and operation of offshore energy sources as well as military activities at sea, have led to a general increase in underwater noise levels over the last hundred years (Ainslie *et al.* 2009; Hildebrand 2009; Kikuchi 2010). It is very important that these sources of noise and their impact on the marine environment are studied so that the already hard pressed aquatic ecosystems do not suffer further. In recent years, offshore wind power has attracted significant attention due to the fact that wind turbines have been built in areas close to the shore with high biodiversity. The turbines differ from other sources of noise because they generate noise continuously when in operation, although the noise varies, in level and frequency, as a function of wind speed, and they will stand in the same location for at least 20 years. (Wahlberg & Westerberg 2005; Madsen *et al.* 2006; Wilhelmsson *et al.* 2010). The underwater noise generated by offshore wind farms may have an impact on fish if the noise is sufficiently high and overlaps with those frequencies which fish use (Slabbekoorn *et al.* 2010).

In order to assess the significance of noise and vibration from an offshore wind farm for fish, the following questions were formulated:

1. What frequencies and noise levels are generated by Lillgrund wind farm?
2. How much does the wind farm contribute to the current soundscape in the Öresund Strait?
3. At what distances can cod, herring and European eel detect noise from the wind farm?
4. Are the noise levels sufficiently high as to directly result in injury to the fish or to have an impact on their behaviour?

To provide a background to the assessments, a brief review of fish hearing and how fish react to sound, as well as the general soundscape in the Öresund area close to the wind farm are presented.

This project was largely financed by the Vindval Research Programme (almost 90 %) and to a lesser extent by Vattenfall (just over 10 %). A detailed description of the methods used and results are provided in the Vindval Research Programme report (Andersson *et al.* 2011).

## Fish Hearing

Sound energy propagates through water via particle motion and these movements create longitudinal pressure differences where the medium is compressed and decompressed, resulting in pressure fluctuations. Sound propagation moves much faster and with much less propagation loss in water than in air. All fish can sense particle motion, but only fish with a swim bladder can sense pressure changes. The body of a fish has roughly the same density as the surrounding water, which means that the fish will move in concert with the sound waves in the water. The inner ear of a fish contains calcium carbonate stones called otoliths, which rest on hair cells (figure 3). When the fish vibrates in the sound waves, the otoliths move at a different pace to the rest of the fish due to the fact that they have a higher density. This creates a differential movement between the hair cells and the otolith and this difference in motion is interpreted as sound (vibrations). The physiology of fish thus means that they are primarily sensitive to the particle motion (or acceleration) created by sound rather than the changes in pressure (Kalmijn 1988, Popper & Fay 2010).

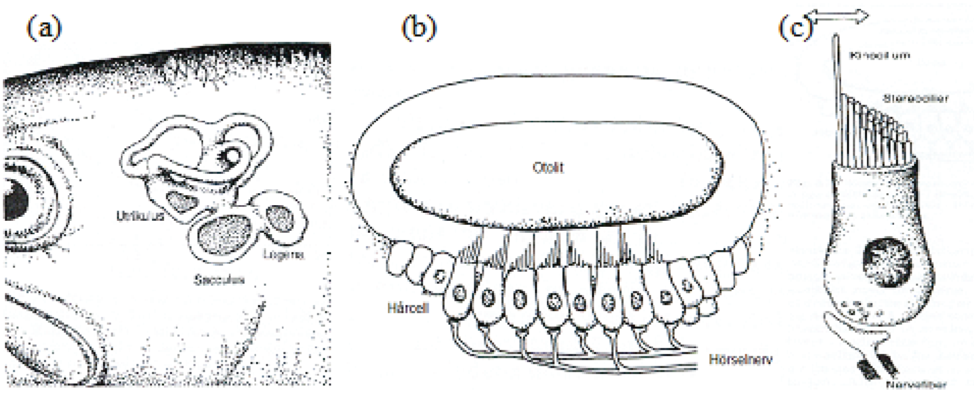


Figure 3. The inner ear of a fish. (a) The location of the inner ear within the head of a fish, with the three semi-circular canals and three otolithic organs (utricle, saccule and legena). (b) A cross section of an otolithic organ with the liquid-filled membrane sac, the hard otholith and hair cells with sensory hairs. (c) Hair cell with sensory hair (one kinocilium and several shorter stereocilia) and a sensory nerve receptor. The figures are modified from Sand (1992).

When fish that have a swim bladder are exposed to a sound wave, there is a consequent pulsation through the swim bladder. The movement in the swim bladder is transferred to the otoliths via a mechanical connection and is registered as sound. Fish are thus sensitive to the particles of the sound field as well as the pressure component. How well fish can register sound pressure varies between species as there is a large anatomical variation in the location of the swim bladder relative to the otoliths. If the fish have a mechanical connection between the swim bladder and the inner ear, this normally results in an increased sensitivity both with regard to the frequency and the strength of the sound (Popper & Fay 2010). The anatomical differences result in a large variation in how well fish register sound, which is illustrated in figure 4 where the audiogramme (auditory threshold values) for different species of fish are compared. Herring *(Clupea harengus)* and goldfish *(Carassius auratus)* are both species of fish which have a special connection between the swim bladder and inner ear which means that they represent some of the species of fish with the best auditory sense. Salmon *(Salmo salar)* and eel *(Anguilla anguilla)* have their swim bladder located further back in their body than cod *(Gadus morhua)* and thus they have a lower auditory threshold value, i.e. they have poorer hearing. The lack of connection between the swim bladder and the inner ear means that salmon, eel and cod do not hear sounds with a frequency higher than 400 Hz and have a generally higher auditory threshold compared with herring and goldfish. As figure 4 highlights, the auditory threshold can vary by around 40 dB between species, which means that care needs to be taken when making generalisations. Sound is measured in the logarithmic scale decibel (dB) which is related to pressure (Pascal) in water with the help of reference values 1μPa. It is worth noting that there is also a variation of several decibels for the threshold values within a species. The values presented in figure 4 are the average values for a number of fish within each species.

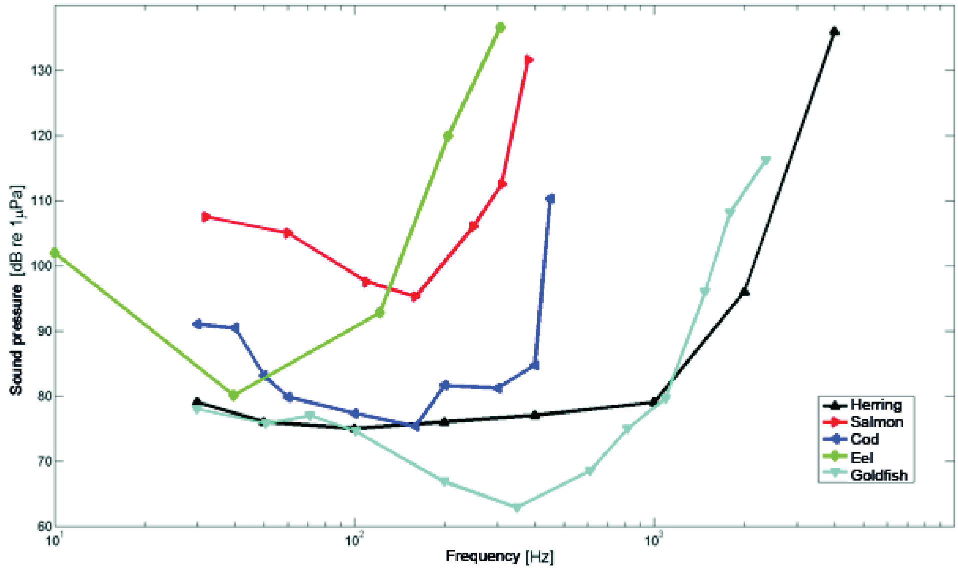


Figure 4. Auditory sensitivity related to sound pressure for a number of species of fish. Black for herring *(Clupea harengus)* (Enger 1967), red for salmon *(Salmo salar)* (Hawkins & Johnston 1978), blue for cod *(Gadus morhua)* (Chapman & Hawkins 1973), green for eel *(Anguilla anguilla)* (Jerkø *et al.* 1989) and magenta for goldfish *(Carassius auratus)* (Fay 1969). The variation in sensitivity for both frequency and sound intensity depends on anatomical differences between species. The figure is modified from Andersson *et al.* (2011).

Fish lacking a swim bladder e.g. many bottom dwelling species such as flat fish and fast swimming pelagic species such as mackerel *(Scomber scombrus)*, can only detect sound with the help of their inner ear. This limits their ability to hear frequencies to between one to 400 Hz (Enger *et al.*, 1993; Horodysky *et al.*, 2008). Fish have roughly the same sensitivity for vibrations with a threshold value which lies between 10–4 to 10–5 m/s² for frequency intervals of between one and 400 Hz. Figure 5 shows the sensitivity for plaice *(Pleuronectes platessa)* which has no swim bladder and cod, salmon and perch *(Perca fluviatilis)* all of which have swim bladders. There is a variation in threshold values for different fish species, both for sound pressure and movement, because there are differences between individuals but also between studies. One example is cod in figure 5, where studies of the sensitivity for vibrations from 0.1 to 20 Hz was carried out by Sand & Karlsen (1986) and for 20 to 400 Hz by Chapman & Hawkins (1973). The results do not overlap with one another like for plaice, but Sand & Karlsen (1986) explain this by the fact that there are different levels of background noise in the two studies.

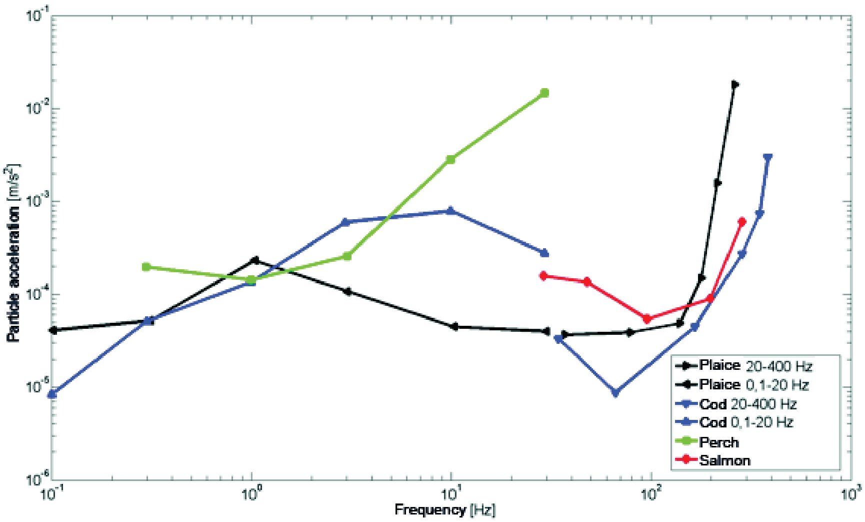


Figure 5. Hearing sensitivity in terms of particle acceleration in red for plaice *(Pleuronectes platessa)* (Karlsen 1992a and Chapman & Sand 1974) and in blue for cod *(Gadus morhua)* (Sand & Karlsen 1986 and Chapman & Hawkins 1973) presented in two different studies, in green for perch *(Perca fluviatilis)* (Karlsen 1992b) and in red salmon *(Salmo salar)* (Hawkins & Johnston 1978). Sensitivity is relatively similar for the majority of species from 1 to 400 Hz. The figure has been modified from Andersson et al. (2011).

Acceleration detection dominates the sound detection at frequencies below roughly 50 Hz (Chapman & Hawkins 1973) whilst pressure detection is more effective at the resonance frequency of the swim bladder (around a few hundred Hertz). The ability to locate the source of the sound has been studied for fish both with and without a swim bladder (Chapman & Hawkins 1973; Schuijf & Buwalda 1980). Cod have been shown to also be able to detect the distance to the source of noise in the acoustic near field (Schuijf & Hawkins 1983). This is a unique quality amongst fish which should give them a three dimensional sound image of the surroundings. The underlying mechanisms for this, have however, not been completely investigated, but the hair cells which react to the movement of the otoliths have some polarity, which help the fish to locate the source of the sound. Studies on plainfin midshipman *(Porichthys notatus)* and for round goby *(Neogobius melanostomus),* showed that the fish quickly adjust to the acoustic sound field direction which is related to the particle motion gradient. (Rollo *et al.* 2007; Zeddis *et al.* 2010). At close range, the fish lateral line can also detect movement. The lateral line consists of canals with hair cells (neuromasts) and of independent hair cells on the surface of their body. The lateral line system of a fish is an organ not usually used to detect acoustic signals, but to detect localised water currents around the fish, but it helps to increase the acoustic resolution in the near field. (Coombs & Braun 2003, Webb *et al.* 2008).

Animals integrate audio signals over a short period of time (from a couple of milliseconds to around a hundredth of a millisecond). Integration occurs not only over time, but also within a specific frequency band, the so-called critical band (Fay 1991). The width of the critical band in fish has only been calculated for a few species (goldfish by Enger 1973; cod by Hawkins & Chapman 1975; and salmon by Hawkins & Johnstone 1978). The width of the critical band determines how broadband sound sources should be treated spectrally, to calculate how the noise levels are perceived. A rough estimate which is often used for vertebrates, is that the critical band follows the technically well-defined 1/3 octave band. See Wahlberg & Westerberg (2005) for a more in-depth discussion regarding how fish detect broadband signals.

Sound propagation in water occurs with significantly less propagation losses and at a higher speed than in air. There are several basic differences between pressure and motion. Particle acceleration for example contains information about the direction of the sound wave. In addition, the propagation loss is different for pressure and acceleration close to the source of a sound. In the so-called acoustic near field (a distance that is dependent upon the size of the sound as well as the frequency and speed of the sound), sound pressure and particle motion are not related to one another; the latter decreases more quickly with distance than the former. In the far field the relationship between the pressure and the acceleration component is proportional. In open water, the relationship between the two components is relatively well known, which means that the acceleration component can be determined from pressure measurements, whilst they need to be quantified separately in shallow seas.

## How Fish are Affected by Noise

Despite the fact that studies on how fish react to noise began early in the 1900s, we still have a relatively poor understanding of how sensitive fish are to noise. It is only in recent years, with the help of new technology for measuring sound that the effects of noise on fish have begun to be investigated. There are however, still large knowledge gaps, and in view of the large variation of species within the bony fish group, it is difficult to generalise the results.

Certain types of noise such as piling noises, seismic explorations (compressed air guns) and explosions can generate very high noise levels over a short period of time in the water. When fish are exposed to these noise levels they can suffer permanent (PTS – Permanent Threshold Shift) or temporary (TTS – Temporary Threshold Shift) hearing damage where the sensory hairs are wrenched away from the inner ear sensory epithelium of the fish. If the fish is situated close to the source of the noise, they can die as a consequence of the damage to the inner organs and swim bladder (Popper & Hastings, 2009). Some studies have noted that the sensory hairs regrow, but contrasting results have also been described in other studies (McCauley *et al.* 2003; Smith *et al.* 2006). Fish hearing can be damaged in a similar way as a consequence of long-term exposure to lower levels of noise. In a study with white noise with sound levels just above 140 dB re 1μPa (RMS), injuries similar to those as a consequence of short term exposure to loud noises were observed for 0.3–4.0 kHz (Scholik & Yan 2001). Even if recovery occurs, the fish experiences a period with an impaired hearing ability which can have an impact on their ability to survive.

In addition to physiological damage, studies have shown that a number of fish species exhibit escape behaviour from powerful noises. At sudden exposure and to unknown noises, the majority of fish react even to low intensity sounds.

Studies have shown escape behaviour in herring and cod in relation to research vessels, seismic investigation and piling noises (Olsen 1971, Engås *et al.* 1996; Muller-Blenkle *et al.* 2010). In many cases, the reaction occurs as soon as the sound can be differentiated from the background noise, but in other cases the sound generated must be above the background noise (Chapman & Hawkins 1973). The operational noise from an offshore wind turbine differs in character from the above mentioned noise because the noise is continuous, in contrast to piling noise which consists of loud pulses and ships which come and go. The noise level and frequency varies however, for a wind turbine, as a function of the wind speed. There is currently no research that has been carried out in the field, on how fish react to the operational noise from a wind turbine. Recorded wind turbine noise replayed in an aquarium has shown clear behaviour reactions to the noise at varying sound levels (Müller 2007; Andersson *et al.* 2007). Even if escape behaviour has been discovered for a number of fish species, it is unclear whether this has any significance for fish at a population level, i.e. their ability to survive and reproduce. Fish are able to become accustomed to noise, that is not too high and that is not associated with danger. Short visits to a location with elevated noise levels can however have negative consequences for a fish and it is not always escape behaviour that is the only reaction that indicates that fish are disturbed (Bejder *et al.* 2009). Fish have been shown to become stressed when they find themselves in an environment that is constantly noisy, which in turn could lead to lower growth rates (Sun *et al.* 2001; Davidson *et al.* 2009) but stress can potentially also disturb reproduction (Pickering 1993). The greatest gap in current knowledge is how eggs and larvae are affected by noise. They lack the ability to escape from a disturbing noise and are therefore more vulnerable than adult fish (Popper & Hastings 2009). In addition, there are no current studies which show whether the operational noise could mask acoustic communication, such as during reproduction (Slabbekoorn *et al.* 2010). Studies have however shown that noise from boat traffic can mask the communication in vocalising fish species (Codarin *et al.* 2009). As a comparison to the noise levels from a wind turbine, studies have shown that cod can generate grunts at roughly 120 to 133 dB re 1µPa at a distance of 1 m (Hawkins & Rasmussen 1978; Nordeide & Kjellsby 1999).

### General Noise Environment in the Öresund Strait

The underwater noise environment in the Öresund Strait is dominated by intensive shipping traffic where more than 36 900 commercial ships (oil tankers, container ships, passenger ferries and fishing boats) pass through the area each year (Sjöfartsverket 2008). These figures are based on AIS (Automatic Identification System) data from the Swedish Maritime Administration and include all ships of more than 300 tonnes. Other boat traffic, such as pleasure boats, is thus not included. This intensive traffic creates a constant noise level below 1 kHz. The noise level below 150 Hz varies a great deal because the sound propagation is influenced by the shallow depths in the Öresund area. In addition to the shipping traffic, there are also seismic investigations of the seabed, military activities as well as a huge fleet of pleasure boats which contribute to the sound environment. The Öresund Bridge has also been shown to contribute to the sound environment in the area. Each day a numerous cars and trains pass across the bridge and vibrations from these passages are transmitted via the pillars of the bridge into the water. The noise levels when a train passes over has been measured to between 110 dB – 120 dB re 1µPa$_{(RMS)}$ at 50 m from the bridge pillars with the majority of the energy below 500 Hz (Appelberg *et al.* 2005). The majority of the sources of the sound described above, generate sound below 1 kHz, which coincides with the frequency where the majority of fish have the best hearing and generate sound themselves (Slabbekoorn *et al.* 2010). Natural sounds also contribute to the sound environment, such as rain and wave action, but also biological sounds produced by fish and marine mammals. These biological sounds are likely to be negligible compared with the artificial sounds in the Öresund region.

## Noise Production from Wind Turbines in Water

There was no pile-driving carried out during the building phase of Lillgrund wind farm, but dredging occurred at a number of places before the gravitational foundations were put in place. Noise was generated from the ship during dredging but also from the dredging activities when a suction device, bucket or other piece of equipment hit the bottom to take up material from the bottom to the surface and put it on a nearby barge. The noise consists of both short, loud pulses of noise and more broadband sound. No sound measurements were made during the construction phase for Lillgrund, but measurements from similar dredging activities in England and the USA showed sound levels up to 120–140 dB re 1µPa$_{(RMS)}$ at distances of 150 m for frequencies below 1 kHz (Clarke *et al.* 2002) and 140 dB re 1µPa$^2$ at distances of 100 m for 125 Hz centre frequency above 1/3-octave band (Robinson *et al.* 2011).

When the wind turbine is in place and in operation, the majority of the noise is generated in the form of vibrations inside the turbine, emanating from the gear box and generator, which are transmitted via the turbine and foundations into the water. The noise that is generated by the blades is largely deflected by the surface of the water (Lindell, 2003; Sigray *et al.* 2009). Previous studies carried out in European waters have shown that offshore wind farms generate a broadband sound with a few powerful tones (see cited references in Madsen *et al.* 2006 and measurements in Lindell 2003; Tougaard & Damsgaard-Henriksen 2009). There seems to be a wide variation in the calculated noise levels between different wind farms. The noise levels which are given in different studies for the dominating tone component (25 to 180 Hz) lies between 120 and 150 dB re 1µPa$_{(RMS)}$ at a distance of 1 m from the turbine. These values originate from measurements from both gravitational foundations of concrete and monopile foundations made of steel. The differences observed cannot only be attributed to the different types of foundation but rather are probably dependant on the type and age of the turbine and the size of the turbine as well as the foundation. The noise level is however in general always related to the wind speed because wind turbines rotate more quickly at higher wind speeds.

The highest levels of particle acceleration measured from Utgrunden wind farm reached 0.018 m/s$^2$ at 1 m (integrated across 2–200 Hz) at 5 m/s, and somewhat higher than 0.010 m/s$^2$ (integrated across 2–200 Hz) at 11 m/s (Sigray *et al.* 2009). This is the first time that particle acceleration has been measured at a wind turbine. The noise levels measured are in line with what other studies have shown to induce changes in fish behaviour (Knudsen *et al.* 1992; Karlsen *et al.* 2004; Sonny *et al.* 2006). The levels reduce quickly with distance, and already at 10–20 m from the wind turbine, the noise is drowned out by the natural background sound from the sea. It can justifiably be assumed that the particle acceleration at Lillgrund is of the same order as Utgrund, and this aspect is therefore not discussed further in this study.

How quickly the noise level from a wind turbine dissipates, as a function of distance, depends on several factors. The single most important factor is the character of the material on the sea bed and if there are noise channels, such as created by shallow water or in thermoclines, which trap the sound and mean that it can travel further than would otherwise be the case. This is why sound can travel further in shallow water than in deeper water. In areas of shallow water, the sound propagates cylindrically and it is often assumed that the sound pressure decreases by 10·log (distance). In deep water, sound spreads spherically and it is usually assumed that the sound pressure reduces by 20·log (distance) (Urick 1983). The real environment is however, often more complex, which makes calculations of the noise levels more difficult, but measurements supported by modelling provides a relatively good picture of the sound levels as a function of different distances from a wind farm. Wind farms consist of several turbines and each individual contributes to the total soundscape. It is therefore important to measure both close to the individual turbines as well as at longer distances to measure the contribution of the entire wind farm. There is otherwise a significant risk that the total noise level from a wind farm is underestimated.

# Method

## Acoustic Equipment and Implementation

In May 2008, a pilot study was undertaken to study the noise pattern at Lillgrund wind farm. A hydrophone (Brüel & Kjær 8101 with a sensitivity of–184 dB re 1V/1µPa in the frequency region 1 Hz to 125 kHz) (figure 6a) was mounted on a tripod and deployed with a boat as a base. Measurements were taken at several distances from the turbines both within and on the outskirts of the wind farm. The results showed a variation in the noise levels due to large variations in wind speed and wind direction.

In order to obtain a better understanding of the sound environment in the Öresund area as well as within and outside of the wind farm, additional noise measurements were made in November 2009 as well as during the period May to June 2010. The Brüel & Kjær hydrophone system was placed 80 m south of the turbine A07 (N55° 30’ 010 E12° 46’ 935) and was connected via a cable to a receiver system inside of the turbine A07 where an amplifier, filter and a computer were stored. The computer was used for storing data but was also connected to a modem so that the system could be managed remotely (figure 6b). The whole system was connected to the local electrical network for power and was programmed to record sound for five minutes, every 30 minutes for five weeks. In addition, a battery-driven hydrophone system, DSG-Ocean (sensitivity -185.6 dB re 1V/uPa in the frequency region 2 Hz–37 kHz) (figure 6c), was moved around and placed at different distances (80, 160, 400 and

1000 m) from wind turbine A07 and from the entire wind farm. The DSG-system was programmed to record over the same five minutes every 30 minutes as the Brüel & Kjær system. Both systems recorded with a speed of 25 kHz. Due to the fact that no sound measurements were made before the wind farm was built, measurements of the underwater sound levels were also carried out at Sjollen (N55° 36' 024 E12° 52' 635), one of the reference sites for fish sampling within the monitoring programme. This site is situated 10 km north of the wind farm and has similar conditions on the sea bed and depth as the wind farm area. It is also affected by the same shipping channel, Flintrännan, which passes Lillgrund. A hand-held GPS was used when placing out the hydrophones at the planned locations. Vibration measurements within the turbines A01 and A07 and data regarding wind speed and direction as well as electricity production for the individual turbines was provided by Vattenfall Wind Power Data Centre in Denmark. For a more detailed description of the measuring equipment and implementation, see Andersson *et al.* (2011).

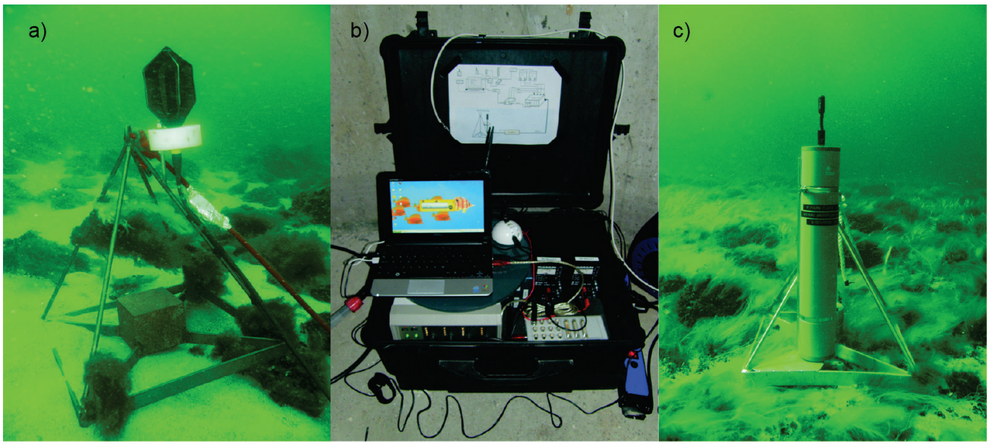


Figure 6. Acoustic measuring systems used at Lillgrund. (a) Brüel & Kjær 8101 hydrophone on a tripod, connected to a boat via a cable and later into a turbine, (b) Receiver equipment from inside a turbine with an amplifier, filter and a computer for storing the data which was also connected to a modem, so that it could be managed remotely, (c) DSG-Ocean hydrophone which is battery-driven and was moved around, within and outside of the wind farm. Photo: Mathias H. Andersson.

## Data Analysis

In total, more than 300 hours of underwater sound was recorded during the study. The data was collated according to wind speed (0–2 m/s, 3–6 m/s, 7–9 m/s and 10–14 m/s). The data was then analysed to determine the passage of ships in the vicinity. This was carried out to differentiate the noise from the wind farm from other sounds in the Öresund Strait, as well as to establish the natural sound environment for the Öresund area without any contribution from nearby ships. All data was analysed with the help of the acoustic programme Raven and MatLab® (MathWorks). The first analyses showed that all turbines contributed noise, and that the estimate of the noise levels at longer distances would be incorrect if only based on the measurements taken close to an individual turbine. A numerical model was developed instead, which was based on and verified with the actual measurements. The model treated all 48 turbines as individual sources of noise and the model parameter was the production efficiency of the wind farm (in percentage) defined by the relationship between the actual electricity production and the maximum possible electricity production of the wind farm. On the basis of the varying distance measurements, the sound propagation was also calculated in the area. The acoustic energy was integrated over different frequency intervals in order to study the contribution to the Öresund sound environment both with regard to broadband sound and dominant tones. The sound level is presented at RMS (Root-Mean-Square) values in the units dB re 1µPa$_{(RMS)}$.

The noise levels in the Öresund Strait vary hugely over time due to the shipping traffic in the shipping channel, which is situated 600 m from the recording station at Sjollen. This variation in soundscape was quantified for the two weeks when the DSG-Ocean system was placed out at Sjollen at the same time as the Brüel & Kjær system was located 80 m from A07. The recordings from Sjollen collected data from a number of passing ships, and with the help of these, a shipping model which described the noise levels from the shipping channel was developed. Due to the fact that on average, four ships an hour passed by, with an average speed of ten knots, the contribution to the total soundscape from the shipping lane was significant and was characterised as a linear source. In addition, the noise level from the wind turbines was calculated for the most dominant tone from the wind farm. This was compared with the audiogramme for herring, cod, salmon and eel, to estimate at what distance the fish would be able to detect the noise from the wind turbines. These species represent the fish species with different types of hearing abilities and are common species in the wind farm area, with the exception of salmon. For a more detailed description of the models and the data analysis, see Andersson *et al.* (2011).

In order to further evaluate the correlation between noise levels and presence of fish in the wind farm area, estimates for the actual sound levels at each position where fish sampling using fyke nets was carried out in 2010, were calculated. This was carried out with the help of the sound propagation model developed for Lillgrund wind farm. The noise level in the model was estimated based on a calculated average production level for that 24 hour period and respective fyke net that was in the water, on the basis of data regarding the prevailing wind and operative conditions. This provided a rough estimate of the average noise level in the vicinity of the location of the fish sampling, even if the actual noise level could vary to some extent over the 24 hour period as a function of the variation in wind strength. The correlation with the presence of fish studied is described below, in the chapter on benthic fish in this report.

# Results

## Ambient Noise at Sjollen

551 recordings were made, over the 12 days that the DSG-Ocean system was placed out at Sjollen, 600 m from the shipping channel Flintrännan. The analysis showed that there was a wide variation in the noise levels over time. The noise levels increased significantly when a ship passed as well as when it was very windy (thin green lines, figure 7). The average noise level was

calculated for all recordings (black line, figure 7). On the days when measurements were recorded, the wind strength varied from 0 to 15 m/s. The noise generated by the ships, was clearly the most dominant noise in the area in the frequency between 20–1000 Hz whilst the soundscape below 20 Hz was dominated by sounds generated by waves. (In figure 7, there is a clear "hump" between 30–150 Hz generated by a ship and was only obvious when a ship passed the hydrophone at a distance of less than one kilometre. The second hump, between 150–800 Hz is due to ships that are further away and is present in virtually all recordings). Between 800–1000 Hz the sound level sank. It has not been possible to explain this result, but it may be an instrument effect. An integration of the acoustic energy between 20–4000 Hz showed that the measured average sound pressure for each five minute period of recording varied to between 85 and 118 dB re 1 $\mu Pa_{(RMS)}$ during the period of measurement at Sjollen.

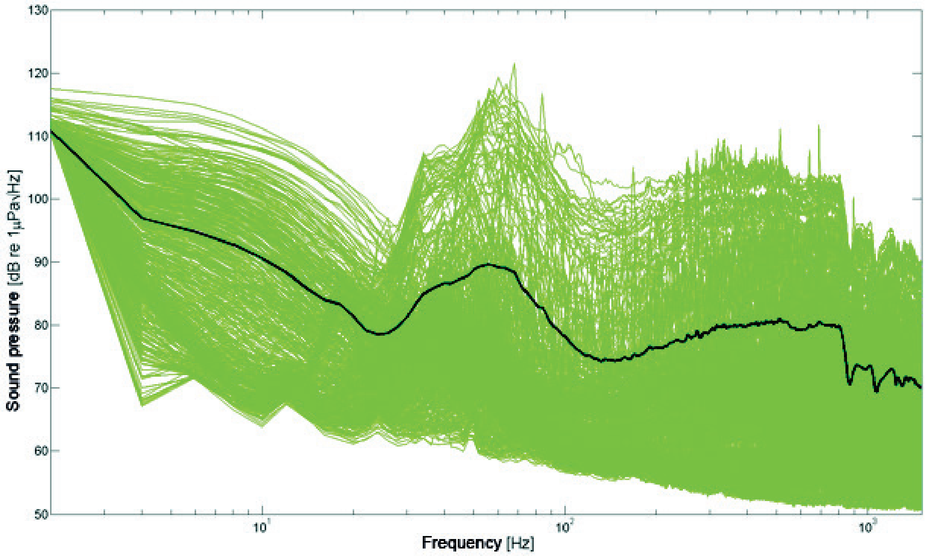


Figure 7. Power density spectra from sound recordings at Sjollen between the 27th May and 8th June, 2010.The thin green lines are the calculated spectra for each five minute recording and the black line is the calculated mean for all recordings. The DSG-Ocean hydrophone was located 600 m to the southeast of the Flintrännan shipping lane. The spectra were calculated at 1 s intervals which then created a mean value for the five minute period. The figure is adapted from Andersson *et al.* (2011). See the text below, for more explanation.

Some of the ships that passed Sjollen during the recording period were studied in detail and the noise level generated as a function of distance was calculated based on AIS data. The results showed that the ships generated different noise levels depending on size, speed and the type of ship (table 2). The data was integrated across the frequency interval of 20–4000 when the ships were at their closest (CPA) to the location of the DSG-Ocean at Sjollen. The source level at 1 m was established by assuming a propagation loss of 17·log (distance) (see below). A calculation of the noise level for the service boat (Lillgrund) which is used by Vattenfall in their daily activities at the wind farm was also made (table 2). High noise levels were created locally when the service boat moored up to a foundation and dropped off technicians.

Table 2. Noise levels (re 1 µPa$_{(RMS)}$) of ships at Sjollen and the service boat at Lillgrund. The data is integrated across different frequency intervals (Hz) for one minute of recorded sound when the ship was closest to the hydrophone. The source level at one metre is calculated with a propagation loss of 17·log (distance). Data regarding the identification number of the ship (MMSI), their position and speed was recorded at an AIS located in Limhamn. The levels were calculated at 2.6 s intervals which created a mean value over one minute. The table is amended from Andersson *et al.* (2011).

| | Type of ship | MMSI | Speed | Dist. to hydrophone | Measured sound level | Measured sound level | Calculated sound level at 1 m | Calculated sound level at 1 m |
|---|---|---|---|---|---|---|---|---|
| | | number | (knots) | (m) | 20–4000 (Hz) | 123–132 (Hz) | 20–4000 (Hz) | 123–132 (Hz) |
| Lillgrund | Service boat | 219010942 | 9 | 30 | 124 | 89 | 149 | 114 |
| Finnpartner | Passenger ferry | 266262000 | 12 | 550 | 133 | 102 | 180 | 149 |
| Viscaria | Tanker | 258897000 | 10 | 630 | 121 | 74 | 169 | 122 |
| Finneagle | Passenger ferry | 265740000 | 11 | 620 | 129 | 99 | 176 | 146 |

## Wind Turbine Noise

The turbine A07 generated a broadband sound underwater, with a few obvious tones, when running at full capacity (2.3 MW; figure 8). Four tones; 10, 40, 127 and 533 Hz were confirmed by measurements of the vibrations in the turbine of A07, whereas the two other tones, 70 and 95 Hz probably come from other turbines nearby. Noise and vibration measurements from turbine A01 showed that the same frequencies were generated by A01. At lower wind speeds, tones at a somewhat lower frequency were also generated. This was interpreted as that the tones changed frequency according to varying wind speeds. The lowest tones; 10 and 40 Hz, lie within a range with a lot of ambient noise as well as electromagnetic disturbance, which made the analysis of the combined noise level more difficult. These tones, along with the 533 Hz tone, are however weak in comparison with the 127 Hz tone. In the subsequent analyses, the acoustic energy in the frequency range 123–132 Hz and 52–343 Hz were integrated respectively. The first interval captures the 127 tone and its variation, whilst the other captures the frequency range within which the wind farm dominates the soundscape.

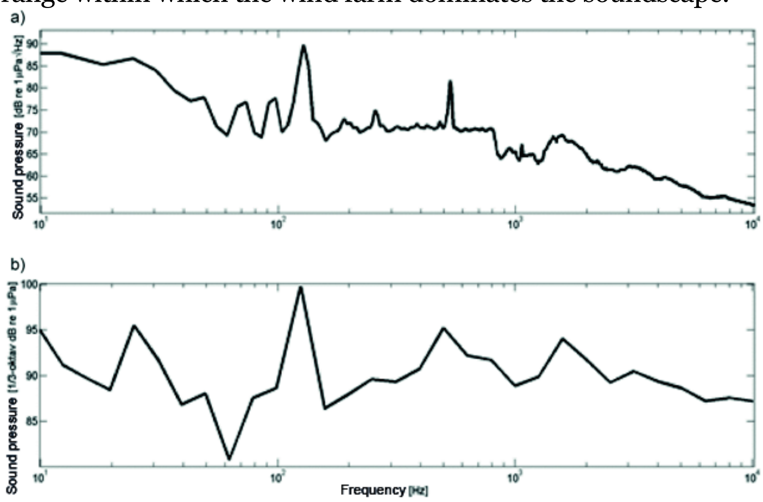


Figure 8. Power density spectra from a five minute recording, 160 m from turbine A07 measured using the DSG-Ocean system. (a) Sound pressure in Hz and (b) sound pressure integrated across the 1/3-octave band. The wind speed at the time of recording was 12.6 m/s and A07 was running at full effect (2,3 MW) whilst the wind park as a whole was running at 67 %. The spectra were calculated at 0.4 s intervals which calculated a mean value over five minutes. The figures are amended from Andersson *et al.* (2011).

The noise level was also found to vary over time at the wind farm. This situation can be seen clearly in figure 9 where each line represents one power spectrum for each and every one of the 551 recordings that were made with the Brüel & Kjær hydrophone system situated 80 m from turbine A07 between the 27th May and 8th June (the black line is the calculated mean of all the spectra). The 127 Hz tone is clearly seen in the individual spectra and the calculated mean value. The obvious peaks in the curves at 50, 100, and 150 Hz are from electromagnetic disturbance from the electricity network that the system has picked up and is therefore not related to the noise in the water.

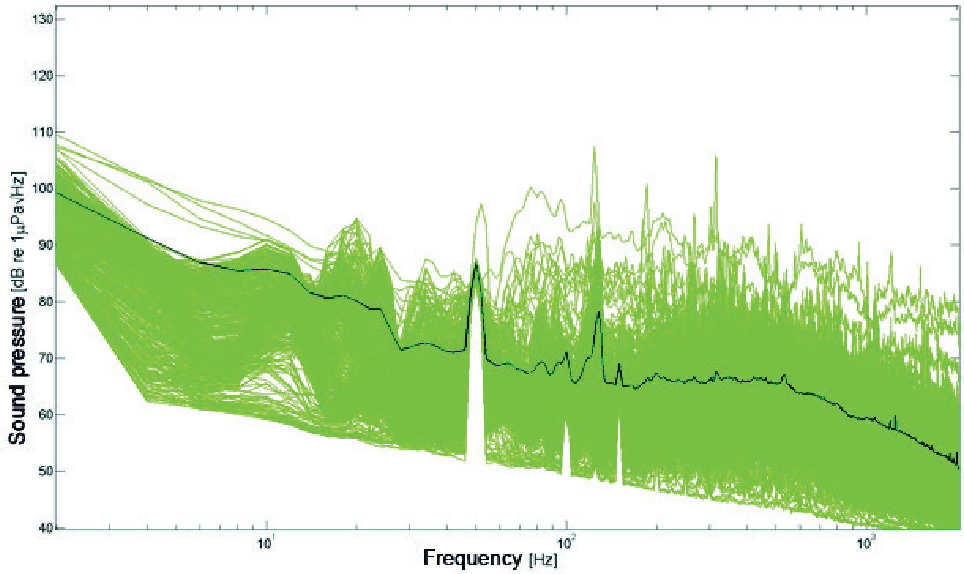


Figure 9. Power density spectra from the sound measurements taken 80 m from the turbine A07 recorded between the 27th May and 8th June 2010. The thin green lines are the calculated spectra for the 551 (5 minute) recordings and the thick black line is the calculated mean value. The spectra were calculated at 1 s intervals which then created a mean value for the five minute period. The recordings were carried out using the Brüel & Kjær hydrophone system and the obvious peaks at 50 Hz, 100 Hz and 150 Hz are electromagnetic disturbance and are not related to the noise in the sea. The figure is amended from Andersson *et al.* (2011).

## Noise from the Entire Wind Farm

With the help of measurements made at different distances from the turbine A07, the sound propagation loss for the area as a whole was calculated. The analysis showed that sound wave propagation could be described as being between cylindrical and spherical propagation. At short distances, < 80 m, the individual turbine dominated the sound environment and the calculated propagation loss was 17·log (distance) (figure 10). At longer distances, 80 m to 7000 m, the propagation loss was less than 17·log (distance). This can be explained by the fact that the other turbines in the wind farm contributed to the total noise levels. At even longer distances (> 7 km) the whole wind farm seemed to be a point source (the distance to the wind farm was greater than the diameter of the wind farm itself) and the propagation loss was once again 17·log (distance). The park effect is an important result because it shows a connection between the noise level and the number of turbines in a wind farm. In this case, the noise level increased by 7 dB due to the fact that there are 48 turbines in the wind farm and thus the wave propagation does not attenuate linearly (figure 10).

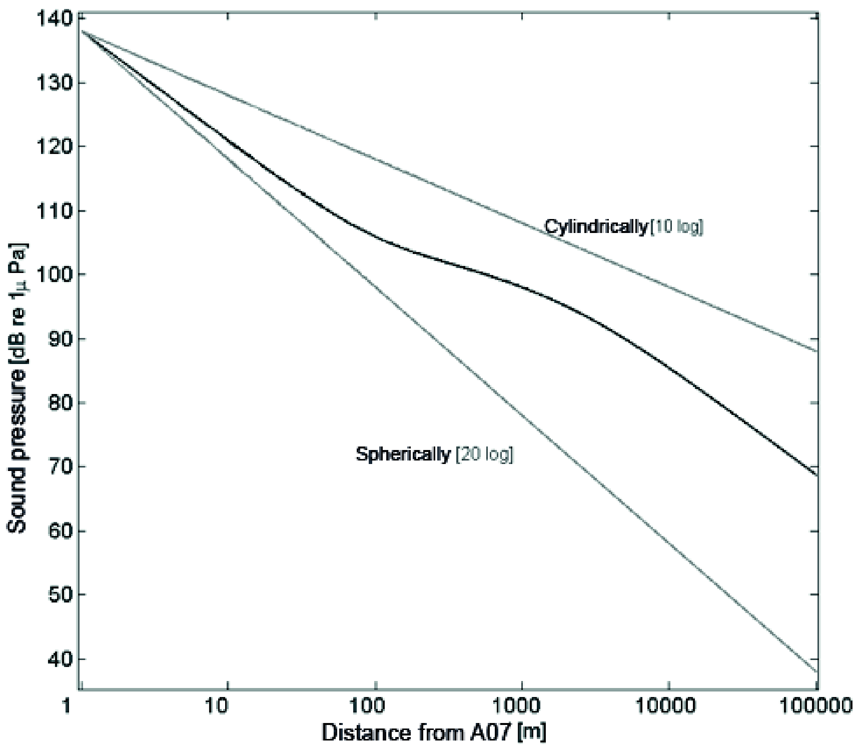


Figure 10. The calculated sound propagation as a function of the distance to turbine A07. The sound pressure is integrated across the 52–343 Hz range and is presented as RMS-values. The sound propagation is 17·log (distance), which lies between the cylindrical (10·log) and spherical (20·log) propagation. The figures are amended from Andersson *et al.* (2011).

With the help of the calculated sound propagation and the numerical model which treated all turbines as independent sound sources, the noise strength for the two frequency intervals as described above; 127 Hz tone and the full spectrum were calculated. Different production levels were used to calculate the noise levels at different wind speeds. The majority of the noise was generated as the 127 Hz tone. This situation became obvious when the source of the noise at 1 m was compared. At full production (100 %) the noise level was 136 dB re 1µPa$_{(RMS)}$ for the 127 Hz tone and 138 dB re 1µPa$_{(RMS)}$ for the full spectrum, but the ambient noise at 127 Hz was 25 dB lower (table 3). This result plays an important role when the audibility zone for fish is calculated in the next section.

Table 3. Noise levels at different distances from the wind farm and at different production levels compared with the ambient noise levels measured at Sjollen without ships in the vicinity. The sound pressure levels are given as RMS across the full spectrum and for the tone 127 Hz. The data is presented in dB re 1μPa$_{(RMS)}$. The figures are amended from Andersson *et al.* (2011).

| | Full Spectrum | 127Hz | Full Spectrum | 127Hz | Full Spectrum | 127Hz |
|---|---|---|---|---|---|---|
| Production Level | 100 % | 100 % | 80 % | 80 % | 60 % | 60 % |
| Wind Farm 1 m | 138 | 136 | 136 | 134 | 134 | 132 |
| Wind Farm 10 m | 121 | 119 | 119 | 117 | 116 | 114 |
| Wind Farm 100 m | 106 | 104 | 104 | 102 | 101 | 99 |
| Wind Farm 1000 m | 98 | 96 | 96 | 94 | 94 | 92 |
| Wind Farm 10000 m | 85 | 83 | 83 | 81 | 81 | 79 |
| Ambient Noise | 105 | 81 | 104 | 79 | 102 | 78 |

The ambient noise in the Öresund area is dominated by shipping traffic and the shipping model that was developed described the noise as a linear source. The wind farm noise levels were related to the other sounds in the area, to estimate the possible environmental effects associated with the wind farm. Comparisons showed clearly that the wind farm was the dominant sound source within an area approximately double the size of the wind farm at 100 % production (figure 11a), and only within the actual wind farm at 60 % production (figure 11c), integrated across the whole frequency spectrum. Outside of these areas, noise generated by shipping traffic dominates the sound environment. If instead, the noise level for the dominant tone of 127 Hz is compared with the ambient noise at the same frequency, the noise from the wind farm dominates across a much larger area, both at 100% and 60% production levels (figure 11bd).

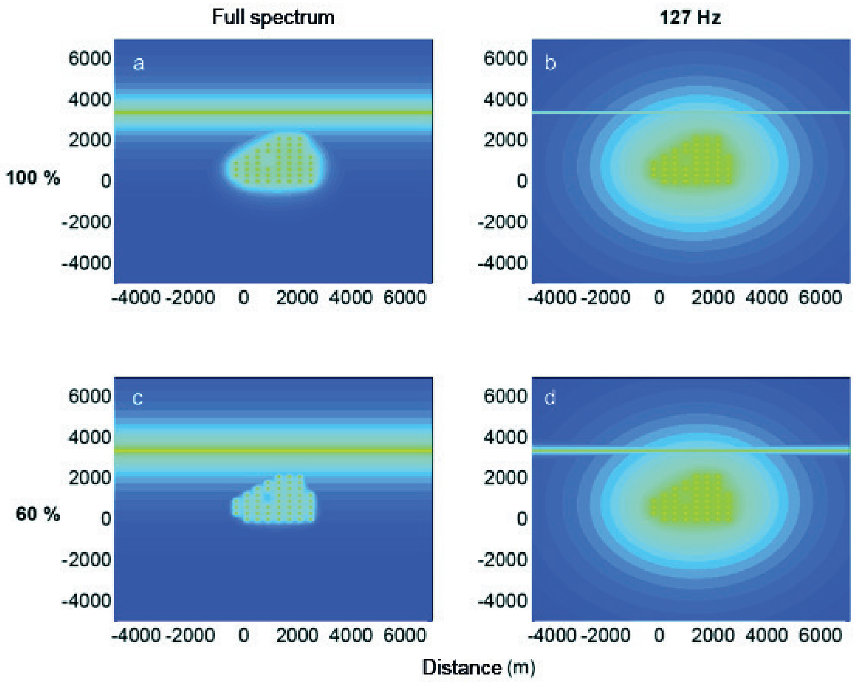


Figure 11. Numerical model of the noise generated by the wind farm in relation to the linear sound source generated by the Flintarännan shipping channel. Each yellow spot represents a turbine and the line above the wind farm represents the shipping channel. The distance scale is the distance from the A07 turbine. (a) 100 % power production, full spectrum, (b) 100 % power production, 127 Hz tone, (c) 60 % power production, full spectrum, (d) 60 % power production, 127 Hz tone. The straight lines show where the sound generated by shipping dominates the sound scape and the circular lines show where the wind farm dominates. The figures are amended from Andersson *et al.* (2011).

### What do Fish Hear?

As a consequence of the fact that different fish species have different hearing abilities, they will be able to detect noise from the wind farm at varying distances (see also the section on fish hearing). The sound analyses from the wind turbines showed that, in addition to the broadband sound, a clear tone component around 127 Hz is also generated. Due to the fact that fish can distinguish tones within a noise, values for the tone 127 Hz (136 dB re 1µPa$_{(RMS)}$ for full production, approx. 12–14 m/s and 132 dB re 1µPa$_{(RMS)}$ for 60 %, approx. 6–8 m/s) was compared with the audiogrammes for salmon, eel, cod and herring, all of which have swim bladders.

At 127 Hz, salmon and eel have a hearing threshold of 96 dB re 1µPa (figure 4). This gives a signal to noise ratio (i.e. the ratio between a signal with meaningful information and background noise) of 40 dB and 36 dB respectively for the two studied production levels. The calculation is based on the fact that the source level intensity was measured at 136 dB re 1µPa$_{(RMS)}$ at 100 % and 132 dB re 1µPa$_{(RMS)}$ at 60 % production respectively, with a threshold value of 0 dB. Based on the calculated sound propagation according to the numerical model, salmon and eel have therefore a theoretical detection threshold of the noise from the wind farm at a distance of 1km at 100% production and 250 m at 60% production. The distance at which salmon and eel can detect noise from the wind farm is thus limited by the species' own auditory ability and not the ambient noise.

For cod and herring, that have better hearing abilities than salmon and eel (75 dB re 1µPa at 127 Hz), the signal to noise ratio is 61 dB and 57 dB respectively for the two levels of production (the source level intensity was calculated to be 136 dB re 1µPa$_{(RMS)}$ for 100 % and 132 dB re 1µPa$_{(RMS)}$ for 60 % productivity respectively). This calculation assumes however, that the local environment is quiet, which is not the case in the Öresund Strait. The ambient noise in the area surrounding the wind farm, excluding the shipping traffic, is calculated to be 81 dB re 1µPa$_{(RMS)}$ at a wind speed of 12–14 m/s (100 % production) and 78 dB re 1µPa$_{(RMS)}$ at 6–8 m/s (60 % production) (table 3). On the basis of these calculations, the ambient noise in the Öresund Strait should mask the noise of the wind farm before the auditory limitations of cod and herring determines the detection distance. The theoretical detection distance would therefore be 16 km at 100% production and 13 km for 60% instead.

# Discussion

Many marine organisms use sound for different biological functions and fish are no exception. It is therefore important to investigate what noise levels are generated by human activities in the marine environment and what impact that may have on fish. In recent decades, the general noise level in our seas has increased due to factors such as increased shipping traffic and other industrial activities that generate noise under water. Offshore wind power is one of the activities that contribute unnatural sounds to the underwater environment, and it is likely that the number of wind farms will increase significantly in the future (EWEA 2010). There is currently relatively limited knowledge regarding how the noise from wind farms contribute to the general soundscape and if there are any risks of serious impacts on fish. This study describes what kind of noise

Lillgrund wind farm generates under water and discusses the possible impacts this noisecan have on some fish.

## The Contribution Made by the Wind Farm to the Soundscape in the Öresund Strait

The Öresund Strait is one of the most trafficked shipping routes in Europe, of which a large proportion is commercial traffic. As this study shows, the soundscape in the Öresund Strait is dominated by the noise generated by ships. The estimates of the source level intensity and the power spectrum from three ships which are presented in this study are in agreement with the values in the literature for other ships in the same size class (Arveson & Vendittis 2000; Hatch *et al.* 2008). Due to the fact that the Öresund area is often shallower than 10 m, the soundscape below 150 Hz will vary a great deal depending on the distance to the passing ship (Betke 2006). If a comparison of the source level for the entire spectrum from an individual ship (> 300 ton) is compared to the source level of one wind turbine, then the ship has a higher intensity, both across the full spectrum and at 127 Hz. Due to the fact that the wind farm is situated between 1 and 3 km from the Flintrännan shipping lane, the wind farm will still dominate the local noise environment, up to an area roughly double the size of the wind farm area.

Wind turbines do not just generate a broadband noise but also a clear tone around 127 Hz. This type of sound signature; a broadband noise with a dominant tone between 100–200 Hz, has also previously been described from other wind farms (Lindell 2003; Madsen *et al.*, 2006; Tougaard & Damsgaard-Henriksen 2009). The measured and calculated noise levels from this study, 136–138 dB dB re 1μPa(RMS) at maximum productivity (12–14 m/s) are also in line with previously published studies, even if both higher and lower levels have been presented. We would like to emphasise that this is the first study that has shown a park effect, where each individual turbine contributes to an increase in the total noise level in the area. At distances of more than 80 m from a turbine, the noise levels will receive a negligible contribution from other nearby turbines. Due to the sound propagation, the noise level is calculated to be reduced by 17·log (distance) at short distances (80 m) and at distances of more than 7 km, whilst the distance in between, the sound propagation is non-linear and is dependent upon the park effect.

Due to the fact that the sound energy is focused on the 127 Hz tone, the noise will reach through the otherwise shipping dominated soundscape and thus be audible to fish at relatively long distances (compare figures 7 and 2.7). For a fish in the area, its location in relation to these two dominant sources of noise: the shipping channel and the wind farm will be critical regarding which sound source it will hear. The noise levels presented in this study are therefore a snap shot of the noise levels at a specific point and if the fish is swimming in one or another direction, the relationship between the shipping channel and the wind farm will change.

## The Impact of Noise on Fish

The maximum calculated noise levels, generated by a wind turbine at full productivity (12 m/s), at a distance of 1 m was 136 dB re 1μPa$_{(RMS)}$ for the dominant tone of 127 Hz[1] tone for the turbine and 138 dB re 1µPa$_{(RMS)}$ for the full spectrum[2]. At a distance of 100 m from a turbine the levels reduced to 104–106 dB re 1µPa$_{(RMS)}$ for the full spectrum, which is close to the measured ambient noise levels in the Öresund Strait, but the noise level still lay around 23 dB above the ambient levels for the 127 Hz tone. There are currently only a limited number of studies that describe the effect different noise levels have on the behaviour of fish. The measured and calculated noise levels at Lillgrund wind farm have not been shown to result in any physical injury to fish according to other studies.

Several studies show however, that fish exhibit escape behaviour at noise levels similar to those generated by Lillgrund wind farm, but where the source of the noise is different. For example in field studies by Jørgensen *et al.* (2004) and Skaret *et al.* (2006), escape behaviour was exhibited in capelin *(Mallotus villosus)* and herring as a consequence of shipping noise with a source level of 140–150 dB re 1µPa at a distance of 1 m. Mitson (1995) suggested that cod has a reaction threshold of 30 dB above the background noise for the frequency interval 40–250 Hz for shipping noise. Furthermore, Westerberg (1994) noted an increased catch of cod, shorthorn sculpin *(Myoxocephalus scorpius)* and roach *(Rutilus rutilus)* at a distance of 100 m from a wind farm that had closed down in contrast from when it was in production when fish sampling was carried out at Svante 1 (Sweden's first offshore wind farm).

Animals can react differently depending on the species and individuals within a species (Beale & Monaghan 2004). This is exemplified by Andersson *et al.* (2007) who noted a variation in the reactions of roach *(Rutilus rutilus)* and three spined stickleback *(Gasterosteus aculeatus)* exposed to the noise of a wind farm replayed in a laboratory study with a sound level of 120 dB re 1µPa at a distance of 1 m; a reaction was primarily seen for the three spined stickleback. Müller (2007) showed that cod avoided the area in a tank where high tones were played (130–140 dB, i.e. 30 dB above the ambient noise for tones between 60–90 Hz). The results were however, not conclusive. In a field study by Mueller-Blenke *et al.* (2010) 40 m circular cages at 15 m depth were used, where the recorded noise of pile driving was replayed at high levels (sound pressure at 140–161 dB re 1µPa$_{(peak)}$, particle motion of $6.5\times10^{-3}$ and $8.6\times10^{-4}$ m/s$^2_{(peak)}$) in the cages. Cod and sole *(Solea solea)* tagged with ultrasonic transmitters showed a variation in the individual behaviour in reaction to the noise. An example included a temporary reduction in swimming speed when the noise was switched on and an increased swimming speed afterwards. Even if the results cannot be directly transferred to this study, due to the fact that the noise re-played consisted of short pulses with high energy, whilst the noise from a wind turbine is continuous with low energy, the studies by Mueller-Blenke *et al.* (2010), Andersson *et al.* (2007) and Kastelein (2008) show in general that fish react differently to noise, both between and within species. Fish are thus likely to have an individual tolerance level for noise disturbance.

[1] (integrated over 123-132 Hz)

[2] (integrated over 52-343 Hz)

It is often easier and more controllable to undertake experiments in tanks and aquaria rather than in the field. It is how however complicated to determine whether the fish react to the sound pressure or the particle motion which are generated in tank tests. Caution must therefore be taken with regard to transferring the results from aquaria and tanks to the situation in the sea. An escape reaction is not either the only possible reaction to a noise. If an animal chooses to move or not, can depend on if it has enough energy to flee. It may also remain in a less favourable area if it is suitably important for its survival or reproduction (Bejder *et al.* 2009). The negative consequences of being present in a noisy environment are for example an increased stress level, which can have an influence on growth and reproduction (Pickering 1993; Small 2004; Davidson *et al.* 2009).

Masking of important biological signals is another factor to consider (Codarin *et al.* 2009), but due to the fact that the majority of interactions where fish use sound, occur over short distances, it is only within a local area around the foundations (< 100 m) that the noise levels are high to risk interfering with communication. Cod fish have been shown to produce a grunting sound and other sounds with a strength of between 120 to 133 dB re 1µPa at a distance of 1m (Hawkins and Rasmussen, 1978; Nordeide and Kjellsby, 1999). In addition, the majority of interactions where sound is involved between fish occur over relatively short distances in our waters, which means that both sound pressure and particle motion are relevant stimuli.

## Assessment of the Situation at Lillgrund

According to the studies at Lillgrund, it was only within an area of approximately 100 m around a turbine that the noise levels were high enough to constitute a risk that fish would react either with escape behaviour or by the masking of communication. At longer distances however, fish may be stressed by the noise because it lies above the ambient level. The risk is greatest at wind speeds of more than 10–12 m/s, and at lower wind speeds the risk zone reduces somewhat. We currently know very little about if, and if so how, fish adjust to noise in the sea that is not associated with danger. It is therefore difficult to draw conclusions regarding whether fish can become accustomed to the noise levels over time.

Sigray *et al.* (2009) showed that the levels of particle motion generated by a 1.5 MW turbine on a monopile foundation of steel were high enough to potentially stimulate escape behaviour in fish within a few metres of the foundation. At distances of more than 20 m, the levels were comparable with the ambient noise. Based on these results, it can be assumed that the impact in the form of particle acceleration within the Lillgrund wind farm is also likely to be low.

In order to establish at what distance the different fish species can theoretically detect the noise from the wind farm, the sound energy in the frequency interval 123–132 Hz was compared with the data on the hearing ability of the different species in the same frequency interval. As described in the introduction, fish have a critical band above which the energy is integrated. In a similar way, this study integrated the recorded sound across different frequency intervals. There are very few studies which describe the critical band width for fish, but for cod, the critical band which includes the 127 Hz tone is calculated to be between 86 Hz and 157 Hz (Hawkins & Chapman 1975). Even if the noise of the wind farm at Lillgrund is integrated across a narrower band, the data can be compared with the values in the literature because the difference is very small. For salmon and eel, the theoretical distance at which they can detect the noise is 250 m and 1 km for productivity levels of 60 and 100 % respectively (which is equivalent to wind speeds of approximately 6 and 12 m/s). These calculated distances are limited by the hearing ability of both fish species and not by the ambient noise in the Öresund Strait, in contrast to herring and cod. With herring and cod the theoretical detection distance was limited by the ambient noise and was calculated to be between 13 and 16 km respectively. This is a long distance and is calculated on the basis of the measured sound propagation loss in the area around the wind farm at Lillgrund. Local variations in depth and physical barriers such as peninsulas (Falsterbonäset) may change the conditions for sound propagation and these assumptions are thus not valid for greater distances from the wind farm. As an example, the 127 Hz tone was not detected in the recordings at Sjollen which is situated 10 km north of the wind farm.

But what does it mean that fish can hear the noise from the wind farm from several kilometres around? As this study shows, the Öresund area is dominated by noise from shipping traffic. To add additional sound energy to the area only increases the sound energy in the area where the wind farm is built, but parts of the sound, the 127 Hz tone, can be detected from longer distances. We currently know very little about what fish listen out for, apart from the acoustic communication that the fish contribute with. It is likely that fish use the soundscape to form a picture of their surrounding and to navigate in a similar way as we humans do with sound (Fay 2009).

# Benthic Fish

## Introduction

The aim of this study was to establish whether the wind farm had an impact on the benthic fish community at Lillgrund during the first three years of operation, and if so, in what way. In this study, the results from fish sampling carried out at Lillgrund before and after the wind farm was built were compared with the corresponding results from two reference areas.

### Expected Impact

The impact of an offshore wind farm occurs primarily as a consequence of the new physical structures in the sea, but also an increase in the noise level and the potential for changes in the electromagnetic field from the cables on the sea bed. The latter two factors could reduce the quality of the habitat for fish and lead to a reduction in the density of fish in the area. The addition of new physical structures may, in contrast, increase the aggregation of fish in the area, providing increased opportunities for protection and foraging. If an increase in the aggregation of fish is seen as positive or negative will however, depend on which species are favoured. There are currently only very few experience-based studies from offshore wind farms in operation (see Wilhelmsson *et al.* 2010, for a summary).

#### *New Physical Structures*

It has previously been noted that fish often aggregate around artificial structures in the sea, such as oil platforms, breakwaters, bridge pillars and pontoons, including constructions which are specifically designed to attract fish (Wilhelmsson *et al.* 1998, Seaman 2007, Egriell *et al.* 2007). An aggregation effect on fish has also been observed close to wind turbines with scour protection (Wilhelmsson *et al.* 2006, Hammar *et al.* 2008, Maar *et al.* 2009). At Lillgrund wind farm, the new physical structures are represented by 48 concrete gravitational base foundations with scour protection in the form of ballast, and a transformer station. The turbines are positioned in eight rows with at least 400m between them and at a depth of between four and seven metres.

#### *Underwater Sound*

A wind farm in operation can also influence fish negatively by the noise which propagates from the turbines through the water (Nedwell *et al.* 2003, Nedwell and Howell 2004, Wahlberg and Westerberg 2005, Thomsen *et al.* 2006). This may result in a reduction in the quality of the habitat for fish and potentially lead to fish avoiding the area, for example if their foraging is impacted negatively or if the possibility for communicating during breeding deteriorates. The general noise environment in the Öresund Strait is relatively loud, primarily due to the heavy shipping traffic, which means that the noise from the wind farm is periodically and frequently masked by the noise from the surrounding area (Andersson *et al.* 2011). An overview of the sound propagation at Lillgrund is described in more detail in an earlier chapter of this report.

### *Electromagnetic Field*

The direct electromagnetic field does not extend beyond an insulated power cable. An indirect electrical field in the surrounding water is however generated by the magnetic field that surrounds the cable (CMACS 2003). Changes in the electromagnetic fields can have an impact on those species which have a well-developed electromagnetic sensory perception. Cartilaginous fish, i.e. sharks and rays, use their electromagnetic sense when they search for food, but do not regularly occur in the area. Eel have also been shown to be affected by power cables in terms of the occurrence of a slight delay in their migration (Westerberg *et al.* 2008). The turbines at Lillgrund wind farm are connected with power cables which leads electricity between the turbines and to a transformer station. The electrical cable network on the sea bed thus covers the entire area of the wind farm, even if the total area it covers is small (Unosson 2009).

## The Fish in the Öresund Strait

The marine water from Kattegatt meets the brackish water from the Baltic Sea in the Öresund Strait. A relatively large number of marine species live close to the edge of their distribution range in the area. Several of the most common species found in the area are also found in the Baltic Sea. In total, more than one hundred different species of fish have been recorded from the Öresund area, with varying frequency (Angantyr *et al.* 2007).

The majority of the fish species in the area are benthic, i.e. they live close to the sea bed rather than in open water. The area primarily contains important nursery grounds for eel, cod and several species of flatfish (Angantyr *et al.* 2007, Carlsson *et al.* 2006). The most common species among the flatfish are flounder and plaice, but dab and sole are also common (Fiskeriverket 2010). The shallow areas are important breeding grounds for species such as lumpfish and turbot (Birklund *et al.* 1992; Dahl *et al.* 1992).

The water currents are often strong in the area, with frequent changes in the direction of the current, which leads to a relatively large variation in the local salinity in comparison with the surrounding area (Dieckmann *et al.* 2010). The currents also lead to an increase in the flow of nutrients, which potentially favours the productivity in the area. An increased supply of nutrients from run-off from the land has however also led to symptoms of eutrophication commonly occurring, including an increase in the presence of fast-growing algae. The nutrient load has however generally reduced over the last decade (Öresundsvattensamarbetet 2008). Another factor which has an impact on the fish population and the marine environment is that trawling is forbidden in the area. This favours the local fish populations partly due to a reduction in mortality, and partly due to the fact that the resident bottom-living organisms are left undisturbed.

# Method

The studies were carried out using two different fish sampling methods; fyke nets and gill net series. Fyke nets were preferentially used in the spring and gill net series in the autumn. The initial purpose for using two different types of gear was to obtain a more general picture of the development of the fish communities in the area, as the different types of equipment sample somewhat different parts of the fish community. In the final year of sampling, only fyke nets were used, however, both in the spring and the autumn, in order to be able to compare the composition of the fish community in the wind farm and the reference areas over two seasons.

Baseline studies were carried out over four years; 2002 to 2005, to provide a basic picture of the benthic fish community before the wind farm was built. Equivalent studies were also carried out in two reference areas. After the wind farm was built, studies to monitor the effects were carried out from 2008 to 2010, which was equivalent to the first three years in operation.

## Fish Sampling Areas

Lillgrund wind farm is situated some seven kilometres southeast of the Öresund Bridge. The turbines stand at between four and seven metres depth, primarily on sandy seabed. There are patches where there are meadows of eel grass and a relatively large amount of floating vegetation on the sandy seabed.

Two reference areas were chosen which had as similar conditions as possible to the wind farm area. The two reference areas selected were Bredgrund (approximately eight kilometres south of Lillgrund) and Sjollen (approximately 13 kilometres north of Lillgrund). Consideration was also taken regarding the practicalities of being able to undertake fish sampling, in relation to the currents, shipping traffic and depth when selecting the reference areas.

## Fish Sampling Method

The stations for sampling were randomly selected before the first sampling occasion. The location of each station has thereafter been the same each year. The shortest distance between two sampling stations was 200 metres. At each station and sampling occasion, the number of individuals and the length in a centimetre class was recorded for all species present. Sampling was carried out according to a standardised method for sampling using fyke nets and gill net series, respectively (Thoresson 1996). The weight per species and station was also recorded when sampling with fyke nets in 2008, but on the other occasions, only the number of individuals was recorded. In addition to the catch, the depth and temperature at the sea bed were recorded for each station. The surface water temperature, salinity at the surface and at the sea bed, water transparency, wind direction, wind speed and direction of the current were recorded on a daily basis for each site.

### *Sampling with Fyke Nets*

Fishing with fyke nets was carried out in May. The fyke nets used were modified small fyke nets for catching eel, 55 cm high with a semi-circular opening, three entrances and a five metre long arm. From 2002 until 2004, 24 stations were sampled within each area, with three pairs (two fyke nets connected together) of fyke nets per station. From 2005 and onwards, 36 stations per site were sampled (figure 12). In 2010 sampling was carried out with fyke nets in October as well, and the number of sampling stations was increased within the wind farm to 76 (figure 13). For this year it was thus possible to compare the fish communities from the spring and the autumn.

#### Additional Fish Sampling within Vindval Research Programme

To study the spatial distribution of the fish within the wind farm in relation to the individual wind turbines, the results from the sampling with fyke nets were analysed together with the results from the sampling carried out within the framework of the Vindval Research Programme (www.naturvardsverket.se). The sampling was carried out in parallel with the sampling carried out as a part of the monitoring programme between 2008 and 2010. Sampling was carried out close to the individual wind turbines, with the aim of seeing if there was an aggregation of fish in close proximity to the foundation or if the fish avoided the area, because for example of the noise disturbance. The sampling was carried out using fyke nets at four different distances along a transect running from ten of the wind turbines. The fishing at the stations took place at slightly different positions each time, depending upon what was practically possible, but as a rule of thumb, starting from the same turbine and in the same direction. Sampling was carried out in May in the period 2008 to 2010, as well as in the autumn (October, November) from 2009 to 2010. The results from the studies within the Vindval Research Programme are presented only in outline here and for more details see Bergström *et al.* (2011).

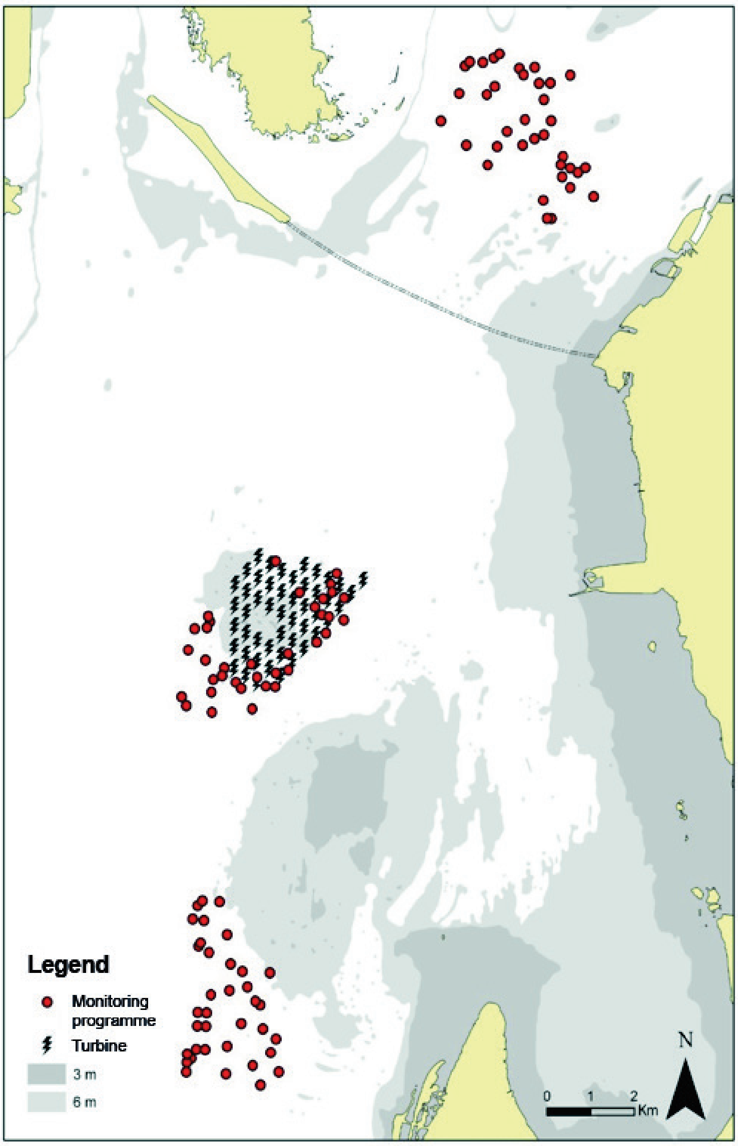


Figure 12. Location of the fish sampling stations at Lillgrund, and the reference areas of Sjollen and Bredgrund. Sampling with fyke nets was carried out between 2002 and 2005 and 2008 to 2010. The 36 stations that were sampled with fyke nets in 2005, 2008, 2009 and 2010 are presented as red dots. Of these, 24 stations were sampled between 2002 and 2004. The black lightning symbols mark the positions of the individual wind turbines.

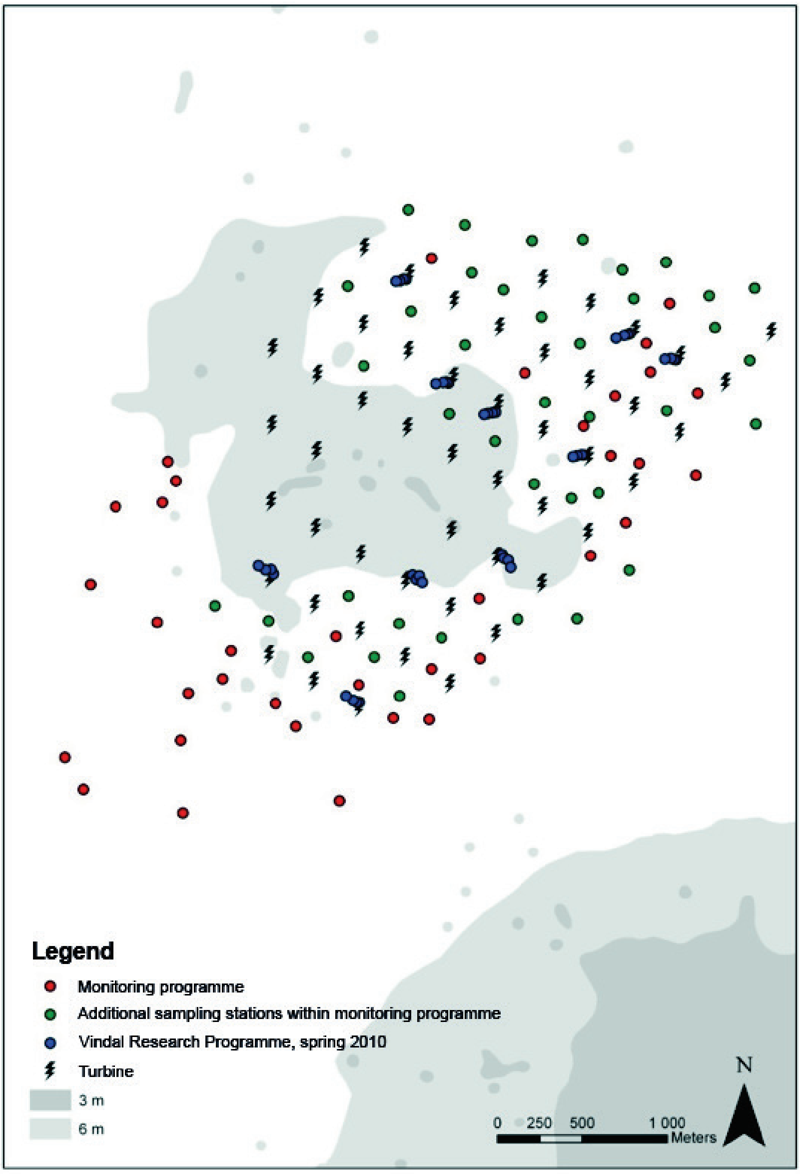


Figure 13. The stations that were sampled using fyke nets at Lillgrund in 2010. The 36 stations that were sampled within the monitoring programme are represented as red dots. The green dots indicate the 40 additional stations that were only sampled in 2010. These stations were sampled in the spring and autumn. The blue dots represent the stations that were sampled closed to the wind turbines in the spring of 2010 (sampled as a part of the Vindval Research Programme). A similar approach was also used for the Vindval Research Programme stations in the autumn of 2010, but the positions were not entirely identical (see the explanation in the main text). The black lightning symbols represent the individual wind turbines.

### *Sampling with Gill Net Series*

Fish sampling using gill net series was carried out in the autumn, at the end of October and beginning of November. Within each area, 24 stations were sampled over the years 2002 to 2005 as well as 2008 and 2009 (figure 14). Each station was sampled over a 24 hour period with a gill net series. A gill net series consisted of five, 27 metre long and 1.8 metre deep nets with mesh sizes of 22, 30, 38, 50 and 60 mm.

In the baseline study, targeted sampling with nets for specific species which may use Lillgrund as a breeding area was also carried out. Sampling to monitor the amount of breeding turbot was carried out between 2002 and 2004 and for lumpfish from 2003 to 2004. This sampling was heavily disrupted by drifting algae in all years, especially at Lillgrund and Bredgrund. Despite attempts to avoid the worst periods with algae by moving the sampling period in time, it was not possible to obtain enough qualitative data to motivate continued monitoring studies. This part of the investigation was thus abandoned after 2004. A description of the results available from the breeding sampling that was carried out is available in the report from the baseline studies (Lagenfelt *et al.* 2006).

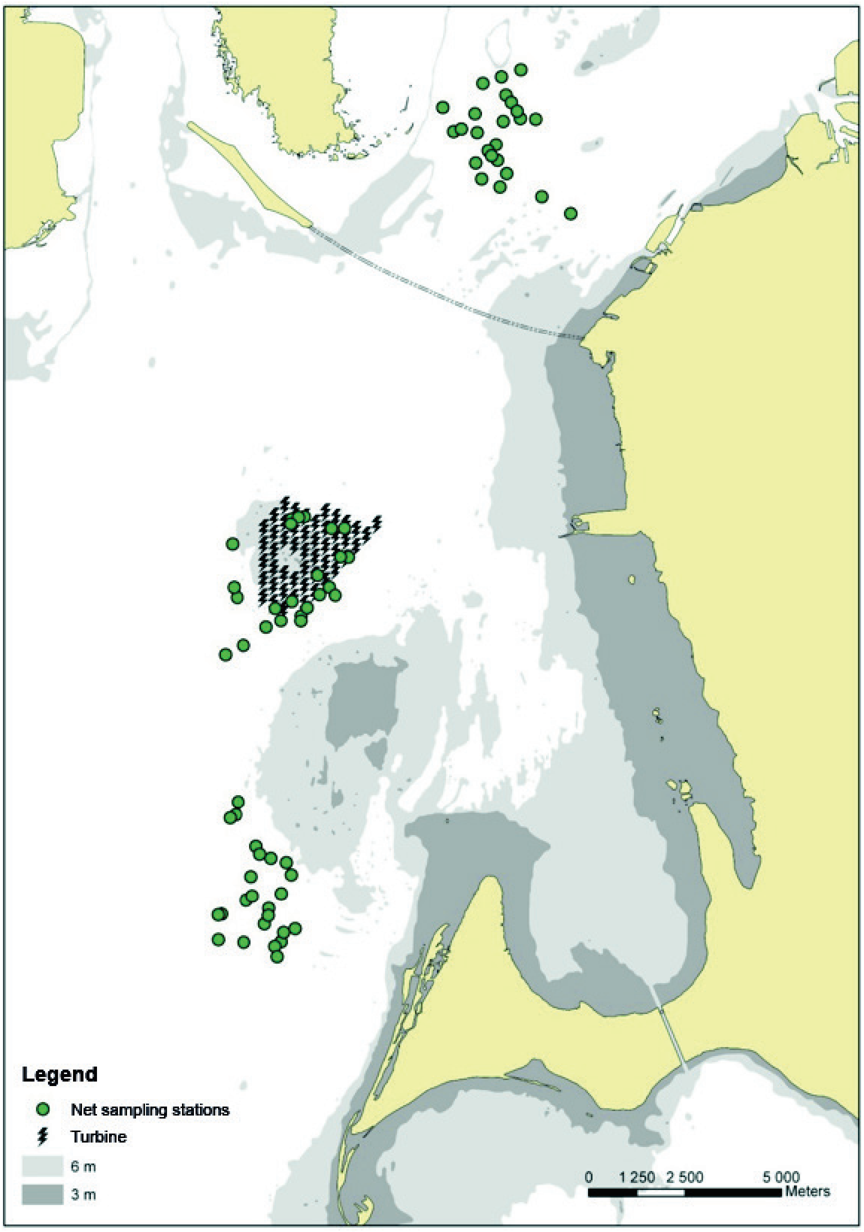


Figure 14. Stations where sampling with gill net series was carried out at Lillgrund, and the reference areas of Sjollen and Bredgrund. Sampling with gill net series was carried out in the years 2002–2005 and 2008–2009, at 24 stations per site and year. The black lightning symbols represent the location of the individual wind turbines.

## Statistical Analyses

Fish sampling data from 2002 was analysed to study the development of the catch over time at Lillgrund wind farm in comparison to the reference areas. The analyses were carried out with a focus on the overarching species composition, and on the most commonly occurring species. The analyses were carried out in the same way for the sampling using fyke nets in the spring and gill net series in the autumn. Differences between the spring and the autumn catches on the basis of data from the extended sampling in 2010 were also analysed.

In order to specifically study the distribution pattern of the fish in relation to the individual wind turbines, data from the sampling using fyke nets within the wind farm between 2008 and 2010 was analysed together with the data from the sampling carried out within the Vindval Research Programme. The results are presented here, and in a somewhat more detailed form in Bergström *et al.* (2011). On the basis of the data from the extended sampling in 2010, a more detailed analysis of the distribution of the fish in relation to the foundations was carried out. The aims of the analyses were to estimate the distances within which a possible altered distribution pattern could be observed, and to relate the distribution effect to different potential explanatory environmental factors. The spatial distribution of the fish was investigated in relation to the distance from the closest turbine foundation, the modelled sound propagation within the wind farm (according to the studies which are described above), as well as depth.

### *Analysis of Changes in Species Composition*

Changes in fish species composition was analysed using an MDS-analysis (non metric multidimensional scaling) according to the programme PRIMER 6.0 (Clarke and Warwick 2001). In the analysis, the species composition in the catch from different sampling stations was compared. The comparison was made using the Bray-Curtis similarity index, which takes into account which species occur in the catch, as well as how common they are. The similarities between the sampling stations were then visualised in a graph, so that the sampling stations which are more similar to one another lie close together, whilst those points which are more different lie further apart. The visualisation is multi-dimensional, but is usually reproduced in two dimensions which capture the main variability in the data set. In order to measure how well the two-dimensional reproduction represents the actual pattern, a stress value is given. A stress value below 0.15, means that the relationship between the points can satisfactorily be represented in two dimensions. The MDS-analyses were complemented with a so-called BIOENV-analysis in the same statistical programme, to identify which species contributed primarily to the observed pattern.

The analysis was based on information on the number of each species and station on average for each site and year, after square root transformation, for all fish species[3]. Shellfish were not included.

[3] For the data from the sampling with fyke nets, three species were excluded; sand goby, two-spotted goby and three-spined stickleback, which were not possible to quantify accurately in the nets. This was on the basis of the initial analyses of the composition of the catch according to length in groups.

### *Analysis of Changes in the Size of the Catch*

Differences in the size of the catch between areas and year was studied in relation to the total abundance of fish, and in relation to the most common fish species found in different seasons. This was eelpout, cod and goldsinny wrasse for the data from sampling with fyke nets in the spring. In addition, yellow eel was included, due to the special interest in this species for fisheries management. For the data from the sampling with nets in the autumn, cod, flounder, shorthorn sculpin and goldsinny wrasse were studied. The same analyses were also carried out for common shore crab.

Due to the fact that the variation between the stations was high for all areas and years, the analysis was carried out at two levels.

In order to focus on the large scale picture, an analysis was carried out focusing on the overarching differences between the periods before, respective after the wind farm was built. For this analysis, an analysis of variance was carried out usingthe factors TIME, SITE, as well as the interaction between these factors. The factor TIME had two levels (before and after the wind farm was built), so that the "before" represented the years 2003 to 2005 and "after" represented the years 2008 to 2010[4]. The analyses were carried out in SPSS 10.0.

In a second step, the development over time in the different areas was analysed more closely, with the focus being on the differences between the years. The analysis was done using a generalised linear model (GLM) with the two factors SITE and YEAR as nominal explanatory variables, and the interaction between them. The interaction SITE * YEAR gave a significant contribution to the level of explanation in all cases, and therefore separate analyses were thereafter carried out for each site to study the differences between different years[5]. The analyses were made assuming a Poisson-distribution, using a corrected distribution (so called quasi-Poisson), as validated by evaluating the models' residual variation in relation to the predicted values and the explanatory variables (Zuur *et al.* 2007). These analyses, and those below, were carried out in R 2.9.1 via the (user) interface Brodgar 2.6.6 (Highland Statistics Ltd).

### *Presence of a Spatial Distribution Pattern*

In order to see if there was any effect on the distribution pattern of the fish within the wind farm, data from sampling carried out in the month of May from 2008 to 2010 was used. In total 228 stations were included, divided across 76 stations per year, due to the fact that the 40 stations from the Vindval Research Programme were combined with the 36 stations from the monitoring programme. Analyses were undertaken separately for each fish species which

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[4] The analyses were carried out using log-transformed values for the response variables. The residuals' normal distribution was verified after each analysis with the help of the Kolmogorov-Smirnovs test, and the homogeneity of the variance with the help of Levenes test.

[5] This was assessed using an ANOVA comparison, were a model including the interaction term was compared to one without. The significant of the interaction term was assessed, based on the difference in the level of explanation (Deviance explained), assuming a F-distribution (Zuur m.fl. 2007).

had occurred in at least 20 percent of the stations in total, i.e. cod, eel (yellow eel), longspined bullhead, shorthorn sculpin, goldsinny wrasse, black goby and eelpout. In addition the presence of shore crab and the total number of fish individuals were also analysed. Two separate analyses were carried out for two different size categories of cod (larger than or smaller than 37 cm).

The relationship between the abundance of fish at each station and the distance of the station to the nearest turbine was studied using a generalised linear model (GLM) [6]. The distance between the respective stations and the closest wind turbine was calculated on the basis of the position measured when sampling and the information on the position of the wind turbine provided by Vattenfall. In the model, in addition to the factor DISTANCE (log-transformed), the factor YEAR was also used as a nominal variable, to incorporate possible differences in the abundance of fish in different years.

To evaluate whether the observed results were consistent between years, the results were compared with an alternative model, which also included the interaction between year and distance. If the alternative model gave a significantly higher degree of explanation than the first model, the alternative model was used. As a result of this, the interaction between DISTANCE and YEAR was also included in the analyses for shore crab and the total abundance of fish.

### Effect Distance

In a second step, the data from fish sampling in May and October in 2010 was used to estimate within what distance from the closest wind turbine a change in the spatial distribution could be observed. In total, 116 stations per season were included, by combining the data from the 76 sampling stations within the monitoring programme with the data from the 40 sampling stations within the Vindval Research Programme. The analyses were carried out separately for each species of fish which had been caught in at least 20 percent of the sampling stations during both seasons, i.e. cod, eel, eelpout and shorthorn sculpin. In addition the presence of shore crab and the total abundance of fish were also analysed. Two separate analyses were carried out for two different size categories of cod; those individuals larger than or smaller than 37 cm.

For these analyses, generalised additive models (GAM) were used, where the variable DISTANCE (log-transformed) was included as a spline-function with a maximum of three degrees of freedom. The analysis was carried out separately for the spring and the autumn. For those species where there was a significant effect of distance ($p < 0.01$) the effect distance from the wind turbine was identified on the basis of graphs over their partial response curves. The distance interval where the curve including the confidence interval was above

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[6] All analyses of spatial distribution were carried out in the programme R 2.9.1 via the (user) interface Brodgar 2.6.6 (Highland Statistics Ltd). After an intial screening of the data and preliminary analyses, the models were based on a corrected Poisson-distribution (*quasi-Poisson*). The procedure was validated by evaluating the diagram from the residual variation from the models in relation to the predicted values and in relation to the explanatory variables. The presence of outliers was evaluated based on Leverage values (Zuur m.fl. 2007).

zero was used to indicate a relatively high abundance of fish in relation to the data material as a whole (Zuur *et al.* 2007).

### Relationship between Different Environmental Factors and the Distribution of Fish

The results from the sampling with fyke nets within the wind farm in 2010 was also analysed in relation to different environmental factors which could potentially explain the spatial distribution pattern of the fish. In the analysis, fish abundance at a certain station was related to three potential explanatory variables; DISTANCE, NOISE and DEPTH, to see i) which of these factors were related to the abundance of fish and ii) the level of the observed variation between the stations that these factors could explain.

The values for the distance variable were calculated in the same way as described for the previous analyses, as the distance between the respective station and the closest wind turbine. In contrast from the above analyses the variable was included without being transformed, because the primary aim was to compare the variables with one another (the other variables included were also in an untransformed form). The values for the noise variable were taken from the acoustic model which was described in the chapter entitled Acoustics in this report. For each station a mean value for noise over a 24 hour period was calculated, on the basis of information on the actual productivity in the wind farm at the respective sampling date. Noise measurements were taken in May, at the same time as the fish sampling was carried out in 2010, and the model is therefore most representative for that sampling event, but the values have also been adapted for the fish sampling during the autumn, on the basis of information on the actual productivity at that time. The values for the variable DEPTH were taken from measurements of depth from fishing.

The analyses were carried out with the help of generalised additive models (GAM). All explanatory variables were included as spline-functions with a maximum of three degrees of freedom. In the first stage, all three factors were included. Thereafter, the model was reduced by the factor that contributed the lowest degree of explanation. This was repeated once more, so that the final model contained only a single factor. From these analyses, the best model was identified as that model which had the lowest *gcv* value. Before the analyses the factors were examined for their correlation on the basis of their VIF value (variance inflation factors*),* of which the highest was 1.34. The correlation between the sound levels and distance from the wind turbine was low, because the fish sampling was partly carried out on different days within a period of approximately two weeks. During this period the productivity of the wind farm also varied and thus the modelling of the noise levels. A specific distance from the wind turbine could therefore represent different noise levels depending on the day in which it was sampled. In addition the same analyses were carried out separately with regard to a single variable at a time. The analyses were carried out for the same fish species as in the analysis of the effect distance.

# Results

## Results from Fish Sampling with Fyke Nets

### *Changes in the Abundance of Species and the Species Composition*

In total, during the entire study period, 30 species of fish were recorded, including species caught in the reference areas (table 4). Of these, 22 fish species were caught in the period between 2002 and 2005, and 29 fish species during the period 2008 to 2010. In addition to the fish species caught, shore crab was caught in all three areas, both before and after the wind farm was built.

The total number of fish species is not directly comparable between the years before and after the wind farm was built, because fewer stations were sampled in the years 2002 to 2004, and the likelihood of catching unusual species increases with the number of sampling stations. In order to make a comparison, the mean value for the number of species per station was calculated. Calculated as a mean number of species per station, the greatest number of fish species was caught at Sjollen before the wind farm was built and at Lillgrund after it was built. In all areas, more species of fish were caught per station in the years when the wind farm was in operation, than in the years after it was built.

After construction, eelpout was the most common species in the samples at Lillgrund and Bredgrund, whilst cod was the most common species caught at Sjollen (figure 15). In total, for all areas, eelpout was the most abundant species, followed by cod, goldsinny wrasse, black goby and yellow eel.

During the period studied, the species composition at Lillgrund had similarities with both reference areas, whilst the reference areas were more different from one another (figure 16). This pattern reflects the fact that the reference areas lie south and north of the wind farm respectively, and is due to the fact that the northerly reference area (Sjollen) is characterised by a greater proportion of marine species than the southern reference area (Bredgrund).

The species which primarily characterise the differences between the areas and years were goldsinny wrasse (most common at Sjollen), cod (most common at Sjollen) and eelpout (most common at Lillgrund and Bredgrund). These species were also the ones which were most abundant in the catches. Yellow eel contributed slightly to differences between the areas, but not to such a large extent (figure 17).

Table 4. List of the fish species which were caught in the fyke nets before (2002–2005) and after (2008 2010) the construction of the wind farm, at Lillgrund and at the reference areas Bredgrund and Sjollen. The total number of species is not directly comparable between years, due to the fact that there were fewer sampling stations in the period 2002–2004 than in later years. In order to enable a comparison, the number of fish species is given as a mean value per station. For more detailed information, see the appendices.

| | Bredgrund | | Lillgrund | | Sjollen | |
|---|---|---|---|---|---|---|
| Species | Before | After | Before | After | Before | After |
| Topknot | | | X | X | | |
| Silver eel | X | X | X | | | |
| Rock cook | | | | | | X |
| Yellow eel | X | X | X | X | X | X |
| Pipefish (undet.) | X | X | | | | X |
| Snake pipefish | | | | | X | X |
| Straightnose pipefish | | X | | | | |
| Longspined bullhead | X | X | X | X | X | X |
| Tadpole fish | | | | X | | |
| Turbot | | X | X | | | |
| Shorthorn sculpin | X | X | X | X | X | X |
| Plaice | | X | X | X | X | X |
| Dab | | X | | X | X | X |
| Herring | | | | | | X |
| Lumpfish | X | | X | X | X | X |
| Sprat | | | | X | X | X |
| Flounder | X | X | X | X | X | X |
| Hooknose | | X | | X | | X |
| Corkwing wrasse | | | | X | X | X |
| Brill | | X | | | | |
| Greater pipefish | | | | | X | |
| Goldsinny wrasse | | X | X | X | X | X |
| Black goby | X | X | X | X | X | X |
| Rock gunnel | | X | | | X | X |
| Sand eel (lesser/small) | | X | | X | | X |
| Cod | X | X | X | X | X | X |
| Eelpout | X | X | X | X | X | X |
| Broadnosed pipefish | X | | X | | | X |
| Fifteen spined stickleback | X | X | X | X | X | X |
| Sole | | | | X | | X |
| Number of species | 11 | 18 | 14 | 19 | 17 | 23 |
| Mean number of fish species per station | 2,71 | 3,42 | 2,95 | 4,31 | 3,28 | 4,23 |

*Same species in a different developmental stage

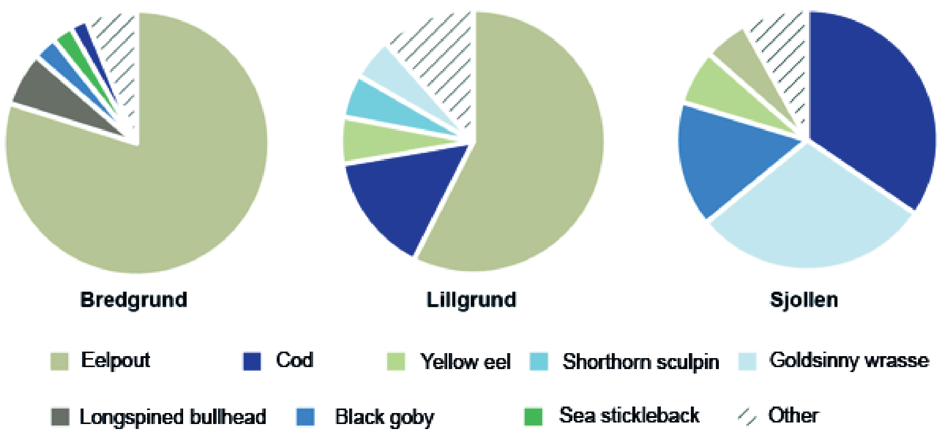


Figure 15. The species distribution from the fish sampling using fyke nets in the years 2008–2010, based on the 36 sampling stations included in the monitoring programme. The figures indicate the relative abundance of the five most common species in each area, in terms of the number of individuals of fish on average for all three years after construction of the wind farm. The remaining species have been combined and are shown as “other”.

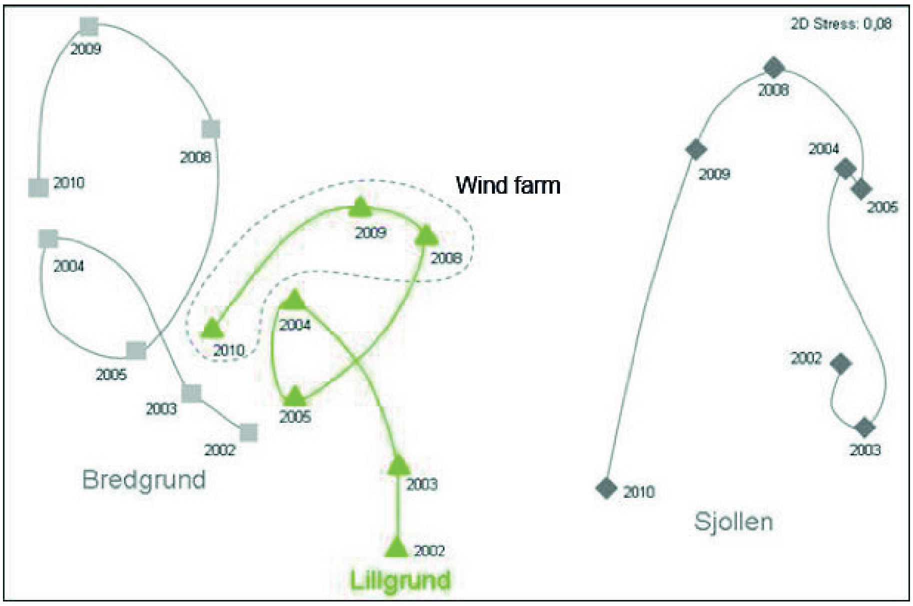


Figure 16. Results of non-metric multidimensional scaling (MDS) which shows similarities in species composition between areas and years, on the basis of the fish sampling data using fyke nets in the spring. The points which are closer together in the figure have a more similar species composition. The lines join up adjacent years within the respective areas. The different areas are clearly separated, but in all areas the composition of the catch also varies between the years. According to this figure, the species composition of fish at Lillgrund has similarities with both of the reference areas, but the two reference areas are more different from one another. The hatched line indicates the fish sampling that took place within the Lillgrund site after the wind farm had been built. The analysis is based on the abundance of fish.

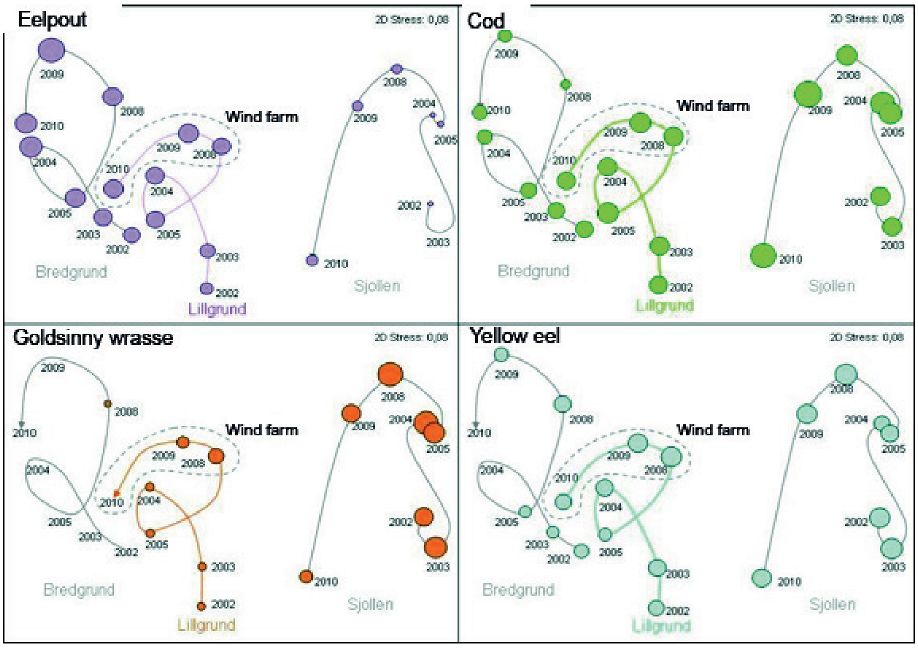


Figure 17. Abundance of eelpout, cod, goldsinny wrasse and yellow eel in the years 2002–2010 at Lillgrund and the two reference areas Bredgrund and Sjollen. The size of the symbols reflect how common the species was in the catch at different areas and years (c.f. figure 19). The figures are based on the same analyses as described in figure 16.

## *Changes in Catch Size*

### Total Abundance of Fish

The fyke net sampling at Lillgrund caught on average between 5 and 11 individuals per station during the baseline study period and between 12 and 16 individuals after the wind farm was built (figure 18).

Seen over the three year period before and after the construction of the wind farm respectively, the total catch of fish was similar in all areas, as well as between the time before and after construction[7]. In terms of the differences between the years, the greatest difference was that the catch at Bredgrund in 2009 was relatively high. The largest catch from Lillgrund was also recorded in 2009. The smallest catch from Lillgrund occurred in 2002 and 2003, as was also the case for both reference areas (table 5).

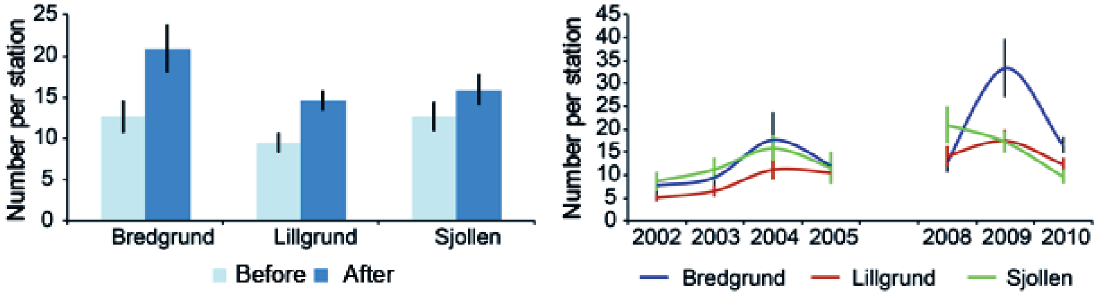


Figure 18. Total number of fish caught using fyke nets in the spring. On the left, the mean number of fish per station and year for the period before (2003–2005) respective after (2008–2010) construction of the wind farm are presented. On the right, the mean number of fish per station for each year (2002–2010) are given. The vertical lines represent 95 % confidence intervals.

[7] Two-way-ANOVA: $F_{1,2}$=1.23, p=0.326 for the factor Site, $F_{1.2}$=4.66, p=0.052 for the factor Before/After, $F_{1.2}$=0.26, p=0.777 for the factor Site * Before/After.

Table 5. The results from the analyses of the differences between the years in the number of fish per station, according to a generalised linear model (GLM). In the analysis, the abundance of fish in the last year of sampling (2010) is related to the catch from previous years. The analyses were carried out separately for each site for the total abundance of fish, as well as for the species eelpout, cod, goldsinny wrasse, yellow eel and shore crab (c.f. figure 18, right hand picture, and figure 20). In each column a "+" means that the catch was larger and a "–" that it was lower, and "ns" means that there was no significant difference compared with 2010 (p < 0.01). In the column "explD %" the degree of explanation from the model as a percentage is presented.

| | | | Comparison with 2010 | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Species** | **Site** | **explD %** | **2002** | **2003** | **2004** | **2005** | **2008** | **2009** |
| Fish | Lillgrund | 33,3 | - | - | ns | ns | ns | + |
| | Bredgrund | 43,4 | - | - | ns | ns | ns | + |
| | Sjollen | 23,2 | ns | ns | + | ns | + | + |
| Eelpout | Lillgrund | 30,6 | - | - | ns | ns | ns | ns |
| | Bredgrund | 45,7 | - | - | ns | ns | ns | - |
| | Sjollen | 34,0 | - | ns | - | - | ns | ns |
| Cod | Lillgrund | 6,6 | ns | ns | ns | + | ns | ns |
| | Bredgrund | 14,0 | ns | ns | ns | ns | ns | ns |
| | Sjollen | 39,8 | - | - | ns | - | - | + |
| Goldsinny wrasse | Lillgrund | 33,8 | ns | ns | ns | ns | ns | ns |
| | Bredgrund | | | | | | | |
| | Sjollen | 34,0 | + | + | + | + | + | + |
| Yellow eel | Lillgrund | 13,4 | ns | ns | ns | ns | + | ns |
| | Bredgrund | 24,2 | ns | ns | ns | ns | ns | ns |
| | Sjollen | 7,6 | ns | ns | ns | ns | ns | ns |
| Shore crab | Lillgrund | 52,8 | - | ns | ns | - | + | + |
| | Bredgrund | 40,1 | - | ns | ns | - | + | ns |
| | Sjollen | 28,0 | ns | ns | ns | ns | + | + |

## *Developments within the Most Common Fish Species*

The species that were most abundant in the catches from fyke nets in the spring, across all years and areas, and which have been studied more closely in this context were eelpout (47 % of the catch on average in terms of numbers of individuals), cod (17 %) and goldsinny wrasse (15 %). In addition to these three species, yellow eel made up 4 % of the catch on average and was also studied more closely, due to the fact that this species is of particular interest for the fisheries managers in the area.

### Eelpout

The catch of eelpout was greatest at Bredgrund and lowest at Sjollen in all years studied. Seen across the three year periods before and after construction respectively, the catch was higher after construction in all three areas, but the increase was not statistically significant (figure 19)[8]. In relation to the differences between the years, an increase in the catch in later years was noted for all areas, however to a somewhat lesser extent at Lillgrund compared with the reference areas. The greatest catch at Bredgrund was recorded in 2009 and the lowest in 2002 and 2003. The catch of eelpout at Lillgrund was also lowest in the years 2002 and 2003, but in other years the catch was at the same level.

[8] Two-way ANOVA: $F_{1.2}$=27.65, p<0,001 for the factor Site, $F_{1.2}$=4.07, p=0.067 for the factor Before/After, $F_{1.2}$=0.25, p=0.781 for the factor Site * Before/After.

At Sjollen, eelpout was more unusual that in the other areas, but the abundance in the catch was significantly higher from the three years after construction that in the majority of years before construction (figure 20, table 5).

### Cod

The abundance of cod in the catch was highest at Sjollen and lowest at Bredgrund (figure 19). Across the three year period before and after construction respectively, there was a difference in the catch between areas, but not between the time periods before and after construction[9]. In relation to the changes in individual years, the largest catch at Lillgrund was recorded in 2009 and 2005 (figure 3.9). At Sjollen the catch fluctuated significantly between the years, but the greatest catches were in 2009 and 2010. At Bredgrund, the catch remained at a similarly low level in all years (table 5).

### Goldsinny Wrasse

Goldsinny wrasse was recorded in greatest abundance from Sjollen and was also recorded from Lillgrund. No goldsinny wrasse was caught from Bredgrund during the baseline studies and only two individuals after the construction of the wind farm (figures 3.8, 3.9). Like in the case of eelpout and cod, there were differences in the sizes of the catch between areas, but not between the years before and after the construction of the wind farm respectively, nor was there any interaction between the years[10]. In 2010, the catch of goldsinny wrasse was low at Sjollen compared with previous years. No significant difference in the size of the catch was seen at Lillgrund between the years. There were so few goldsinny wrasse caught from Bredgrund that it was not meaningful to carry out any analyses (table 5).

### Yellow Eel

The average catch of yellow eel varied with site and year (figure 3.9). There was a significant difference in the catch between areas but not between before and after the construction of the wind farm, nor was there any significant interaction between these factors (figure 3.8)[11]. In relation to changes from individual years, a larger catch of yellow eel was noted from Lillgrund in the first two years after the wind farm was built, but in 2010, the catch was at the same level as the baseline studies. At Bredgrund and Sjollen no differences in the catch was noted between the different years (table 5).

[9] Two-way-ANOVA: $F_{1.2}=17.83$, $p<0.001$ for the factor Site, $F_{1.2}=0.26$, $p=0.620$ for the factor Before/After, $F_{1.2}=1.61$, $p=0.240$ for the factor Site * Before/After.

[10] Two-way-ANOVA: $F_{1.2}=21.10$, $p<0.001$ for the factor Site, $F_{1.2}=0.25$, $p=0.626$ for the factor Before/After, $F_{1.2}=1.23$, $p=0.235$ for the factor Site * Before/After.

[11] Two-way-ANOVA: $F_{1.2}=9.76$, $p=0.003$ for the factor Site, $F_{1.2}=3.49$, $p=0.086$ for the factor Before/After, $F_{1.2}=0.12$, $p=0.890$ for the factor Site * Before/After.

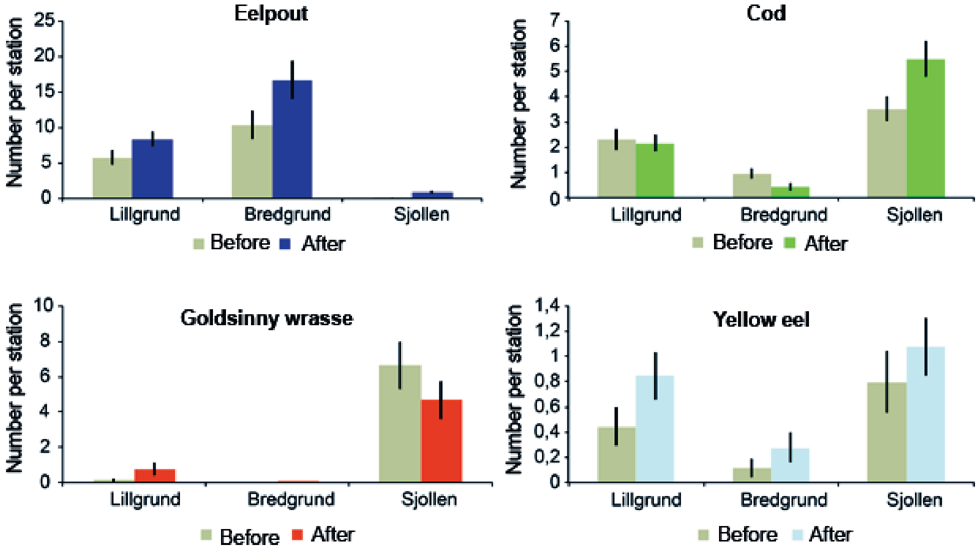


Figure 19. Total catch for some common species using fyke net sampling in the spring. Number of individuals of eelpout, cod, goldsinny wrasse and yellow eel at Lillgrund as well as the reference areas of Bredgrund and Sjollen, presented as mean values for the three years before (2003–2005) and the three years after (2008–2010) the construction of the wind farm. The vertical lines represent a 95 % confidence interval.

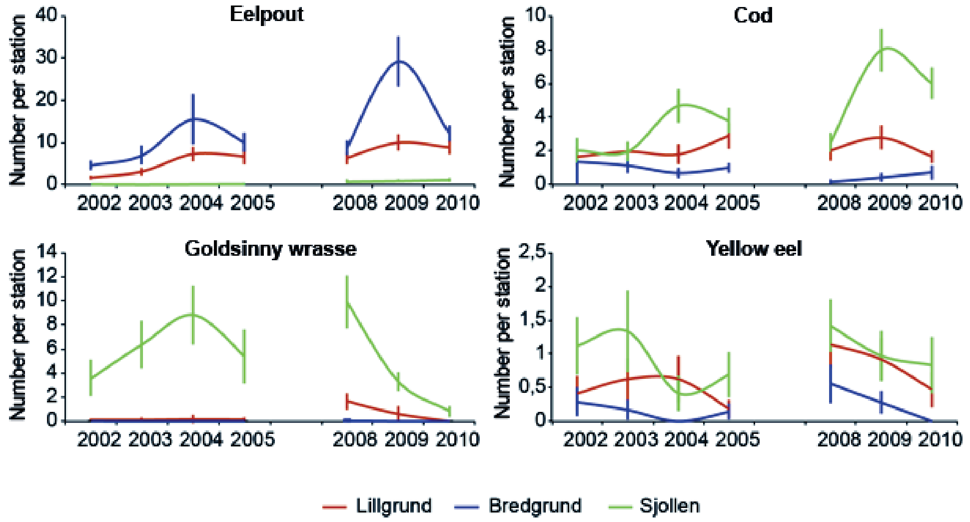


Figure 20. Catch by year of some of the common species using fyke nets in the spring. The mean number of individuals per station and year for eelpout, cod, goldsinny wrasse and yellow eel, at Lillgrund and the reference areas Bredgrund and Sjollen. The vertical lines represent a 95 % confidence interval.

## Shore Crab

The number of shore crabs caught at Lillgrund and Sjollen was of the same order of magnitude as the fish in the catch, but the catch was lower at Bredgrund (figure 21). Over the three year period before and after the construction of the wind farm, a difference between the areas was noted, with a lower number caught at Bredgrund compared with the other areas. There was also a difference between the years before and after the construction, with a larger catch after construction[12]. At Lillgrund, four crabs on average were caught per station before the construction of the wind farm (2003–2005), and 12 shore crabs on average per station after the construction of the wind farm (2008–2010). The increase was very obvious in the years 2008 and 2009, but in 2010, the catch of shore crabs returned to the levels during the years of the baseline studies. The smallest catch of shore crab was recorded from 2002. A similar pattern was seen at Sjollen, with the largest catch in 2009 and the lowest in 2002 (table 5).

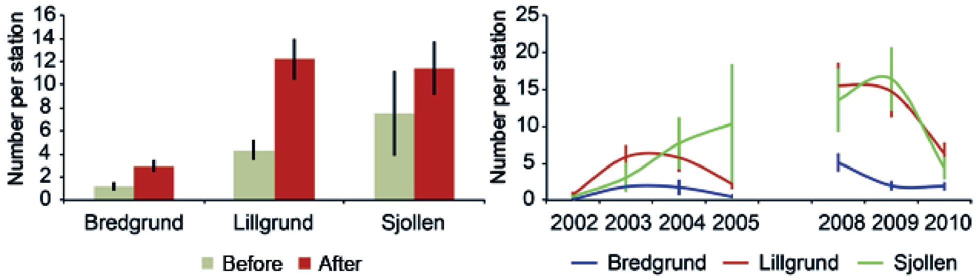


Figure 21. The number of shore crabs caught using fyke nets in the spring. On the left, the average number of shore crabs per station and year for the period before (2003–2005) and after (2008–2010) the construction of the wind farm. On the right, the mean number of shore crabs per station divided by year are presented (2002–2010). The vertical lines represent a 95 % confidence interval.

### *Differences between the Spring and the Autumn in 2010*

In 2010 sampling with fyke nets was also carried out in October, which made it possible to make a comparison of the situation at Lillgrund in the spring and the autumn. In the comparison, data from 76 sampling stations sampled within the monitoring programme (the 36 ordinary stations and an additional 40 sampled in 2010) and from 40 stations fished within the Vindval Research Programme was included. Shore crab was the most numerous species in both the spring and the autumn, but it was significantly more common in the autumn. Roughly six times more shore crabs were caught per station from the fyke nets in the autumn compared with the equivalent sampling in the spring (figure 22). The number of fish per station was, in contrast, greater in the spring than in the autumn. Roughly twice as many fish were caught per station in the spring than in the autumn.

The five most abundant fish species in the fyke net sampling both in the spring and the autumn were eelpout, cod, yellow eel, shorthorn sculpin and flounder. Eelpout constituted 62 percent of the proportion of fish in the catch in the spring, which was equivalent to approximately nine individuals per station (figure 23). In the autumn, eelpout was the second most common fish species in the catch with just under one individual per station. Cod was the most common species caught in the autumn and constituted 45 percent of the proportion of fish in the catch compared to 19 % in the

[12] Two-way-ANOVA: $F_{1.2}$=8.21, p<0.006 for the factor Site, $F_{1.2}$=6.68, p=0.024 for the factor Before/After, $F_{1.2}$=0.58, p=0.573 for the factor Site * Before/After.

spring. The difference in the proportion of cod in relation to the total catch between the spring and the autumn depended primarily on changes in the abundance of the other species, in particular eelpout. Calculated as the number per station, the catch of cod was similar in the spring and the autumn of 2010. The other common species were also caught in comparable quantities in the spring and autumn.

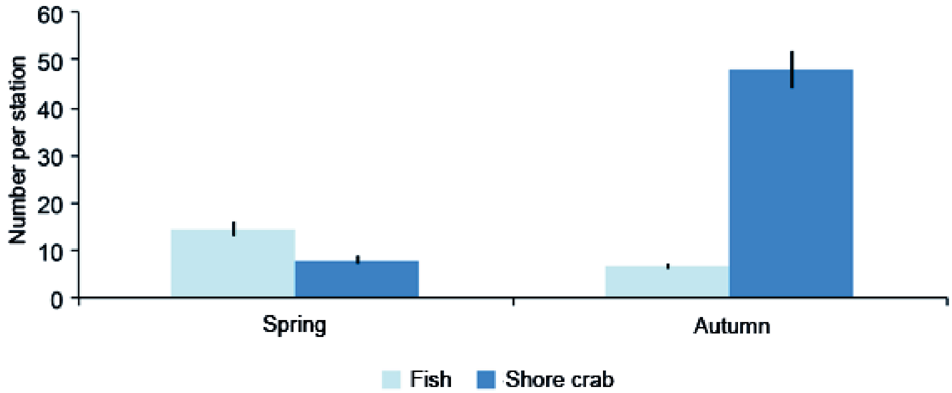


Figure 22. The number of shore crabs caught at Lillgrund sampled using fyke nets in the spring (May) and the autumn (October) 2010, presented as the mean number per station. Based on information from all sampling stations fished (monitoring programme – 76 stations, Vindval Research Programme– 40 stations). The vertical lines represent a 95 % confidence interval.

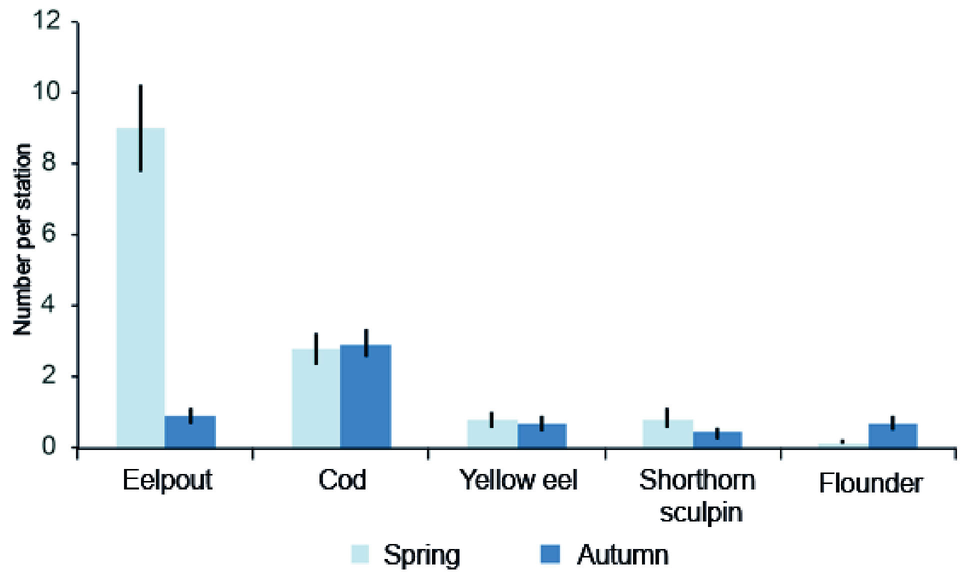


Figure 23. The number of the most abundant fish species; eelpout, cod, yellow eel, shorthorn sculpin and flounder, from fish sampling using fyke nets in the spring and autumn of 2010, presented as a mean number per station. Based on information from all sampling stations fished (monitoring programme – 76 stations, Vindval Research Programme – 40 stations). The vertical lines represent a 95 % confidence interval.

### *Presence of an Aggregation Effect*

Analyses of the distribution of the fish in relation to the foundations showed that in four of the eight species studied, there was an increase in their abundance in close proximity to the wind farm in comparison with at longer distances. The effect could be seen after the first year in production and was of a similar magnitude in each of the three years studied. A relatively high number of fish close to the wind turbines was seen for eel, cod, goldsinny wrasse and shorthorn sculpin. The effect was not seen for longspined bullhead, flounder and black goby, despite the fact that these were also relatively common in the catches (figure 24).

No aggregation effect was seen for eelpout on the basis of the data that was used to compare the distribution over the three years after the wind farm was in production (table 6, figure 24), but in the increased data material from 2010, an increase in the quantity of eelpout close to the foundations in comparison with further away (see below, and table 7) was seen.

An altered distribution pattern for shore crabs was recorded, which varied between years. In the first two years, a pattern was recorded where there was a reduced abundance of shore crabs close to the wind turbines but in the last year, an aggregation was observed (figure 24).

Table 6. Summary of the analyses to study the effect of distance from the foundations and the abundance of fish for eight species. The analysis for cod was carried out separately for larger and smaller cod. For a more detailed description of the results, see Bergström *et al.* (2011).

| Species | Effect of distance | Direction |
|---|---|---|
| **Longspined bullhead** | No | - |
| **Shorthorn sculpin** | Yes | Attraction |
| **Flounder** | No | - |
| **Goldsinny wrasse** | Yes | Attraction |
| **Black goby** | No | - |
| **Cod < 37 cm** | Yes | Attraction |
| **Cod > 37 cm** | Yes | Attraction |
| **Eelpout** | No | - |
| **Eel (Yellow eel)** | Yes | Attraction |

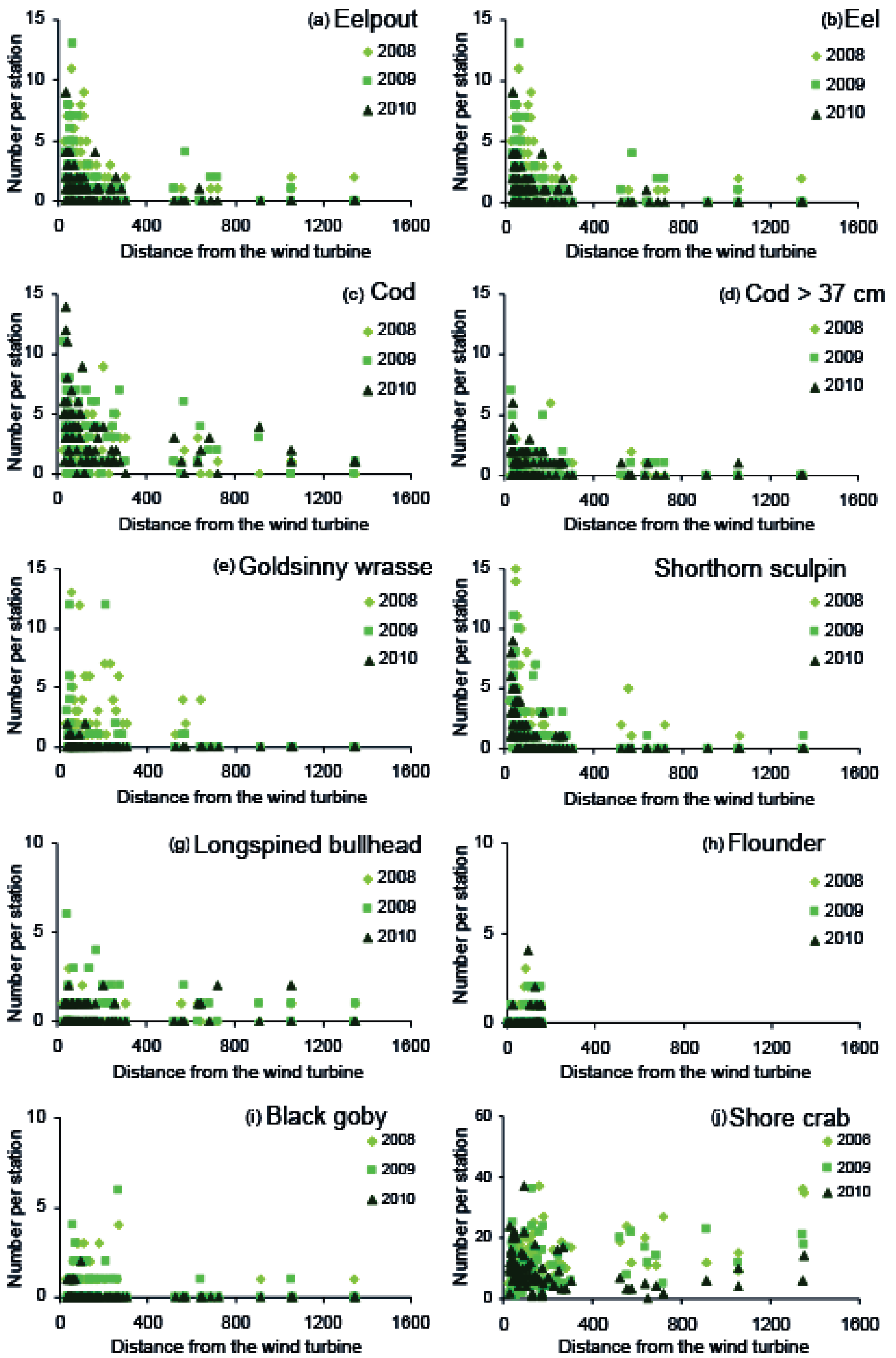


Figure 24. Number of individuals per station of a) eelpout, b) eel, c) cod, d) cod larger than 37 cm, e) goldsinny wrasse, f) shorthorn sculpin, g) black goby, h) longspined bullhead, i) flounder, j) shore crab in relation to the distance from the wind turbines at Lillgrund in the years 2008–2010.

## Effect Distance

On the basis of the increased data from 2010, the distance from the foundations at which an increased abundance of fish could be observed in the spring and the autumn respectively was estimated.

The analyses indicated a more obvious effect, for the species studied, on the spatial distribution in the spring than in the autumn. In the spring an increased total number of fish at between 0 and 100 metres from the wind turbines was observed. According to the statistical model applied, 36 % of the variation (Explained Deviance) of the total number of fish between stations could be explained by the distance to the closest wind turbine. In relation to the individual species, an increase in abundance was noted at a distance of between 0 and 50 metres from the wind turbine for cod <37 cm (level of explanation 20 %), 0 and 160 metres for eel and shorthorn sculpin (level of explanation 18 and 51 % respectively), and for the other species studied (cod >37 cm, eelpout and shore crab) between 0 and 90 metres (level of explanation 15, 13 and 21 % respectively).

In the autumn, the aggregation effect was weaker than in the spring. For cod > 37 cm and eelpout, no effect of distance from the wind turbine could be seen, and for shore crab, the response was significant, but showed an inconsistent pattern. For the other species studied, (eel, cod < 37 cm, shorthorn sculpin) an increased abundance at between 0 and 50–100 m from the wind turbine could be seen. The distance to the wind turbine only explained 7.4 % however, of the total variation between stations, for cod <37 cm. For eel and shorthorn sculpin, the level of explanation was somewhat higher (19.4 and 42 % respectively). Calculations based on the total number of fish, regardless of species, noted an increased abundance within a distance of 0 and 50 m, and the level of explanation from the model was 30 %.

### Correlation between Different Environmental Factors and the Spatial Distribution of Fish

The relative correlation between abundance of fish at the sampling station and the environmental factors DISTANCE, NOISE and DEPTH were investigated for the four most common fish species in the samples (eel, eelpout, cod, shorthorn sculpin), for the total number of fish and for shore crab. For cod, the analysis was carried out separately for larger and smaller individuals.

In the results, only models with a total level of explanation greater than 10 % are presented, which was achieved for 12 of the 14 models studied in total. The level of explanation was however, relatively low for some of the models presented, which shows that a large amount of the variation observed in the material analysed depended on factors other than distance, noise and/or depth. The greatest level of explanation was achieved for shorthorn sculpin (54.3 and 46.6 % in the spring and autumn respectively) and for the total number of fish in the spring (50.3 %). For all species apart from shore crab, a higher level of explanation was noted in the spring than in the autumn.

The most common variable in the final models was DISTANCE, which was included ($p < 0.05$) for all species apart from eelpout (table 7). In all cases where the factor DISTANCE made a significant contribution to the model, this reflected an increased number of individuals closer to the wind turbine. In addition, in relation to the comparison of DISTANCE and NOISE individually (table 8) a greater level of explanation was achieved in respect of DISTANCE for all species except eelpout.

The variable NOISE was included ($p < 0.05$) in seven of the models. With regard to the total abundance of fish (all species), a greater abundance of fish was seen in the spring at noise levels in the interval of 75–90 dB re 1 1μPa (RMS) than at noise levels higher than this (figure 25). At the lowest noise levels, the effect was not significant. This result is difficult to explain biologically, but could depend on the fact there were relatively few data points with low noise levels. In the autumn, no effect of noise was seen. This may be due to biological factors but may also be due to the fact that the noise model upon which the analyses are based, was based on measurements made in the spring. The models were not considered to be adequate enough to be able to estimate the effect distance in relation to noise levels for individual species. The clearest response for individual species was seen however, with eelpout and eel, similar to that seen for the total quantity of fish. For cod, no correlation was seen between abundance and noise level, and for shorthorn sculpin and shore crab, a correlation was only seen in the autumn (table 7). When interpreting the results it is important to take into consideration that they are dependent upon the level of precision in the noise model that the analyses were based on, in particular with regard to the data for the autumn, as well as to a certain extent on how the statistical model has been designed (e.g. the number of degrees of freedom which were accepted). The results may also potentially reflect the impact of wind speed, due to the fact that the noise level is correlated with the productivity of the wind turbine.

The variable DEPTH was included in six of the models, but in general had a relatively low impact ($p < 0.05$ in only two of the models). The variable was included in the final models primarily in the spring and for only one species also in the autumn. The result could be explained by the fact that fish perceive differences between different depths more in the spring, when temperature stratification (thermoclines) is more prominent compared with the autumn. The generally weak correlation between abundance of fish and depth is to some extent expected, because the differences in depth between the stations are considered to be low. Before the wind farm was established at Lillgrund the area was relatively homogenous in terms of the physical structure. The results of the analyses show however that the observed variation between stations with regard to the abundance of fish can be largely explained by factors associated with the wind farm (proximity to wind turbines and soundscape respectively) than by the existing topography in the area.

Table 7. Correlation between abundance of fish and the factors; distance from a wind turbine, noise levels and depth, according to the generalised additive models (GAM) based on data from spring (May) and autumn (October) in 2010. Where there is a number value given, this indicates that the factor was included in the final model, and a "–" means that the factor was not included. Low values indicate a stronger contribution. The results are presented for those models with a level of explanation (D %) of more than 10.

| | | Distance | Sound | Depth | D% |
|---|---|---|---|---|---|
| **Total number of fish** | | | | | |
| | Spring | <0.001 | <0.001 | - | 50,3 |
| | Autumn | 0,010 | 0,170 | - | 14,1 |
| **Eel** | | | | | |
| | Spring | 0,003 | 0,018 | 0,085 | 31,1 |
| | Autumn | 0,025 | 0,012 | 0,130 | 18,6 |
| **Cod >37 cm** | | | | | |
| | Spring | 0,011 | - | 0,193 | 10,7 |
| | Autumn | no model | | | <10 |
| **Cod < 37 cm** | | | | | |
| | Spring | <0,001 | - | - | 19,7 |
| | Autumn | no model | | | <10 |
| **Eelpout** | | | | | |
| | Spring | - | <0.001 | 0,006 | 34,2 |
| | Autumn | 0,181 | <0.001 | - | 22,3 |
| **Shorthorn sculpin** | | | | | |
| | Spring | <0,001 | - | 0,207 | 54,3 |
| | Autumn | <0,001 | 0,005 | - | 46,6 |
| **Shore crab** | | | | | |
| | Spring | <0,001 | - | 0,036 | 25,2 |
| | Autumn | 0,044 | <0,001 | - | 29,4 |

Table 8. Correlation between abundance of fish and the factors distance from a wind turbine, and noise level, analysed (GAM) separately for the spring (May) and the autumn (October) in 2010. The level of significance is given if the variable contributed to the model if p<0.05 (ns = no significant effect from the variable), in these cases, the level of explanation is also presented as D %.

| | DISTANCE | | SOUND | |
|---|---|---|---|---|
| | p | D % | p | D % |
| **Total number of fish** | | | | |
| Spring | <0,001 | 40,3 | <0,001 | 37,9 |
| Autumn | <0,001 | 8,610 | ns | - |
| **Eel** | | | | |
| Spring | <0,001 | 15,400 | ns | 10,3 |
| Autumn | ns | - | ns | - |
| **Cod >37 cm** | | | | |
| Spring | 0.014 | 7,09 | ns | - |
| Autumn | ns | - | ns | - |
| **Cod < 37 cm** | | | | |
| Spring | 0,004 | 19,7 | 0,014 | 8,52 |
| Autumn | ns | - | ns | - |
| **Eelpout** | | | | |
| Spring | <0,001 | 21,2 | <0,001 | |
| Autumn | ns | - | ns | - |
| **Shorthorn sculpin** | | | | |
| Spring | <0,001 | 50,3 | <0,001 | 36 |
| Autumn | <0,001 | 38,5 | <0,001 | 9,41 |
| **Shore crab** | | | | |
| Spring | <0,001 | 22,1 | <0,001 | 11,7 |
| Autumn | 0.001 | 15,6 | <0,001 | 24,1 |

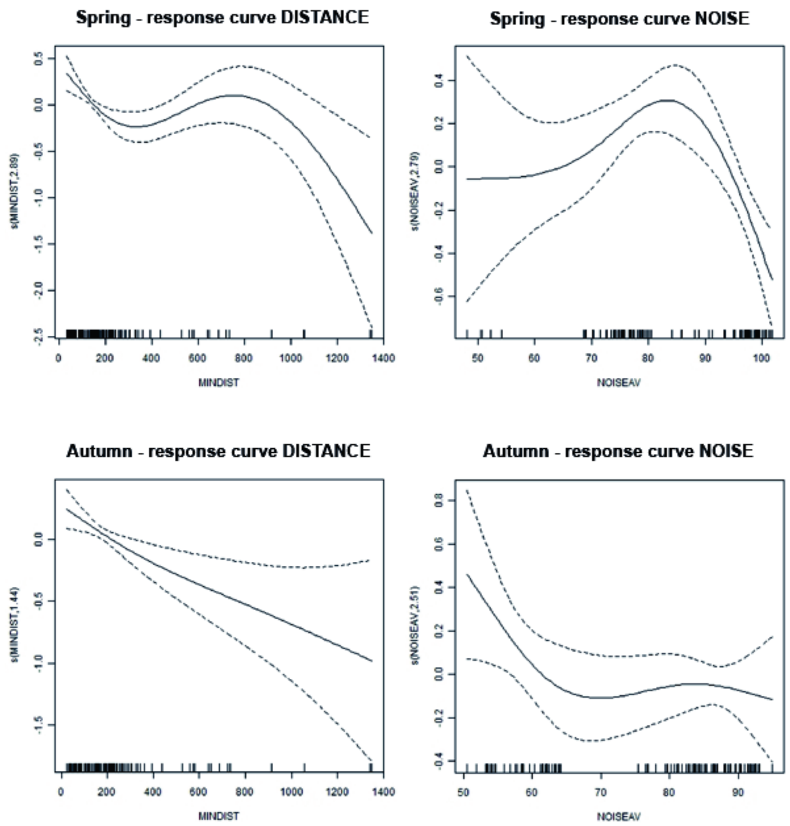


Figure 25. Response curves according to GAM to analyse the correlation between distance from the wind turbine and the noise levels with the catch of fish in the spring and autumn respectively (in total for all species). The factors were included as spline-functions (k<5). A greater quantity of fish was noted at distances of less than approximately one hundred metres from the closest wind turbine during both the spring and the autumn ($p < 0.01$). With regard to the noise levels, the highest quantities of fish were seen at noise levels in the interval of 75–90 dB re 1 1μPa (RMS) in the spring, whilst at higher noise levels, the quantity of fish was less ($p < 0.01$). At the lowest noise levels, no effect was seen, which is probably due to the fact that there were relatively few data points at that noise interval. In the autumn, no effect from noise was seen ($p = 0.17$). The differences between the seasons may be due to biological factors, or that the noise model on which the analyses are based was developed on the basis of the sampling conditions in the spring.

## Results from Sampling with Gill Net Series

### *Changes in the Number of Species and Species Composition*

Over the entire period studied, a total of 22 species were caught in the samples. Of these, 19 fish species were caught during the years 2002 to 2005 before the construction of the wind farm and 20 fish species from 2008 to 2009, after construction (table 9, Appendix 2). Shore crab occurred in all areas both before and after construction of the wind farm.

In the study period after the wind farm was constructed, flounder was the most common species at Lillgrund, whilst longspined bullhead was the most common at Bredgrund and cod most common at Sjollen (figure 26). For all three areas combined over the whole period studied (2002–2010), cod was most common, followed by flounder, shorthorn sculpin, longspined bullhead and goldsinny wrasse.

Table 9. List of the species that were caught using gill net series before (2002–2005) and after (2008–2009) the construction of the wind farm at Lillgrund and the two reference areas at Bredgrund and Sjollen. The total number of species is not directly comparable between the two periods because fishing was undertaken over a fewer number of years after construction compared with before. As a comparison, the calculated number of species as an average per station is given instead. For more detailed information see Appendix 2.

| | Bredgrund | | Lillgrund | | Sjollen | |
|---|---|---|---|---|---|---|
| *Species* | *Before* | *After* | *Before* | *After* | *Before* | *After* |
| Perch | | X | | | | |
| Yellow eel | X | | X | X | | X |
| Pipefish (undet.) | X | | | | | |
| Longspined bullhead | X | X | X | X | X | X |
| Turbot | X | X | X | X | X | |
| Plaice | X | X | X | X | X | X |
| Shorthorn sculpin | X | X | X | X | X | X |
| Dab | X | X | X | X | X | X |
| Herring | X | X | X | X | | |
| Sprat | | | X | | X | |
| Flounder | X | X | X | X | X | X |
| Hooknose | X | X | X | X | X | X |
| Corkwing wrasse | | | | | | X |
| Brill | | | | | | X |
| Goldsinny wrasse | | | X | X | X | X |
| Shore crab | X | X | X | X | X | X |
| Black goby | X | X | X | X | X | X |
| Sand eel (lesser/small) | X | X | | | | |
| Cod | X | X | X | X | X | X |
| Eelpout | X | X | X | X | | X |
| Whiting | X | X | X | X | X | |
| Sole | X | X | X | X | X | X |
| Trout | | | X | X | | |
| Number of species | 17 | 16 | 18 | 17 | 14 | 15 |
| Average number of species per *station* | 3,80 | 3,77 | 4,31 | 4,35 | 3,24 | 3,26 |

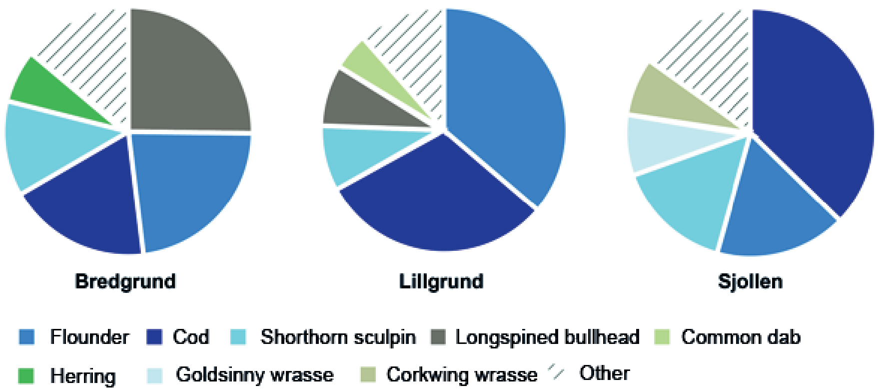


Figure 26. The distribution of the catch between species from sampling using gill net series at Lillgrund in the years 2008–2009. The distribution shows the abundance of the five most common species in each area, based on the average number per station for both years. The remaining species have been combined and are shown under "other".

The fish community species composition was different at Lillgrund compared with the two reference areas, but had an intermediate position between the two reference areas, which were more different from one another (figure 27). Just as was observed for the results from sampling with fyke nets, the pattern reflected the fact that the reference areas lay south and north of the wind farm area respectively, where the northern site was characterised by a greater marine component.

The species which primarily characterised the differences between the areas and years were goldsinny wrasse (most common at Sjollen), flounder (most common at Lillgrund) and cod (most common at Sjollen, figure 28). Shorthorn sculpin, which was the third most abundant species in the catch, in terms of total number for all areas, contributed to a lesser extent to the observed pattern.

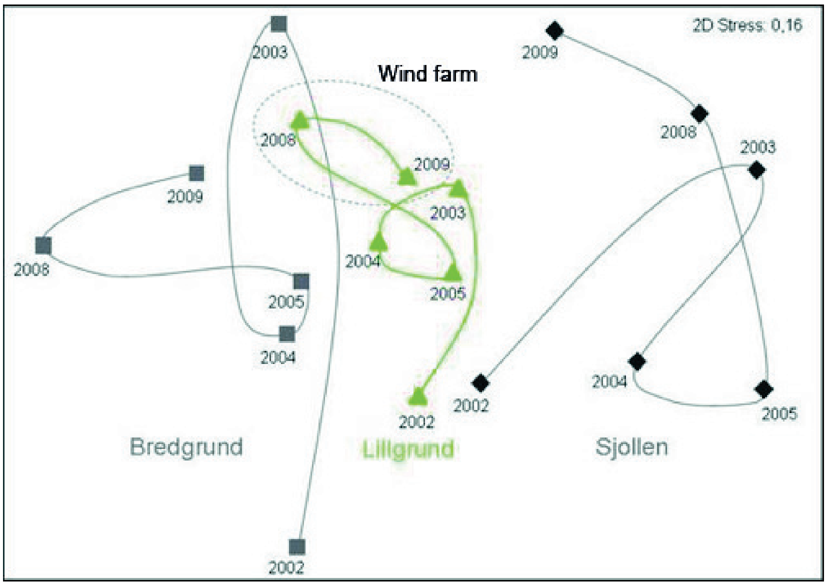


Figure 27. The results of the analysis (MDS, non-metric multidimensional scaling) which shows similarities in the species composition between areas and years, on the basis of the sampling with gill net series in the autumn. In the figure, the points which are closer to one another have a more similar species composition. One example is that the fish community at Sjollen and Lillgrund were relatively similar in 2002, but developed differently after this time. The lines join up adjacent years within the respective areas. The fish community at Lillgrund has similarities with both of the reference areas, whilst the two reference areas are more different from one another. The circles indicate where the sampling took place within Lillgrund after the wind farm was constructed.

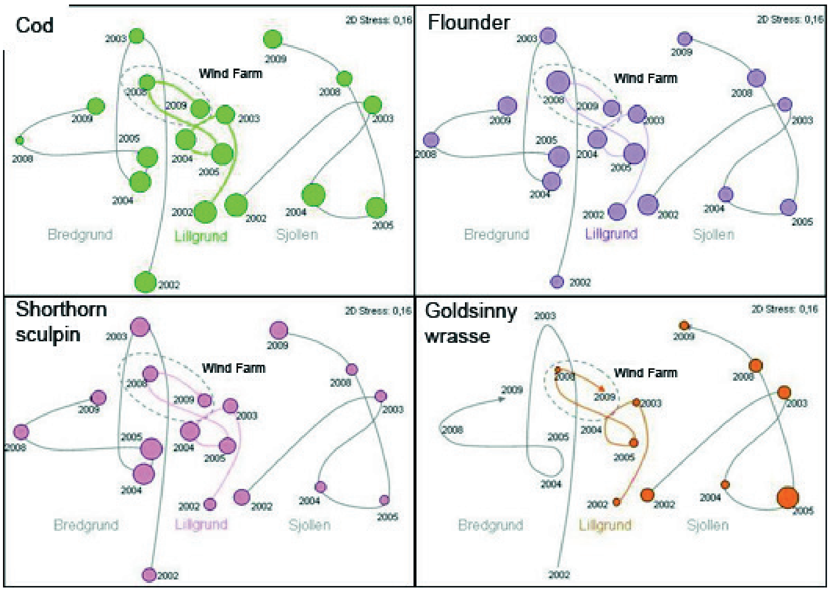


Figure 28. The abundance of cod, flounder, shorthorn sculpin and goldsinny wrasse in the years 2002 to 2009 at Lillgrund and the two reference areas. The size of the symbols indicate the number of individuals caught per site and year, so that the larger the symbol, the larger the catch. One example is characterised by the catch at Sjollen of a greater number of goldsinny wrasse than from the other areas, and the relative abundance of cod was higher during the baseline years in all areas (cf figure 30). The figures are based on the same analyses as are presented in figure 27.

## *Changes in the Size of the Catch*

### Total Number of Fish

The catch of fish varied greatly between years, but has had a similar pattern for all three areas (figure 29). During the baseline study, 2002 to 2005, the average number of fish caught was between 10 and 19 fish per station at Lillgrund. After the construction of the wind farm an average of 14 fish were caught per station in 2008, and 10 fish per station in 2009. The catch of fish at Lillgrund, as well as in the reference area Sjollen, was lower during the production phase than in some of the years included in the baseline study (table 4). At Bredgrund the catch of fish was similar between all years.

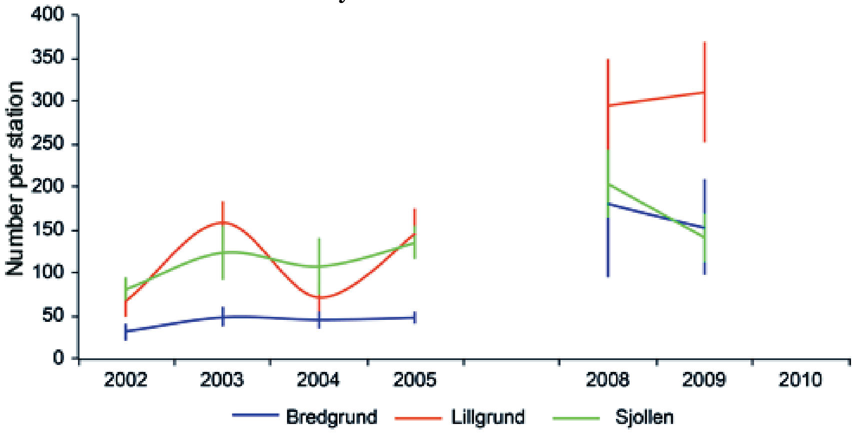


Figure 29. The total average number of fish per station and year, according to sampling with gill net series at Lillgrund and the two reference areas of Bredgrund and Sjollen in the autumn in the years 2002 to 2009. The vertical lines indicate a 95 % confidence interval.

Table 10. Results from the analyses of the differences between years in the number of fish per station, according to a generalised linear model (GLM). The abundance of fish in the final year of sampling (2009) is related to previous years in the analysis. The analyses were carried out separately for each site and for the total number of fish, as well as for the individual species cod, flounder, shorthorn sculpin, goldsinny wrasse and shore crab (cf figures 29–31). In the respective column, a “+” means that the catch was greater, and a “–” means that it was lower, and “ns” means that there was no significant difference compared with 2009 (p= 0.01). In the column “explD % ” the level of explanation of the model is presented as a percentage.

| | | | Comparison with 2009 | | | | |
|---|---|---|---|---|---|---|---|
| **Species** | **Site** | **explD %** | **2002** | **2003** | **2004** | **2005** | **2008** |
| **Fish** | Lillgrund | 17.7 | + | ns | + | + | ns |
| | Bredgrund | 28.1 | ns- | ns | ns | ns | ns |
| | Sjollen | 30.9 | + | ns | ns | + | ns |
| **Cod** | Lillgrund | 29.6 | + | ns | ns | + | ns |
| | Bredgrund | 42.5 | + | ns | + | + | ns |
| | Sjollen | 33.3 | + | ns | + | ns | ns |
| **Flounder** | Lillgrund | 23.4 | ns | ns | ns | + | + |
| | Bredgrund | 17.8 | ns | ns | ns | ns | ns |
| | Sjollen | 24.4 | + | ns | ns | ns | ns |
| **Shorthorn sculpin** | Lillgrund | 26.5 | ns | ns | + | ns | ns |
| | Bredgrund | 35.6 | ns | + | + | + | ns |
| | Sjollen | 34.0 | ns | - | - | - | - |
| **Goldsinny wrasse** | Lillgrund | 19.7 | ns | ns | ns | ns | ns |
| | Bredgrund | | | | | | |
| | Sjollen | 52.7 | ns | ns | ns | + | ns |
| **Shore crab** | Lillgrund | 58.6 | - | - | - | - | ns |
| | Bredgrund | 46.4 | - | - | - | - | ns |
| | Sjollen | 23.1 | ns | ns | ns | ns | ns |

### *Development of the Most Abundant Fish Species*

The development over time was studied in more detail for the most abundant species from the sampling. In terms of number, calculated for all years in all areas, cod (42 % of the catch on average), flounder (19 %) and shorthorn sculpin (12 %) were the most common species in the sampling with gill net series. In addition to these three species, goldsinny wrasse was also included, which made up five percent of the catch on average.

#### Cod

The abundance of cod, in terms of number per station, was highest at Sjollen and least, further to the south at Bredgrund (figure 30). At Lillgrund the largest catch was recorded from 2002 and 2005. In all areas, the largest catches occurred in the two to three years before the construction of the wind farm (table 10).

#### Flounder

The catch of flounder was greatest at Lillgrund, whilst the species was caught in relatively similar quantities in the two reference areas (figure 30). At Lillgrund the largest catch was recorded in 2005 and 2008 (table 10). There was no significant difference between years in the two reference areas, apart from a relatively high abundance of flounder recorded in the first year of the study (2002) from Sjollen.

#### Shorthorn Sculpin

The abundance of shorthorn sculpin was highest at Bredgrund in the south and lowest at Sjollen furthest to the north (figure 30). At Lillgrund and Bredgrund, the largest catch of shorthorn sculpin was recorded in 2004 and 2003–2005 respectively. The catch of shorthorn sculpin at Sjollen was largest in 2002 and 2010 (table 10).

#### Goldsinny Wrasse

Goldsinny wrasse had its greatest abundance per station at Sjollen, whilst only limited numbers were caught from Lillgrund and none from Bredgrund (figure 30). The catch of goldsinny wrasse at Lillgrund was the same between years, whilst at Sjollen it was greater in 2005 than in the other years (table 10).

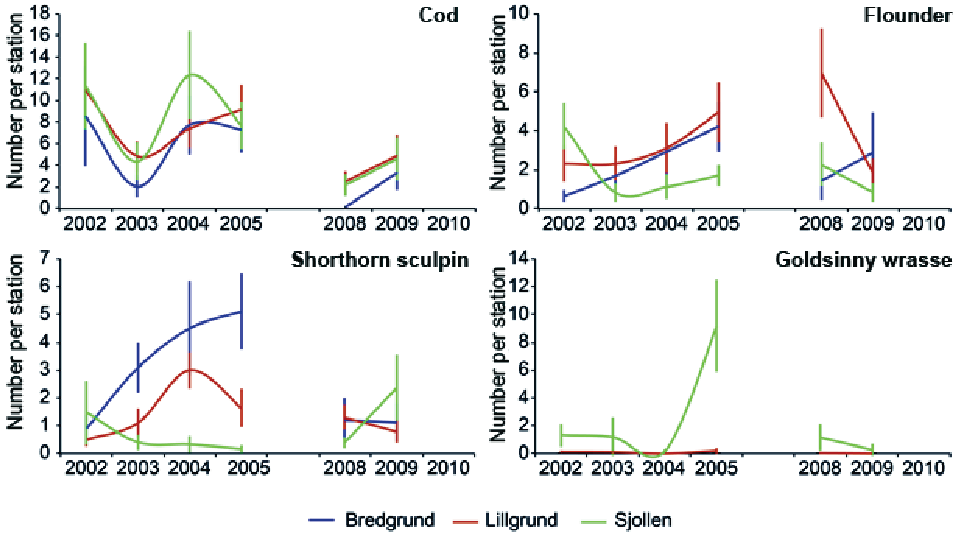


Figure 30. Results per year from the sampling using gill net series in the autumn. The average number of individuals per station and year for cod, flounder, shorthorn sculpin and goldsinny wrasse at Lillgrund and the reference areas of Bredgrund and Sjollen in the years 2002 to 2009. Sampling using gill net series was not carried out in 2010. The vertical lines indicate 95 % confidence intervals.

## Shore Crab

The shore crab was in terms of numbers, the dominant species in the sampling both before and after construction of the wind farm (64–97 % of the total number of individuals). At both Lillgrund and Bredgrund the catch of shore crab was greater after the construction than during the base line studies, whilst the number of shore crabs caught was the same at Sjollen between years (table 10, figure 31).

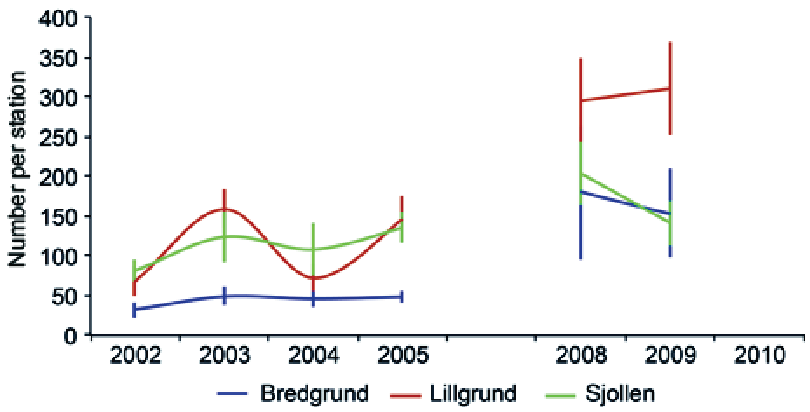


Figure 31. The results from the sampling with gill net series in the autumn. The average catch of shore crab per station and year at Lillgrund and the two reference areas Bredgrund and Sjollen in the years 2002 to 2009. Sampling using gill net series was not carried out in 2010. The vertical lines indicate 95 % confidence intervals.

*Size Distribution of Cod.*

The cod at Lillgrund in the autumn of 2008 and 2009 were smaller in size than they were in the same area during the baseline study period[13] (figure 12). The cod were also smaller in the reference areas in the years 2008 and 2009 than during the base line study period[14]. The difference in the length of the cod at Lillgrund in 2008 and 2009 is not significantly different from the difference in length of the cod at Sjollen in the same year[15]. The difference in length at Lillgrund and Sjollen is however significantly different from Bredgund[16] (figure 32).

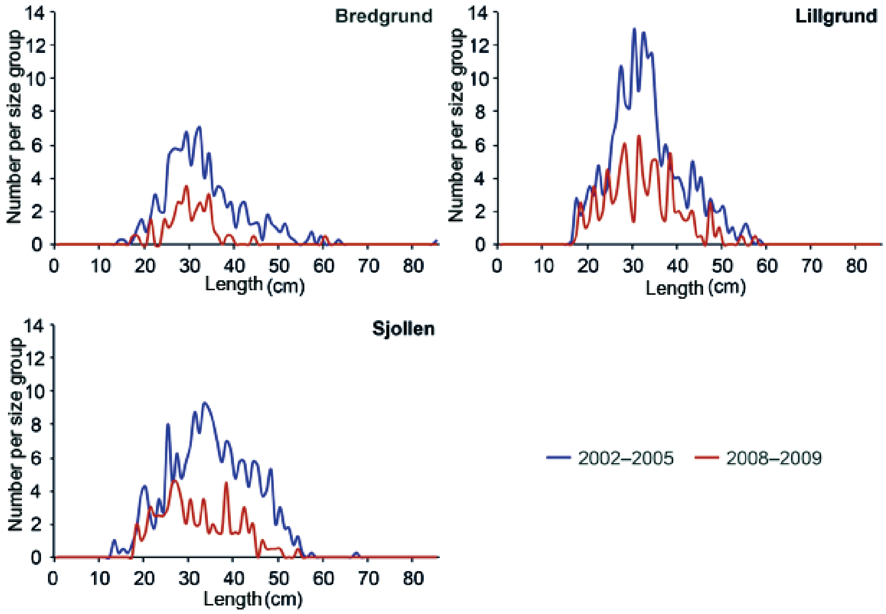


Figure 32. Comparison between the size distribution of cod before and after the wind farm was constructed, according to the sampling using gill net series, presented separately for Lillgrund and the two reference areas Bredgrund and Sjollen.

# Discussion

The aim of the fish sampling was to obtain an understanding of the benthic fish communities at Lillgrund, in order to see if there were any changes in the species composition and the quantity of fish in the area after the construction of the wind farm. The sampling was undertaken using fyke nets and gill net

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13 Two-tailed Z-test, Lillgrund; mean value for the distribution 2008-2009 compared with the distribution in 2002-2005 n=86, Z=2.96, p=0.003.

14 Two-tailed Z-test, mean value for the distribution 2008-2009 compared with the distribution in 2002-2005. Bredgrund; n=86, Z=3.87, p<0.001, Sjollen; n=86, Z=3.99, p<0.001.

15 Two-tailed Z-test; mean value for the distribution 2008-2009 at Lillgrund compared with the distribution at Sjollen, n=86, Z=0.86, p=0.39.

16 Two-tailed Z-test; mean value for the distribution 2008-2009 at Lillgrund and Sjollen compared with the distribution at Bredgrund. Lillgrund vs Bredgrund; n=86, Z=3.32, p<0.001, Bredgrund vs Sjollen; n=86, Z=-2.89, p=0.004.

series. These methods catch different parts of the benthic fish communities. Two reference areas were chosen in order to highlight changes at Lillgrund in relation to more general changes in the benthic fish communities in the Öresund Strait.

The fish sampling with fyke nets and gill net series in general worked well, despite the fact that there were occasional problems with large numbers of shore crabs that got stuck in the nets. The large quantities of shore crabs in the catches may have had an impact on the catch of fish, as it may have been easier for the fish to avoid the nets or the shore crabs may have removed fish that were caught in the nets. The results were however, still considered to be possible to interpret, but with some caution regarding gill nets.

The results show that there have not been any major changes in the species composition or abundance of fish in the area following the construction of the wind farm. In those cases where changes in the species composition or abundance have been observed, these changes have also been observed in at least one of the reference areas. This indicates that the abundance of fish within the wind farm is primarily influenced by the same overarching factors as in the reference areas, rather than the developments within the wind farm.

A distinct change that took place during the study period was an increase in the abundance of shore crab. Shore crabs increased at Lillgrund as well as in the reference areas, but the relative change was greater at Lillgrund. It is likely that shore crab is favoured because it can easily find hiding places around the foundations of the wind turbines with their surrounding scour protection, where it can avoid being eaten by predators. The increase was obvious in the first two years of production, whilst the catch of shore crab in the third year of production was similar to that during some of the years included in the baseline study. It is interesting to compare the observed pattern with observations from the artificial reefs at Vinga outside of Göteborg (Andersson & Bergström 2007). At Vinga, an increase primarily of lobster and cod was seen after three years, at the same time as the quantity of their prey, primarily shore crab and other smaller shell fish, declined. The increase in lobster and cod was explained by an improved access to shelter and food in the artificial structures, but also because of the reduced fishing pressure because the artificial reef was covered by a fishing ban. It is possible that a similar effect could occur at Lillgrund in the longer term. On the basis of the current data, an increase in the total abundance of cod could however, not be observed.

The clearest result was that an aggregation of fish in close proximity to the wind turbines has occurred, primarily of cod and yellow eel (but not flounder despite the fact that this species was relatively abundant in the catch samples). The response is however, relatively weak and limited to the areas closest to the foundations. Due to the fact that there was no increase observed in the quantity of fish within the entire wind farm, the results most likely reflect a redistribution of the fish within the area, rather than an altered productivity or migration of fish from surrounding areas.

A comparison of the different factors influencing the area showed that the distribution pattern of the fish at Lillgrund could be, to a larger extent, explained by the proximity of the wind farm rather than the natural topography of the area (depth conditions). The most obvious effect was that the physical presence of the foundations had an aggregation effect on the fish. The analyses also indicated a correlation between the abundance of fish and the local noise environment, at least for some species, with a reduced abundance of fish at higher noise levels. The clearest response from individual species was seen in eelpout and eel. No response in relation to the noise levels was seen in cod, and in shorthorn sculpin and shore crab a correlation was seen, but only in the autumn. Due to the fact that the noise levels were calculated on the basis of productivity in the wind farm, which is correlated with wind speed, the results may potentially also reflect an effect of wind speed. The results however, agree with results from fish sampling from the Svante wind farm in the Baltic Sea, where an attraction to the wind turbine effect was noted both under production and when the turbines were standing still, but with a relatively pronounced effect when the turbines were not moving (Westerberg 1994). The magnitude of the effect from noise was however lower than the aggregation effect in the area close to the turbines. These results can be interpreted as such that the fish aggregate in an area close to the wind turbine under all conditions, but that the effect was weaker, in relative terms, under conditions of higher noise levels.

The results from the studies presented reflect results for species which can be caught in the fish sampling equipment used (fyke nets and gill net series). Fish species which are either too small to be caught in this type of equipment, or have a behaviour that reduces the chances that they are caught by the gear, for example fish species living in open water, and were not included. Close to the wind turbines, divers have observed an increase in the abundance of small fish in the same areas, primarily of black goby (Mathias Andersson, *pers comm*). Both shore crab and these smaller fish species are important prey for predatory fish, and may potentially increase the attractiveness of the wind farm as a feeding ground for larger predatory fish over time. It would be recommended to revisit the wind farm after some more years to follow up the long term development of the fish communities, and see if the observed aggregation of certain fish species close to the wind turbines continues, and potentially increases to become a quantitative effect. One of the conditions for this type of development is that the removal of fish, such as from commercial fishing or predation by marine mammals or fish-eating birds does not increase in the area.

# Pelagic Fish

## Introduction

The pelagic fish species make up the larger proportion of the fish biomass in the Öresund Strait. The dominating pelagic species in the Öresund Strait are herring (*Clupea harrengus*) and sprat (*Sprattus sprattus*).

Fishing for herring is important both for the Swedish and Danish commercial fishing industries in the area. The Swedish fishing industry in the Öresund Strait consists to some 90 % of herring. Herring show seasonal migrations through the Öresund Strait between spawning grounds and feeding areas in the Baltic Sea and Skagerrak and Kattegatt respectively (Beister 1979; ICES 1983; Jönsson & Beister 1979; Kalejs & Ojaveer 1989; Otterlind 1984; Otterlind 1987). Sprat occurs in large quantities in the Öresund Strait. Fishing for this species is restricted in the area, but sprat are of great significance as food for cod and other commercial species. Mackerel, which is also a pelagic species, also occurs in the Öresund Strait, but there is only limited commercial fishing for this species. Herring caught in the Öresund Strait are primarily Rügen herring (western Baltic herring), which spawn in the spring in the western Baltic Sea around the island of Rügen. The Rügen herring normally migrate north through Öresund Strait after spawning around Rügen from February –April. In the summer they are found in feeding areas located in Skagerrak and the north–eastern part of the North Sea. In August–September they migrate to the Öresund Strait where they overwinter before migrating further south for spawning.

### Expected Impact

The underwater noise from wind farms in the Öresund Strait at full production, could theoretically be heard by herring at a distance of up to 16 km. Herring are one of the fish species which have a special adaptation for transmitting sound from their swim bladder to their inner ear and have a relatively wide hearing spectrum (figure 4). The degree of impact from external sound disturbance is dependent on the species of fish. If the fish use the soundscape actively, for example during spawning, orientation or to avoid predators, then there may be a reaction even at low sound levels. If the sound does not contain any specific information for the fish, the reaction may only occur at very short distances (Wahlberg and Westerberg 2005). See the chapter on acoustics.

In order to investigate potential impact from the wind farm at Lillgrund on the migration of the Rügen herring to and from their spawning ground in the Baltic Sea, hydroacoustic studies were carried out before the wind farm was constructed. The results from the baseline studies showed that the statistical strength was low in terms of being able to identify differences between years. The statistical strength was even lower in terms of identifying differences between sites due to the fact that herring have a natural tendency to form shoals. A decision was taken to exclude the hydroacoustic studies from during the period when the wind farm was in production and replace this with commercial fishing statistics and studies of potential changes in the fishing patterns. A description of the results available from the hydroacoustic studies, which were carried out, is available in the report from the baseline studies (Lagenfelt *et.al.* 2006).

# Method

## Commercial Fishing Catch Statistics

The catch statistics from Swedish commercial fishing is based on the fishermen's logbook notations of their daily catch. There has been a complete ban on trawling in the Öresund Strait since 1932 and no catches from trawling or seine nets are thus included in the results. A compilation from herring net data (equipment nr 721) for the ICES subdivision 23 (catch area Öresund) in the logbook database was used (figure 33) instead. The starting positions for the net fishing and the catches were filtered, according to "outside" and "inside" a distance of 10 km from the wind farm. This is an approximation of the distance within which herring could detect noise from the wind farm. In the logbook, the starting position was given in degrees and whole minutes (one distance minute = 1852 metres), which provides an accuracy of ± 926 metres.

The catch results selected were for the three months of the year, when herring fishing primarily takes place; September, October and November. Approximately 60 % of the catch is taken during these months. The catch data for three, three-year periods was used:

- The period before the establishment of the wind farm; the years 2003–2005 (baseline period)
- The period after establishment of the wind farm; the years 2008–2010 (production period).
- The period before the construction work on the Öresund Link (including the bridge) began was also included (years 1993–1995).

The latter period was included because the soundscape was influenced by the Öresund Link and its construction (figure 35). This data was used in order to be able to interpret changes in the fishing patterns in the Öresund Strait. The Öresund Link was constructed during the period 1995-11-01–2000-05-31, and was put in operation on 2000-06-01 (Appelberg *et.al.* 2005). Data was analysed in relation to the amount of fishing equipment, the number of metres of net that was used as well as the catch and the catch per unit effort.

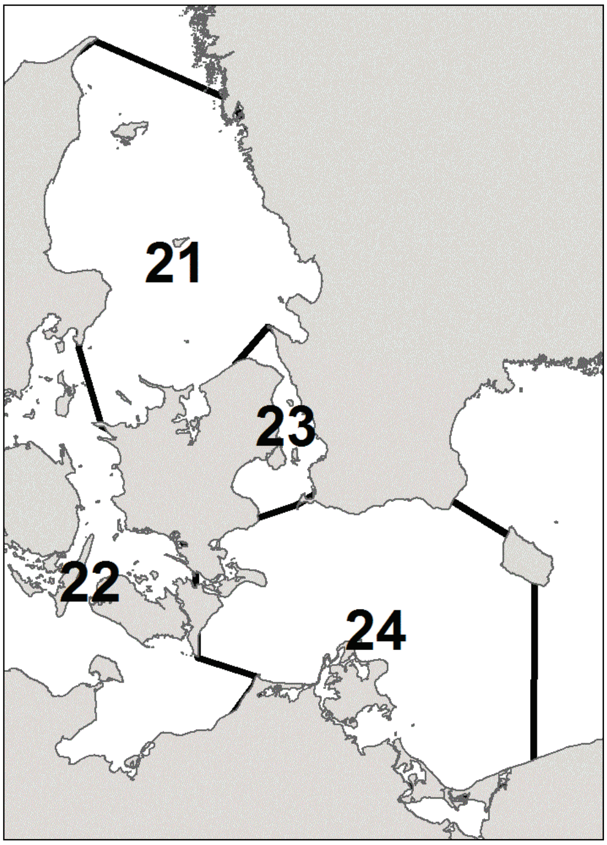


Figure 33. Catch area map with the ICES subdivisions (SD) no. 21–24. The statistical squares which are used by the commercial fishing industry are also included. © Ulf Bergström.

### Fisheries independent statistics

Information on the density of herring, independent of commercial fishing (number of individuals and biomass) from the ICES HAWG REPORT 2010 "Herring in Subdivisions 21–24" (Western Baltic Sea and Southern Kattegatt) was used. The information regarding adult fish (3 years and older) used, comes from the hydroacoustic studies carried out by Denmark and Germany in September to October and which were reported internationally through the ICES. The herring genetic data is from Greifswalder Bodden and the adjacent subdivisions (SD 24). The investigations were carried out on a weekly basis in these areas during the spawning period (March/April until June). The index used is defined as the total number of larvae which have reached 20 mm in length. The preliminary data for 2010 was obtained from ICES.

# Results

### Catch Statistics from Commercial Fishing

The number of fishing occasions recorded varied from between 117 and 153 per year in the part of the Öresund Strait which is characterised as "outside" the area where the herring would be expected to be able to detect noise from the wind farm (area north of Sjollen and the Öresund Bridge) during the baseline years (2003–2005). During 2008 the number of fishing occasions was approximately the same in this area. In the years 2009 and 2010 the number of fishing occasions increased dramatically in this area, and was up to 319 in 2010 (figures 34 and 35). Fishing from within the area “inside” where the herring would be expected to detect noise from the wind farm (an area south of Sjollen and the Öresund Bridge) lay at 17 to 20 fishing occasions during the baseline period and virtually ceased during the period when the wind farm was in operation (2008–2010).

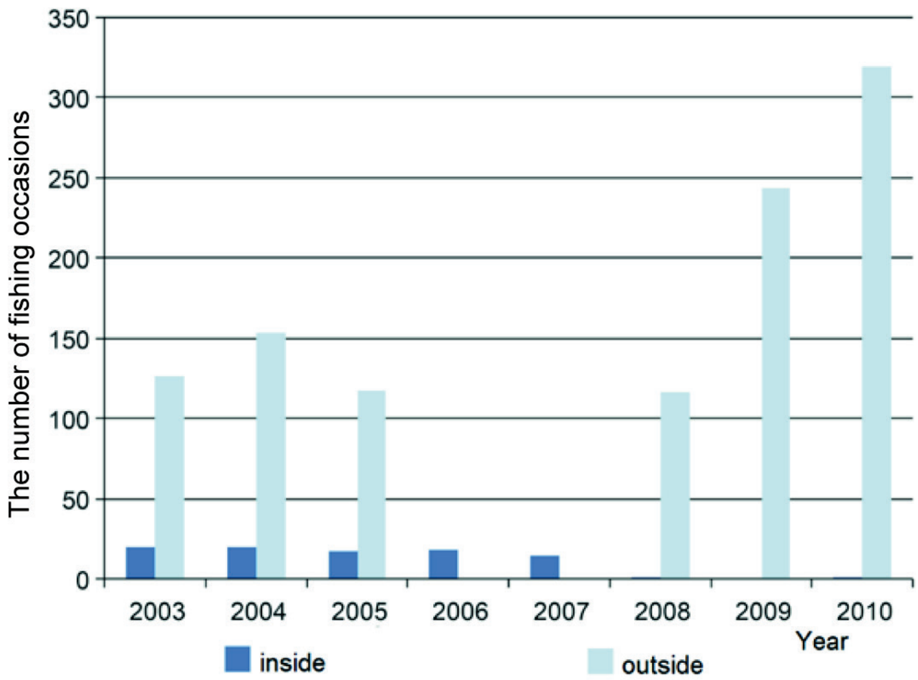


Figure 34. The number of recorded fishing occasions with herring nets for the ICES subdivision 23 (catch area Öresund) period 2003 to 2010. “Inside” and “outside” respectively include areas where herring can be expected to detect or not detect sound from the wind farm respectively (see text). The baseline period includes the years 2003 to 2005 and the production years 2008 to 2010. The years 2006 and 2007 were not included in the analyses.

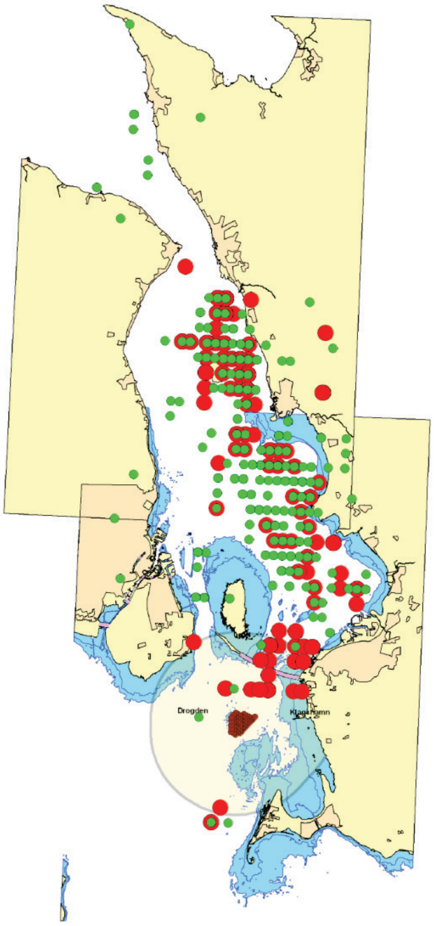


Figure 35. The number of recorded fishing occasions with herring nets for the ICES subdivision 23 (catch area Öresund) period 2003 to 2010. The area "inside" where herring can be expected to detect sound from the wind farm is marked with a light yellow buffer zone (circle) around the wind farm. The baseline period includes the years 2003 to 2005 (red spots) and the production years 2008 to 2010 (green spots). © Swedish Maritime Administration permit no. 09-03671.

The catch per unit effort was lower during the baseline years in the area "inside" and was between 0.14 to 0.28 kg catch of herring per metre of net and in the other parts of the Strait between 0.82 and 1.6 kg. The catch per unit effort south of Sjollen and the Öresund Link (area for the wind farm) was thus only 16 to 18 percent of that taken from the area north of Sjollen and the Öresund Link (figure 35). The very low total quantity of fish in the area close to the wind farm meant that the estimate of the annual catch per unit effort during the years when the wind farm was in operation was uncertain. In the area "outside", the size of the catch per unit effort was of the same order, between 0.63 and 1.6 kg herring per metre of net, during the operation phase as during the baseline period, despite the significant increase in the amount of fishing (figure 34) and a significant increase in the length of nets used (figure 36). The average catch per unit effort in the area "inside" during the baseline period was 0.20 kg of herring per metre of net and for the three years when the wind farm was in operation, it was 0.24 kg of herring per metre of net. The equivalent figures for the area "outside" were 1.2 kg and 1.3 kg catch of herring per metre of net respectively (figure 36).

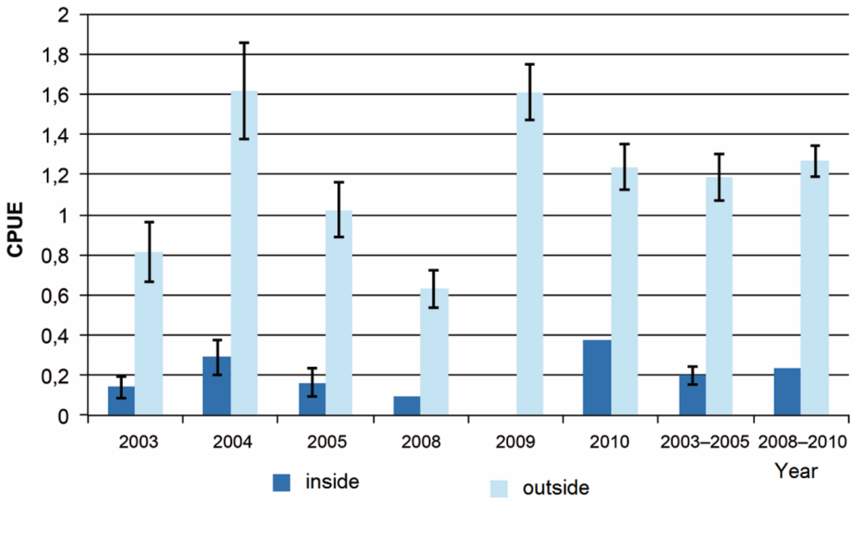


Figure 36. Catch of herring (kg per metre of net and effort) for the ICES subdivision 23 (catch area Öresund) baseline years 2003–2005 and production years 2008–2010 respectively. Average ± 95 % confidence interval. For the years 2008 and 2010 there was only one fishing occasion per year during the months of interest. No fishing took place in 2009.

There was a relatively large variation in the amount of net used when fishing in the area "inside" during the baseline years (figure 37). Due to the limited amount of fishing that took place in the area when the wind farm was in operation, it was not possible to undertake equivalent calculations for these years, but some occasional fishing events took place with up to 4000 metres of net. The average length of net during the baseline study period was 1700 metres and during the period when the wind farm was in operation it was 2400 metres (based on a limited amount of data).

In the area "outside", the annual average varied from 1040 metres to 1137 metres of net during the baseline study period with an average of 1070 metres. During the period when the wind farm was in production, the values were between 1482 metres to 2407 metres with an average for the entire period of 1651 metres (figure 37).

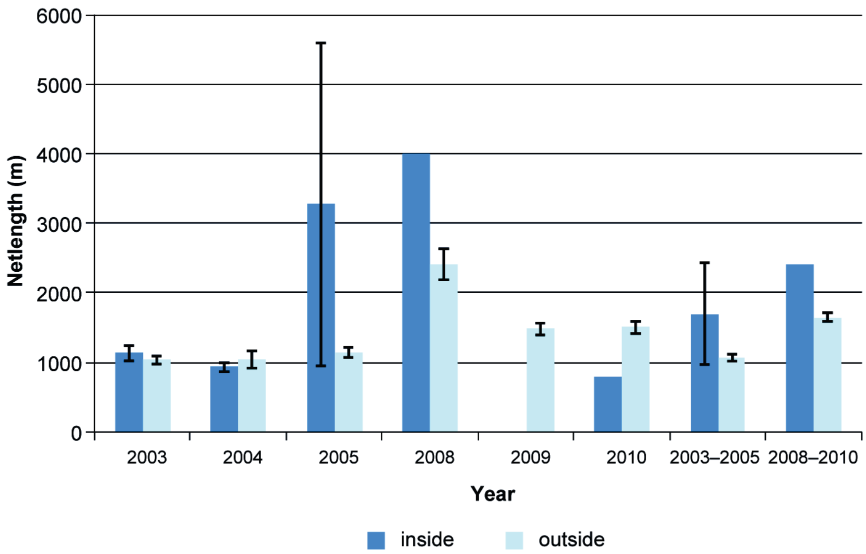


Figure 37. The length of net (metres) for herring nets within the ICES subdivision 23 (catch area Öresund) baseline period 2003–2005 and production period 2008–2010 respectively. Average ± 95 % confidence interval. For the years 2008 and 2010, there was only one fishing occasion per year during the months studied. No fishing took place in 2009.

## Statistics Independent of Commercial Fishing

Impact on herring migration could have an influence on both the migration between Skagerrak/Kattegatt and the Baltic Sea via the Öresund Strait and recruitment in the western Baltic Sea.

The recruitment success (given as abundance of larvae) is the index which is used to estimate the future biomass of adult fish. The recruitment success can be expected to have significance for the abundance of adult herring in the Öresund Strait two to three years after the larvae have started to migrate to the Öresund Strait and have become sexually mature. At two years of age, approximately a fifth of the herring are mature enough to take part in spawning (ICES HAWG 2010). The proportion of sexually mature herring increases to 75 % at three years of age and all herring are sexually mature when they are five years or more old.

On the basis of the data from the ICES it was not possible to establish any correlation between the number of herring of two years or older and the number of year-old juveniles (0+) equivalent to number of years earlier, for any of the years studied (figure 38). There was also no correlation between the spawning biomass of the parent generation of herring and the number of juveniles born this season.

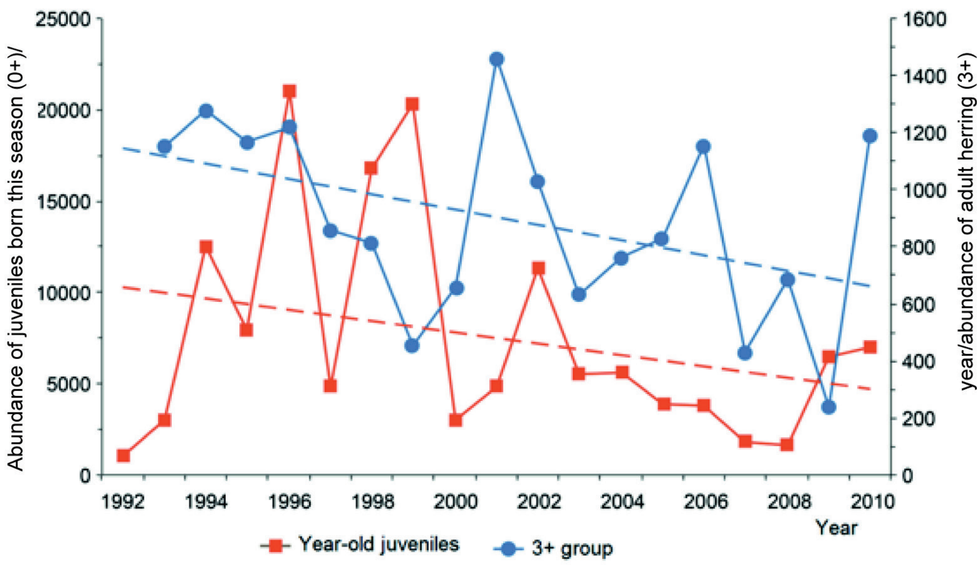


Figure 38. Abundance (number in millions) of adult herring (3+-group) and herring larvae (born this season = 0+-grupp). Abundance of juvenile herring (number in 0+-group) is taken from the ICES-study in Greifswalder Bodden (~Rügen herring spawning grounds) with a limited area (SD 24). The abundance of adult herring (3+-group) is taken from the ICES studies in the southern Kattegatt, Öresund-Belt and western Baltic Sea (SD21-24) (ICES HAWG 2010). Preliminary data from 2010 was provided by the ICES. The declining trends are not significant (P>0.05).

The abundance of juveniles born this season *(*0+) over the period 1992-2010 showed a tendency towards a decline, which was not however significant according $p<0.05$[17] (figure 38). The tendency was strongest for the period

[17] Linear regression, r = -0.285 n = 19, p = 0.236

1993–2010[18]. In relation to the abundance of adults (3+-group) there was also an observed tendency towards a decline[19].

A comparison between the baseline period (2003–2005) and the production phase (2008–2010) for the wind farm as well as a period before the Öresund Link was built (1993–1995) (figure 39) showed that the biomass of adult herring (3+) in the area SD 21–24 was highest in the period before the Öresund Link was built, and it then declined ($r^2 = 0.995$). The declining trend was however not significant for the whole time period 1993–2010[20].

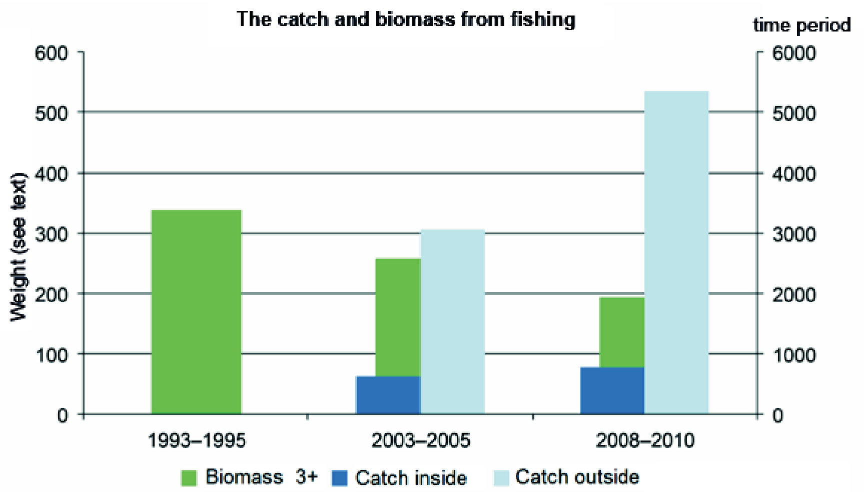


Figure 39. Biomass [1000s of tonnes] of adult herring (3+) within ICES SD 21–24 according to ICES HAWG (2010, preliminary data for 2010), over three time periods (total sum); before the Öresund Link 1993–1995, the baseline study period for the wind farm 2003–2005 and the production phase of the wind farm 2008–2010. The catch of herring [kg] within the area close to the wind farm (catch inside) compared with the rest of the Öresund Strait (rest of SD 23 = catch outside).

# Discussion

The abundance of Rügen herring and fishing for this pelagic species exhibits large natural variations between years. Several different factors may influence the size of the population and it is difficult to distinguish any possible effects from the establishment of the wind farm after only three years of operation.

That herring fishing in effect completely ceased within a zone which stretches 10 km (+1000 m) out from the wind farm coincides well with the ban on drift-net fishing in the Baltic Sea. The phasing out of drift-net fishing began in 2005. From the 1st January 2008, it became forbidden to carry drift-nets on board ship or use drift-nets for fishing (FIFS 2006:29). During 2007, Swedish fishing vessels were allowed to use drift-nets in the Baltic Sea if they had had permission to use drift-nets in 2006.

[18] Linear regression, r = -0.431 n = 18, p = 0.074

[19] Linear regression, r = -0.425 n = 18, p = 0.079

[20] Linear regression based on log-transformed data, r = -0.411, n = 18, p = 0.090

The ban on drift-net fishing does not however explain why fishing for herring within the other areas of SD 23 (north of Sjollen and the Öresund Link) increased significantly. During the baseline study period 2003–2005, fishing events took place on average approximately 130 times per year in the area north of Sjollen and the Öresund Link, and in 2010 more than 300 fishing occasions were registered. The catch per unit effort remained unchanged during the period when the wind farm was in operation compared with the baseline study period (2003–2005) whilst the length of the nets increased by approximately 50 percent. The increase could not be explained by changes in the fishing quota. The herring quota for subdivision 22–24 decreased linearly from just over 10 000 tonnes per year in 2005 to just under 3000 tonnes per year in 2011[21].

One explanation may be that the fishermen have changed their focus regarding the target species. This may have occured partly due to an increased price for herring in relation to other species, or that the herring for some reason had become easier to catch than previously. An analysis of the wholesale commercial fishing herring prices per kg showed that the herring prices increased from just over 2 kr per kg in 2004 to just over 4 kr per kg in 2010 (figure 40). The price trends for herring were similar on the south coast and on the west coast. The analysis also showed that the wholesale prices for cod were relatively stable over time (2001–2010), with a slightly higher price for cod on the west coast than on the south coast. With regard to the operational period for the wind farm (2008–2010), the price analysis showed that the fishermen got paid more for herring per kg in 2009 and 2010 than in 2008, at the same time as they got lower prices per kg for cod in the same year.

The changes in fishing patterns for herring in the Öresund Strait were probably an effect of the favourable pricing development for herring. This does not however provide an answer to the question of whether the herring slow down on their migration due to the noise from the Öresund Link and/or the wind farm. The soundscape from the bridge coincides with the area where herring would be expected to be able to detect sound from the wind farm (figure 35).

If more herring have stayed north of the Öresund Link in recent years, this may be due either to the fact that the herring population has increased in size or that the migration of herring through the Öresund Strait is slowed down. Due to the fact that the herring population in the Öresund Strait is primarily made up of adults, it could be expected that changes in recruitment success in the western Baltic Sea would have an impact on the quantity of herring in the Öresund Strait a few years after spawning. The ICES data did not show any significant correlation between the density of herring juveniles in the western Baltic Sea and the number/biomass of adult herring (3 years or older) a number of years later in the Öresund Strait. There is a tendency towards a negative trend over the time period 1993–2010 (figure 38).

[21] Linear regression, $r = -0.957$, $n = 7$, $p = 0.00072$

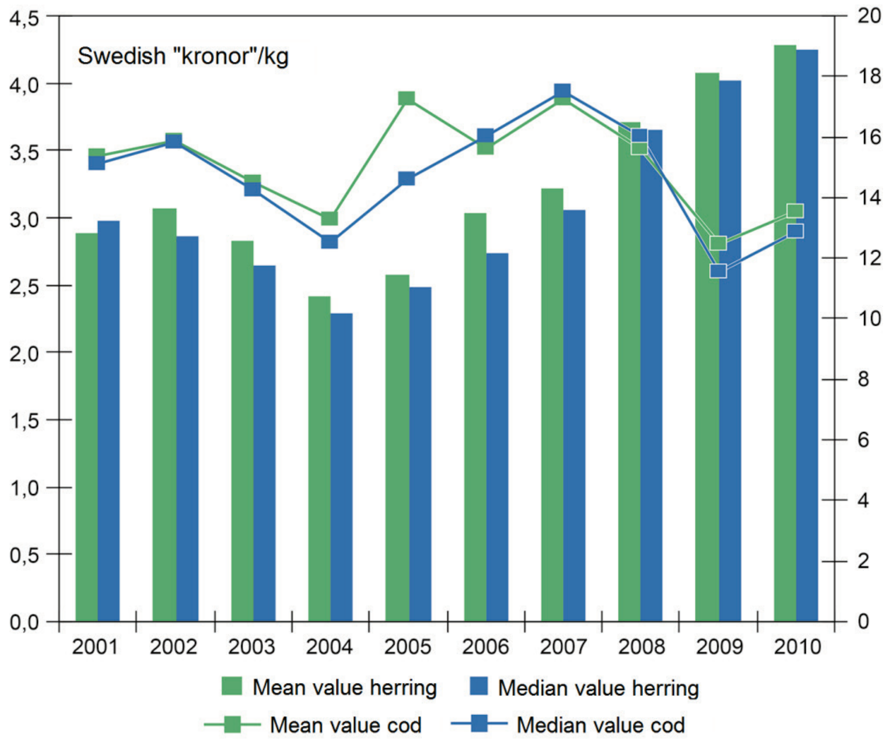


Figure 40. Wholesale fish prices for herring and cod (mean price kr/kg) and areas South Coast and West Coast respectively.

In short it is difficult to distinguish possible effects caused by the wind farm, from the ban on drift-net fishing and the establishment of the Öresund Link, because of the limited resolution in the catch statistics before the bridge was constructed (pre 1995). In the final report on the impact of the Öresund Link on fish communities and fishing, it is stated that there are no clear results showing that the migration of Rügen herring has been influenced by the bridge, after three years of study following the bridge coming into operation (2000–2003) (Appelberg *et.al.* 2005).

# Fish Migration

## Introduction

The Öresund Strait represents an important area for several large-scale migrating fish species that pass between the Baltic Sea and the North Sea such as Rügen herring (see the chapter on pelagic fish), eel and garfish.

The fish migration monitoring programme was focused on eel, for which migration to and from the Baltic Sea nursery areas occurs through the Öresund Strait and the Belt areas. Eel is classified as critically endangered (CR) (Gärdenfors *et.al.* 2010) in Sweden and according to the International Union for the Conservation of Nature (IUCN). The fact that an impact on the spawning migration of eel cannot be excluded, must be regarded as serious and leads to an emphasis on the risks and remaining uncertainties in the following work.

The eels that have begun their spawning migration to the Sargasso Sea are called silver eels. They are dark on their back, white on their abdomen and they have stored fat in order to cope with the long migration to their spawning grounds (Tesch 2003). It is still not fully clear how the silver eel find their way on their migration. There are several theories which include orienteering according to different components of the earth's magnetic field, currents and the use of taste and smell (Tesch 1973, Tesch & al 1992, Westin 1998, Westerberg 1979). The silver eels have a relatively predictable pattern of migration out of the Baltic Sea. They migrate south through the Baltic Sea, then north through the Öresund Strait or the Great and Little Belts in Denmark (Tesch 1973, Tesch & al 1991, Westerberg, & al 2007, Sjöberg 2004; Svärdson 1976).

### Expected Impact

The disturbances that could have an impact on the migrating eel from the establishment of offshore wind farms are those which may alter the speed or direction of migration. The primary effect of a hindrance, such as wind farms or power cables, is that the eel chooses an alternative route and loses time and the stored energy necessary for reproduction. Even very limited local disturbances can have significance for a long-distance migratory fish such as eel. If there are repeated disturbances these can have a substantial effect. There are already a number of wind farms and more planned, along the migration route of the eel in and out of the Baltic Sea.

The aim of this study was to establish whether the Lillgrund wind farm, in the first three years of operation, had an impact on the spawning migration of eel through the Öresund Strait, and if so, how.

The investigations have been carried out in a wind farm in commercial production in its entirety, including sound production, electrical currents and physical structures. In order to determine the significance of the effects from a wind farm, the following issues are important to consider:

1. What proportion of the eels released south of the wind farm, cross the potential obstacle to migration?
2. How do the eels pass in relation to the potential obstacle (migration pattern)?
3. How long does it take for the eels to pass the potential obstacle (migration speed)?

## The Impact of Sound and Magnetic Fields on Eel

Knowledge regarding the impact of electromagnetic DC fields on migrating eel is currently quite good. DC currents result in a change in course in the migrating eel coupled with the sum total of the earth's magnetic field and the induced magnetic field from the cable (Westerberg and Begout-Anras 2000, Öhman *et.al.* 2007)). A diversion of the course results primarily in an increase in the time taken for the migration. The magnetic field from the AC cable also result in a delay in the migration of the silver eels, but the mechanism for this is not fully understood (Westerberg and Lagenfelt 2008).

With regard to vibrations and sound, there are still large gaps in the knowledge regarding how fish are affected. The following section provides a brief review of how eel relates to sound. Eels have a swim bladder and can detect both the particle acceleration and pressure changes from sound waves (see the section on fish hearing). For eel, the sound they hear is dominated by particle acceleration at low frequencies (below approximately 50 Hz), whilst sound pressure detection is best at the resonance frequency of the swim bladder (about one hundred Hertz). The swim bladder is important for hearing at higher frequencies. In the frequency range 50–200 Hz (figure 41), the eel can detect both sound pressure and acceleration (Sand 1992). Eel is thought, according to Jerkø *et.al.* (1989) to have more sensitive hearing than can be explained anatomically, as there is an absence of specialised mechanisms known to relay the sound from the swim bladder to the inner ear of the eel (figure 42). In the soundscape within the Öresund Strait, eel can be expected to detect the wind farm from a distance of 250 metres at 60 % production and one kilometre at full production (Andersson *et.al.* 2011) (See also the chapter on acoustics and fish hearing). Information regarding which levels eels can be expected to react to sound, is missing in the scientific literature, apart from the fact that eel is heavily affected and is scared away by infrasound (below 20 Hz) if the particle acceleration is higher than approximately 0.01 $m/s^2$ (Sand *et.al.* 2001). This level of particle acceleration occurs however only at a few metres distance from a wind turbine foundation (Sigray *et.al.* 2009).

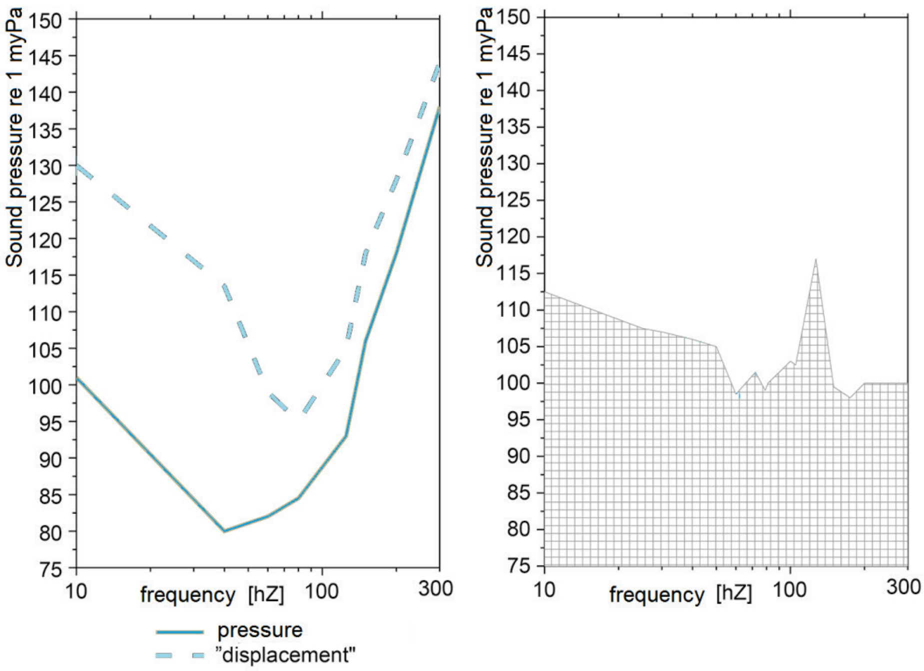


Figure 41. Left hand figure: Audibility thresholds for sound pressure in eel, measured in tubes in a laboratory (recalculated and based on Jerkø *et.al.* 1989). "Displacement" on the left hand figure gives a measure of the particle acceleration. Right hand figure: The shaded area with the peak indicates one of the dominating frequencies which is emitted from the wind farm. The sound from the wind farm at Lillgrund has a peak at 127 Hz which is caused by the gear box of the turbine. The frequency lies well within the audibility area for eel even outside of the physical extent of the wind farm (from Andersson *et.al.* 2011).

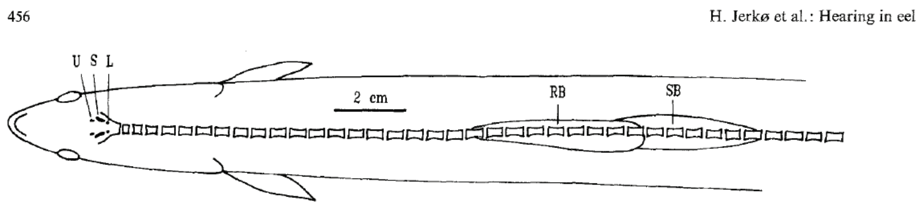


Figure 42. The position of the swim bladder in relation to the inner ear in a 50 cm long eel. The swim bladder of an eel consists of two parts; a secretory bladder (SB) and resorbent bladder (RB) (= ductus pneumaticus). The parts of the inner ear: L, lagena; S, sacculus; U, utriculus. Used directly from Jerkø *et.al.* 1989, figure 1.

The impact on eel and eel behaviour may be different during the different life stages of the eel. The developing yellow eel may theoretically react differently to sound than silver eels on their spawning migration. In the sampling which was carried out at Lillgrund wind farm and which was aimed at catching benthic fish, yellow eel were caught. The catch of this species was higher within the wind farm compared with outside (Bergström *et.al.* 2011).

Statistical evaluations of the catch data for silver eel in the area around the first Swedish marine wind turbine at Nogersund in the Bight of Hanö showed a significant reduction in the catch immediately south of the wind turbine at high wind speeds (Westerberg 1997). No clear causal relationship has been shown, and a reduction in the catch may also be a direct effect of the wind and hydrographic conditions which are independent of the wind turbine.

As well as the wind farm and shipping traffic, the impact in the Öresund Strait in the form of the Öresund Link, a gas pipe along the sea bed between Klagshamn and Denmark as well as a number of underwater cables of different types may also have an impact on the migration of silver eel. Due to the fact that commercial fishing, which previously resulted in a significant mortality, has reduced due to regulation, other anthropogenic activities increase in significance.

# Method

Direct measurements of fish behaviour and migration in the open sea are technically difficult. Tagging with conventional passive tags is relatively cheap, but do not provide enough information. Such studies can easily show if there is a complete migration obstacle, but quantifying delays in migration or if the route is shifted in a way that has an impact on the continued reproductive success of the fish is difficult. Telemetry tracking with a boat provides real time behaviour observations, but in terms of statistics, the information has limited use because the cost for each tracking occasion is high.

The theoretical changes in conditions for fish migration that a wind farm may mean are also of interest. The most important environmental factors which have significance for fish to orientate themselves are acoustic, chemical and visual stimuli. How noise and vibrations from Lillgrund wind farm can be perceived by fish has been studied with the help of sound measurements at different distances from the wind turbines at different production levels (Andersson *et.al.* 2011).

Two different methods were used to follow the migration of the eel. In 2001 and 2004, the eels were actively tracked individually from a boat, and in 2005, and 2008 to 2010, there was an automated system with fixed receivers available.

## Active Telemetry

Tracking of silver eels tagged with ultrasonic tags was carried out from a boat with a hydrophone of the model Vemco VR28 or a four-channel receiver and a hydrophone of the model Vemco VH40 with a piezo element that recognises the sound signals separately in four 90 degree sections. The hydrophone was mounted on the research vessels Sabella or Ancylus. To record the data, the programme Vemco TRACK28 was used. When tracking, ultrasonic tags had a frequency of 51–77 kHz and a pulse period of 1–2 s. The tags were audible up to a distance of approximately 200 metres in the shipping areas and up towards 800 metres around Lillgrund itself.

The telemetry trials were carried out in the period from the end of August up to and including November under varying currents and moon phases. The eels were released in an area south of Lillgrund (figure 45). Due to the fact that silver eels are active when it is dark, the tracking began after dark. The tracking ended once the silver eels had passed the shallow marine area, if contact with the silver eels was lost or if the silver eels had not moved more than approximately 0.1 nautical miles (approx. 200 m) in one hour. The tracking time varied from one to nine hours. For the majority of silver eels, the tracking time was between two and seven hours. The position of the ship was recorded continuously with a differential GPS with an accuracy of less than 10 m. In the majority of cases when tracking, the ultrasound receiver and GPS were connected to a computer and the time, location and strength of the signal for each channel was logged for each pulse from the ultrasonic tags. Manual position settings were used when interference from the navigation equipment or other equipment made it impossible to record the data automatically from the tag on the silver eel. The location of the ship was plotted regularly every other minute or every fifth minute depending on the speed of the eel and the signal to noise ratio and the risk of losing the signal.

Experience from previous trials using active telemetry from a boat suggests that the migration of the eels is not affected by the research vessel (Tesch, Westerberg and Karlsson 1991, Westerberg and Begout-Anras 2000).

## Passive Telemetry

Using passive telemetry of eel movements using individually coded transmitters in transects with fixed receivers provides the opportunity for collecting information for several eels at the same time. The level of detail in the information is however limited because it is only possible to collect the time of passage in a specific area. The method requires therefore a prior understanding of the possible migration routes for the eels. Prior to the final study period in 2010, information was available regarding the sound propagation under water around the wind farm, which is why the method was modified in 2010 in order to detect the eel behaviour in relation to sound propagation.

The eels were tagged with acoustic tags of the model Vemco V13 or Thelma Biotel type 13S (figure 43). The transmitters give out a coded signal with a randomised time interval of between 30 to 60 seconds at the frequency of 69 kHz and a signal strength of approximately 150 dB re 1µPa, 1 m. Several different transmitters can be recorded without interfering with one another even if they are in the same area at the same time. The movements of the eel were recorded with the help of a hydrophone receiver of the model Vemco VR2 or VR2W (figure 44). A data log in the hydrophone recorded the time and position for each individual silver eel. This allowed the movement pattern of the silver eels at the wind farm to be determined. The receivers were put out in the months of September–October and were taken up in December.

The transmitters were attached externally with a stainless steel suture in front of the dorsal fin (figure 3). The weight of the transmitters in water was less than 6 grams. The individual eels varied in weight between 0.625 to 2.14 kg when they were tagged. A transmitter weighing less than one percent of the weight of the silver eel is not considered to result in any significant disturbance for the fish (Westerberg 1983). An advantage with the passive telemetry method is also that the eels can spend time recovering if necessary for some time after tagging and provide useful data afterwards (with the active telemetry, the tracking is abandoned with eels that are not immediately active). None of the silver eels were tranquilised before tagging because this is considered to be stressful for the fish (from previous experience). The silver eels were in good condition when they were tagged and when they were released. Around 40 % of all of the eels detected were observed from the transect 26 km north of the release site in 2008 and 2009.

In the years 2001 to 2004, eels weighing between 0.5–1.2 kg were present. The smallest were also silver eels, but were not tagged.

Figure 43a. Eels with coded ultrasonic transmitters for recording by fixed receivers (passive telemetry, photo Ingvar Lagenfelt).

Figure 43b. Eel with a “home-made” ultrasonic transmitter for use with individual tracking from a boat (active telemetry, photo Ingvar Lagenfelt).

The detection distance for the hydrophone was tested in relation to the trials. In relatively undisturbed periods in terms of shipping traffic, the likelihood of detection was high at distance of 700 to 900 m.

Trials were also carried out in and adjacent to the shipping channel Flintrännan with the aim of simulating the worst possible conditions for detection. With shipping traffic in relation to the passage of one large or two large Ro-Ro/passenger ships passing one another, the detection of each individual coded transmission, was relatively unlikely up to a distance of some hundred metres over a period of 30 to 60 minutes. In each 24 hour day, 11 ships on average pass through the Flintrännan shipping channel of which two per night consist of the specific relatively large type (passage period roughly 6pm and 11pm, on Saturdays roughly 7 pm and midnight). On the condition that the eels do not avoid being close to the ships or their wake, it can theoretically not be excluded that eels pass the shipping channel at the same time as the ships do, and thus avoid detection. The risk, in practice, of completely missing a tagged eel is however small due to the fact that the tag emits at least one coded transmission per minute. The risk of missing transmissions is however the same under the baseline period as when the wind farm was in operation. The noise from the same ship was studied within the 20–4000 Hz range (table 2).

When the hydrophones were retrieved, the data recorded was transferred to a computer using an inductive link or bluetooth. Analysis of the passage times was done using the VEMCO programme ”VUE” and in Excel. In many cases, the signal from a transmitter was recorded on two or more hydrophones at the same time in connection with the eel passing a transect. The moment of the passage, could in the best case, be established with a precision of a few minutes using the fact that there was a short period without any received pings when the transmitter was closest to the receiver.

The location of the receivers and the shape of the transect in 2005, 2008 and 2009 and the release area for the tagged eels are presented in figure 45. Three receivers from the area within the wind farm in 2008 were never re-found. Information from the central part of the receiving area for these receivers is thus missing. In the statistical tests that have been carried out, the results from 2008 have either been completely excluded or results from these three receivers have been excluded for all years. In the illustration presented in figure 49, the average values for the other receivers within the wind farm have been used.

The distance between the release area for the eel and the wind farm was relatively large. The study was designed so that the eels had time to establish a clear swimming direction and speed before they could be expected to detect the wind farm. The disadvantage with this is that the migration was measured along a section where the wind farm was only expected to have an impact over a part of it. The analyses of the swimming speed and the time from release to the wind farm is thus dependent on that no major changes in the surroundings took place at the same time as the wind farm was established.

In 2010, the objective was to study the migration in an area of the sea which included the wind farm and a “reference area” west of the wind farm close by and avoid extended swimming distances. The pattern of the receivers in 2010 and the area where the tagging and releasing took place in that year is indicated in figure 46.

Figure 44. A hydrophone with the attached buoy and the line stretched along the bottom to allow recovery of the device by dragging (photo Ingvar Lagenfelt).

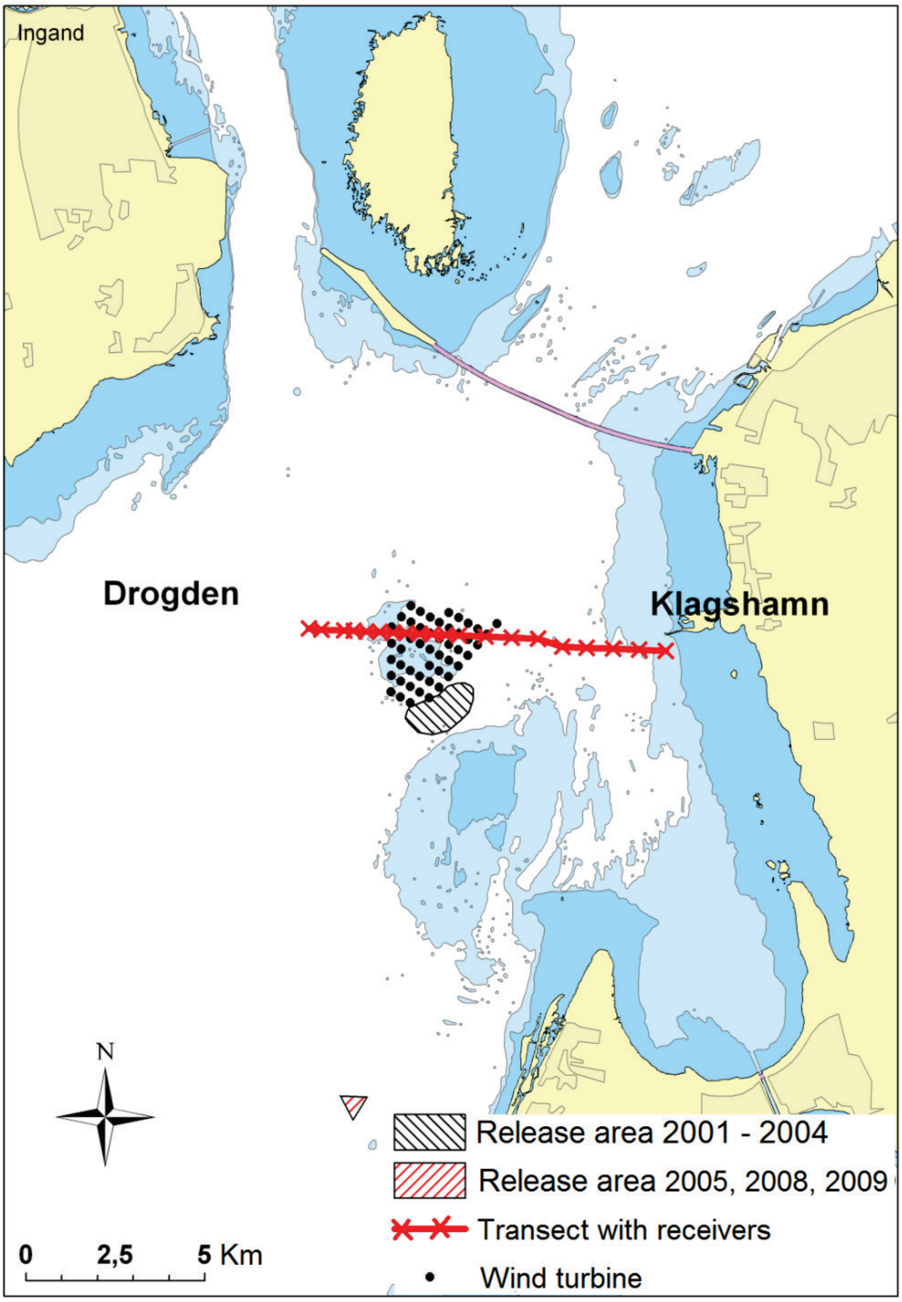


Figure 45. Map of the Öresund Strait showing the location of Lillgrund wind farm. The release area for the tagged silver eels and the location of the ultrasound receivers in a transect through the wind farm are marked. The red-marked triangular release area was used in 2005, 2008 and 2009. Receivers were also used in the release area. © Swedish Maritime Administration permit no. 09-03671.

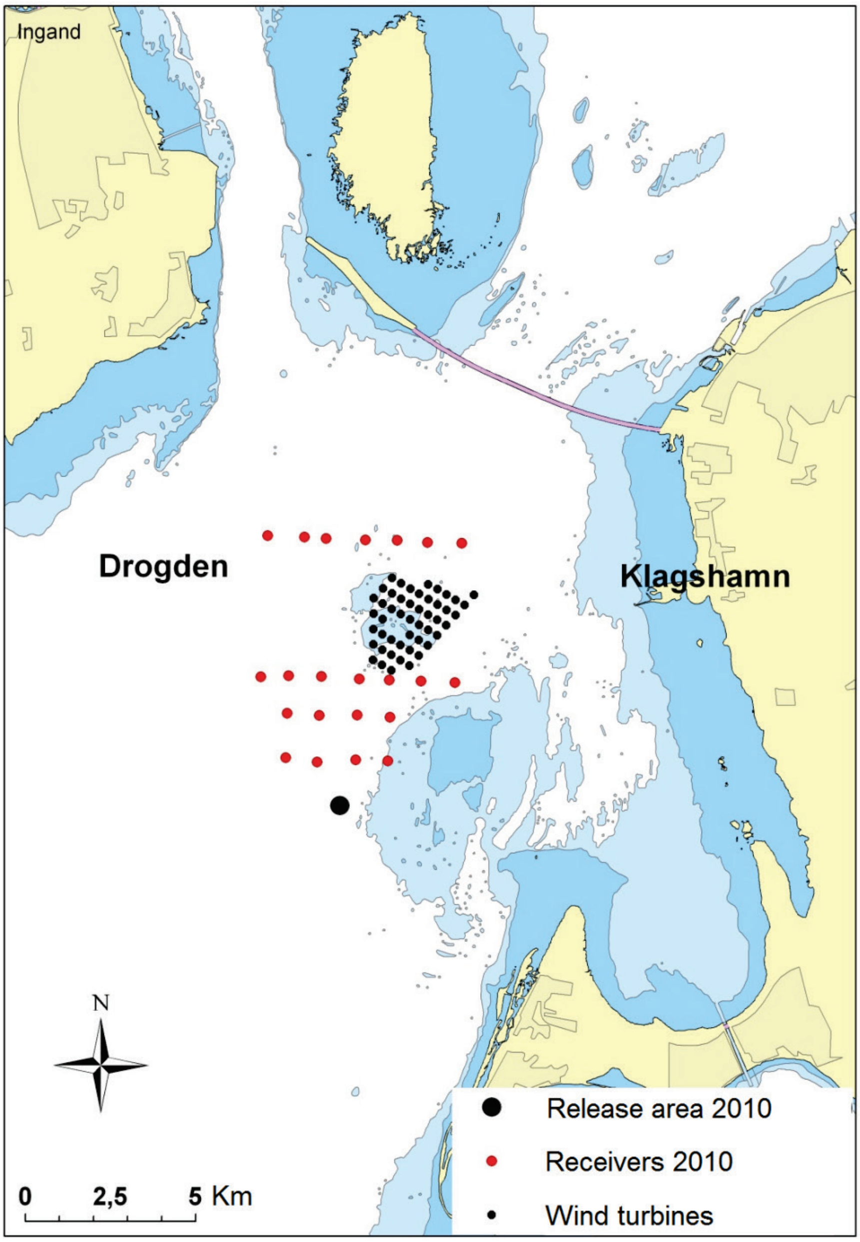


Figure 46. Map of the Öresund Strait with the location of Lillgrund wind farm in relation to the study in 2010. The release area for the tagged silver eels as well as the location of the ultrasound receivers in four transects surrounding the wind farm are illustrated. Swedish Maritime Administration permit no. 09-03671©.

## The Eels

The eels which were used for the telemetry studies were caught using eel trap nets at Smygehamn east of the release area, the night before they were tagged. The silver eels were kept in dark and humid conditions and in damp grass/seaweed on board the ship R/V Sabella which was used for the work. The length and weight of all eels was measured. The weight and size of the eels indicated that all were females. Only eels which were assessed to be in the migratory phase: silver eels, were used.

The silver eels were tagged with ultrasound transmitters immediately before tracking. The heads of the silver eels was covered with a damp cloth when the transmitters were attached. Immediately after they were tagged, the silver eels were released back into the sea within a release area south of the wind farm (figure 45 for the years 2001 to 2009 and figure 46 for 2010). The release area for the tagged eels in 2005, 2008 and 2009, which was 11 km away from the southern point of the wind farm, was chosen in order to be absolutely certain that the eels could not detect and be influenced by the wind farm from the start. When it was established at what distance the eels could likely detect the noise from the wind farm, the release area was moved closer to the wind farm so that more eels could be detected. The tagging was done in the day time, but in the vast majority of cases, the eels only started their migration under darkness.

The tagging days for the in total 280 eels, were spread out in time over the migration period for the three years to pick up variation in both the environmental factors and production in the wind farm (table 11). The first tagging was carried out at the beginning of October and the last in the first half of November which fully covered the migration season. In total, eels were tagged on 14 different occasions with between 13 and 33 individuals per day. The number of tagged silver eels was dimensioned in order to be able to make comparisons in migration behaviours under varying wind and productivity conditions in the wind farm (see the introduction).

Table 11. Tagging days and number of tagged silver eels during the baseline and production periods.

| | Year | Date | Number | |
|---|---|---|---|---|
| Baseline | 2001 | 4–7 Oct | Active | 4[A] |
| | 2002 | 1–2 Oct | Active | 2 |
| | 2003 | 25 Aug–4 Sept | Active | 11[B] |
| | 2004 | 11 Nov | Active | 8[C] |
| | 2005 | 15–20 Oct | Passive | 31[D] |
| | Total | | | 56 |
| Production Phase | 2008 | 1 Oct | Passive | 25 |
| | | 3 Oct | Passive | 25 |
| | | 17 Oct | Passive | 15 |
| | | 8 Nov | Passive | 22 |
| | 2009 | 8 Oct | Passive | 17 |
| | | 19 Oct | Passive | 33 |
| | | 21 Oct | Passive | 17 |
| | | 22 Oct | Passive | 13 |
| | | 3 Nov | Passive | 27 |
| | | 5 Nov | Passive | 16 |
| | 2010 | 14 Oct | Passive | 13 |
| | | 15 Oct | Passive | 18 |
| | | 26 Oct | Passive | 23 |
| | | 29 Oct | Passive | 13 |
| | Total | | | 277 |

[A] of which one did not begin their migration with 60 minutes and was thus not included in the results
[B] of which six did not begin their migration with 60 minutes and were thus not included in the results
[C] of which three did not begin their migration with 60 minutes and were thus not included in the results
[D] including two individuals released in Kalmar Strait and passed the transect 4–6 Oct 2005.

In total, 25 silver eels were tagged in the telemetry studies in the period 2001–2004. The eels used were silver females with a length of between 60–100 cm (figure 47). In 2005, the average length was 78 cm and lengths between 64 and

95 cm were recorded. The length of the eels in 2009 was 85 cm on average, and in the subsequent two years 81 to 82 cm on average (figure 47). The longest individuals were a meter or just over a metre long in all three years (2008–2010) and the shortest eels which were tagged were between 69 and 71 cm long. The lengths were however not assessed to be significantly different between years.

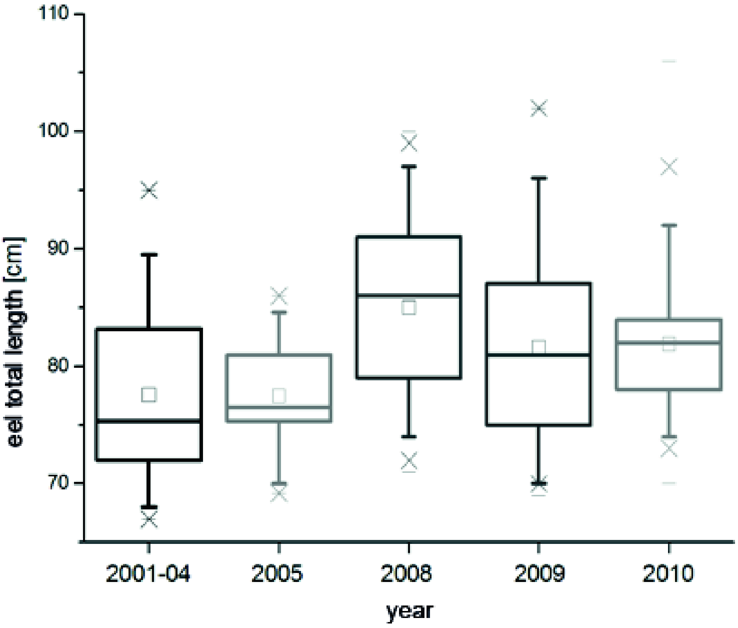


Figure 47. The total length of the tagged silver eels. The results from the years 2001 to 2004 include those eels that were tracked from a boat. The boxes represent the median and quartile values (25 and 75 % percentiles), the bars 5 % percentiles and × 1 % percentiles. — max- and min- as well as mean values.

## Data Processing and Statistical Analyses

As a measure of the noise level in the wind farm a two-hour average wind farm production value was used. The results were analysed on the basis of the sound measurements made at Lillgrund wind farm and in the Öresund Strait (Andersson *et.al.* 2011). The wind farm functions at full capacity at approximately 12 m/s and the sound emissions level out at the maximum. At 60 % of full capacity, equivalent to a wind speed of 9 m/s, the sound levels are halved. The eels can thus, theoretically, detect the wind farm from one kilometre or 250 metres respectively.

The quick variations in production in the wind farm meant that it was difficult to make a connection between the migration behaviour and for example high and low productivity. Periods when there was no productivity in the wind farm were few and covered only shorter periods during the study. In order to maintain an adequately large statistical data set, to be able to study possible connections between migration behaviour and production status/productivity, the results from the baseline years were combined with the results from 2008 and 2009, when the wind farm functioned at a productivity level of less than 20 % of its maximum capacity (SGL park power average ). The combining of the data is not judged to have a negative impact on the analysis, even if this means that eels from 2005 in high winds are included in the group with less than 20 % production.

At a productivity level of 20 percent or less of the maximum capacity, equivalent to approximately 6 m/s wind speed, the migrating eels can theoretically hear the tones from the gear boxes at a distance of less than 100 metres from the wind turbine foundation. (Calculated according to the equation for figure 10, compared with figure 11).

Data from the transects of receivers in 2005, 2008 and 2009 were processed partly in terms of the total number of recordings of individual eels registered, and partly in terms of the number of clear passages recorded. *Passage* was indicated as a short pause in the series of signals received. The average production in the wind farm for the two hours before and during the passage was recorded for each individual eel.

Information regarding eels *registered* (passages and detection without passages combined) gives a somewhat different approach than just pure passages. This includes for example eels which hesitate or delay and then later pass a different part of the transect. A registration within the area of the wind farm for example may result in a delayed passage or registration across the transect outside of the wind farm.

In order to study if there is a connection between migration behaviour and productivity status/production in the wind farm, information in contingency tables were collated, with the nominal variables site (inside and outside of the wind farm respectively) and productivity levels (more or less than 20 % of maximum productivity for the wind farm).

The sites ”inside” and ”outside” the wind farm respectively are defined by the distance to the first receiver outside the physical boundary of the wind farm, which gives seven receivers inside the area including the one on the western boundary. In 2008 three receivers were lost from inside the wind farm. Two different ways of making calculations were used for the statistical tests to deal with the loss of these receivers. In comparisons for all three years (2005, 2008 and 2009), the three receivers with the equivalent positions to those lost in 2008 were not included. Comparisons between the years 2005 and 2009, all receivers were included.

Potential differences in the frequency of the registrations or passes respectively were analysed using $\chi^2$-test (test for if the number of observations in the different categories are significantly different from an expected distribution). In case the test design only included two categories (one degree of freedom), a Yates correction was made in the calculation of the tested variables, to reduce the risk of assessing a distribution as being significantly different from the theoretical one, when it is in fact not (at type I-error). The analyses were carried out in Statistica version 8.0.

The potential differences in the migration time from where the eels were released to the transect inside and outside of the wind farm was tested with ANOVA rank sum Kruskal-Wallis (non-parametric). Potential differences, or interaction effects, between the groups were tested using t-tests, after first testing for a normal distribution (and homogenic variation) according to Kolmogorov-Smirnov. The analyses were carried out in Statistica version 8.0. Complementary analyses were done using ANOVA where the F-value was replace by a Wald $\chi^2$ distribution and assuming a Gamma distribution instead of a normal distribution in the statistical programme SAS. A linear regression analysis was used to assess if there was a continuous correlation.

The observed “transport” speed for the eels is the vector sum of the eel’s swimming speed and the water current. Data for the water current was obtained from a permanent Acoustic Doppler Current Profiler, (ADCP) placed at Drogden by the Danish Maritime Safety Administration in Denmark. In the calculations, the values every half an hour from a depth of one metre was used, due to the fact that in the studies with data-recording tags, showed that silver eels primarily swim just below the surface. (see e.g. Westerberg *et.al.* 2007). For a period during 2010 the ADCP was out of function. In that period, one eel passed through. This is why data regarding water currents is missing for that eel.

# Results

## Baseline Study

During the baseline study, a total of 56 silver eels were released, divided between active telemetry tracking (25 individuals) and passive telemetry tracking (31 individuals, table 12). Of these, a total of 25 records of silver eels were made which reached or passed the transect across Lillgrund. During the entire base line study period, in total, 19 of the 56 eels (approx. 34 %) passed the transect line.

Nine of the 15 silver eels tracked using active telemetry, which left the release area in the years 2001 to 2004, were judged to have come within detection distance of the planned transect line. Figure 48 illustrates how the tagged eels moved around in Lillgrund before the wind farm was built. The eels presented are examples of eels that moved to the west and east of Lillgrund, and where there were continuous positions without any break are available for the whole period of when they were tracked. For one of these (grey track in the figure, eel no. nr 9103), tracking started southeast of Lillgrund on the 15th October, 2003 at 20:31 and finished on the 16th October at 03:09 at Pepparholmen. The other three eel tracks which are illustrated, had a northerly course at the end of the tracking period. One of the 15 eels tracked using active telemetry showed a divergent behaviour and swam with a direct southerly course for three hours.

In the autumn of 2005 passive transmitters were used in a transect and the area by Falsterbo was used for releasing the silver eels. That year, approximately 30 % of the eels released were detected at Lillgrund. During this tracking period, ten silver eels passed from the normal release group and in addition two silver eels from a previous release of 60 individuals in Kalmarsund (Westerberg *et.al.* 2006) passed Lillgrund. The two eels from Kalmarsund reached the transect in the Öresund Strait 22–23 days after being released. One of these individuals was recorded in the transect on two occasions and is included in the passage patterns presented below.

## Production Phase

In total 280 silver eels were tagged during the production phase and the results include information from 107 occasions when the eels came into contact with the wind farm.

The total number of silver eels released during the first two years of the production phase (2008 and 2009) was 201 of which 59 eels (approx. 28 %) were detected from the transect. Some eels were detected on several occasions, and there is information from 76 occasions, including from two eels that passed the transect twice. The number of eels that are included in the calculations varies depending on the availability of other related information and at which accuracy the passage time etc. could be established.

In 2010 70 silver eels were tagged and 29 possible contact opportunities between the wind farm and eels were recorded (approx. 41 %). In the most northerly transect (transect number four, north of the wind farm), only seven of the eels were recorded. One of these was not recorded prior to their passage of the wind farm (table 12). During the production phase four eels returned to the release site after having been detected at the wind farm.

Table 12. Number of transects, number of silver eels released and the number of silver eels that passed through the transect/transects through the wind farm in total. In addition, there were a number of eels that were recorded, but that did not pass through.

| Phase | Year | Telemetry | No of Transects | Number of eels released | Number of eels that passed transect | Number of eels returned to release site |
|---|---|---|---|---|---|---|
| Production phase | 2010 | passive | 4 | 70 | 30 | 1 |
| | 2009 | passive | 1+1[A] | 123 | 28 | 3 |
| | 2008 | passive | 1+1[A] | 87 | 35 | 0 |
| Baseline | 2005 | passive | 1+1[A] | 31 | 10+3[C] | 0 |
| | 2004 | active | 1[D] | 8 | 1[B] | |
| | 2003 | active | 1[D] | 11 | 5[B] | |
| | 2002 | active | 1[D] | 2 | 2[B] | |
| | 2001 | active | 1[D] | 2 | 1[B] | |

[A] Release site and wind farm.
[B] Calculated from a calibration of ultrasound range at the trial area undertaken in 2005. Not comparable with the release area.
[C] Information is available for an additional three passages of two silver eels that were recorded from other telemetry studies in the same year (Westerberg & Lagenfelt, 2006).
[D] Simulated transect calculated with the help of the calibration of signal audibility in the area.

## Passage Pattern

Of the silver eels that were tagged and released from 2001 to 2004 southeast of Lillgrund, nine were calculated as having passed the transect line. All passed through after having begun a northerly migratory course relatively soon after they were released. The release area was situated relatively close to the shallow marine area known as Södra Lillgrund and the silver eels passed either to the west or the east of the shallow area (figure 48). The migration behaviour was relatively similar for these eels which all followed the contours of the shallow marine area. An additional silver eel, which began a northerly course and one which travelled between both parts of Lillgrund could well have passed the transect line if it could have been followed for a longer period. The only eel which proved to have a divergent behaviour was one which started its migration on a southerly course.

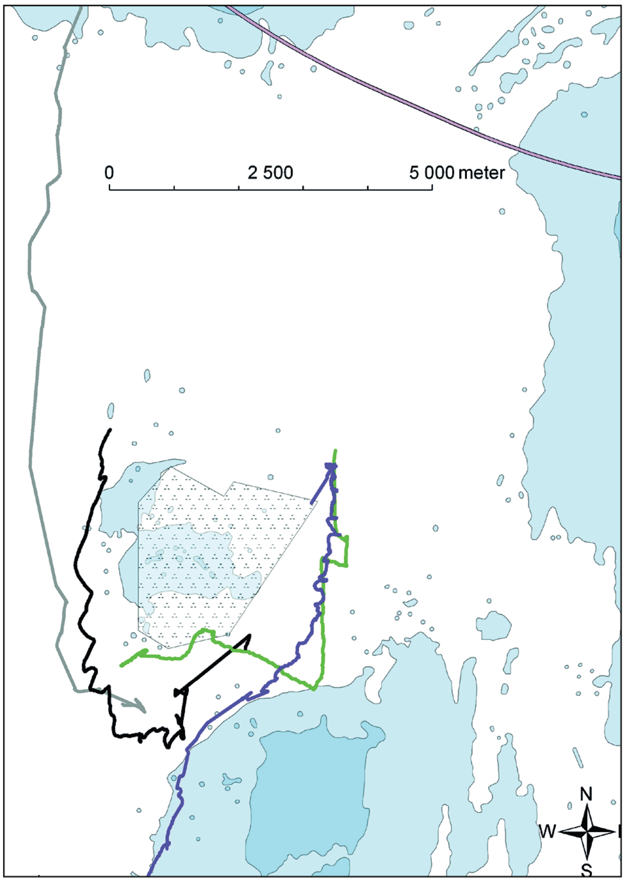


Figure 48. An example of the migration pattern from active telemetry tracking of silver eels. The trail is made up by the route of the tracking boat, the eels position varies at most by two hundred metres. Two, of the three eels, which passed the eastern side of the planned wind farm are shown. The wind farm has been illustrated but the tracking data is from the baseline period.

The thirteen eel passages that were recorded in 2005 were spread across the breadth of the transect with the largest proportion passing the deepest part furthest to the west near Drogden (figure 49).

In 2008 and 2009 the eel passages were relatively evenly distributed per nautical mile along the east–west transect. A somewhat larger proportion of the eels passed however, either side of the Flintrännan shipping channel close to the Danish border at Drogden, both during the production phase and the entire baseline period (approximately 31 % and 43 % respectively). A somewhat larger proportion of the eels were also recorded as passing the most easterly part of the transect near to Klagshamn in the production phase, almost 14 %, compared with the baseline period, when it was less than 5 % (figure 49).

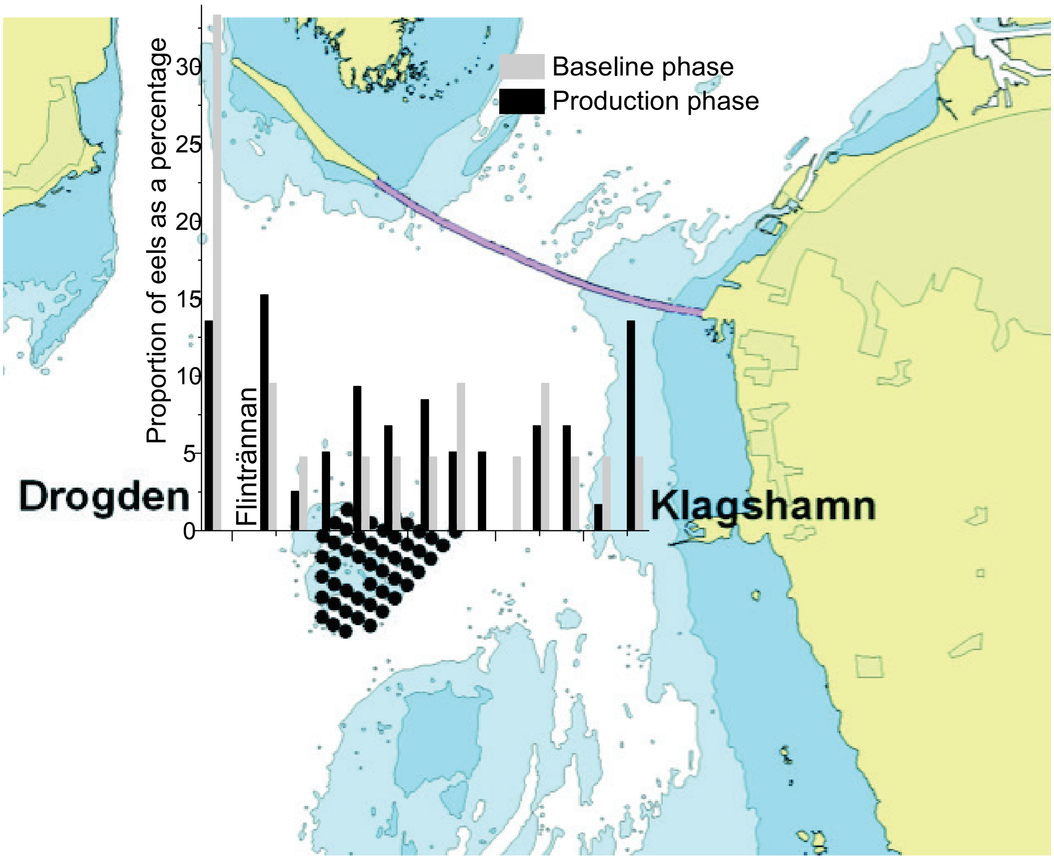


Figure 49. The passage pattern in a west–easterly direction for the silver eels during the baseline and production phases. This includes data from 24 eels in the years 2001–2005 and 58 eels in the years 2008 and 2009. Different areas for tagging were used in the years 2001–2004 and subsequent years (c.f. with the map in figure 45). "Flintrännan" is a shipping channel. In the figure, a relative measurement has been used of the number of eel passages which has been compensated with 1.4 eels per nautical mile for the section where three receivers were lost in 2008. © Swedish Maritime Administration permit no. 09-03671.

Comparing the number of eels recorded (passages and detection without passing the transect combined) (figure 50, includes all data) within and outside of the wind farm respectively, there is no significant difference when the value of $p < 0.05$[22].

The low p-values ($0.05 < p < 0.10$) indicate however that the likelihood is different that an observation will occur in a particular row in a column, that it is not the same for all rows. This is valid with comparisons with both two or three years (table 13). In order to see which cells in the table diverge from the expected value, and which thus give a "high" value on the test variable ($\chi^2$), the expected frequencies were studied and Chi² values for each cell. The analyses indicate/suggest that a lower number of eels than expected are present within the wind farm at low production levels (< 20 % of the maximum) and that a larger number of eels than expected are present within the wind farm at higher production levels (> 20 % of the maximum).

[22] $\chi^{2}$-test with Yates correction, 0,05 < p < 0,10.

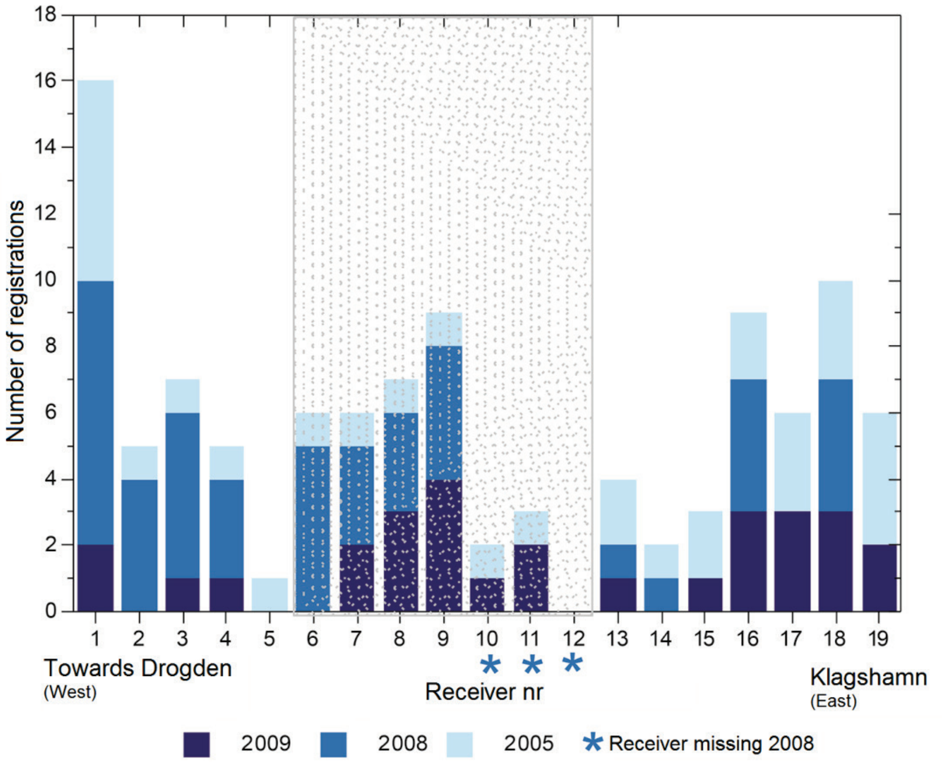


Figure 50. Distribution pattern of the recordings, passages and detections, of the silver eels from the transect through the wind farm in the years 2005, 2008 and 2009. The eels are divided according to the receiver they have passed, or been closest to. Data in this figure are not corrected for the varying receiver distances as this was not possible for eels, which were recorded but that did not pass the transect. The grey shaded area shows the part of the transect which is located within the wind farm. The figure is based on all data (statistical tests with two subsets of the data are presented including or excluding the results from 2008 are given in table 13)

Table 13. The number of eels recorded within and outside of the wind farm physical boundaries at an average production level of above and below 20 % of the maximum average hourly production respectively. With the comparisons between all three years, the receivers for which data is missing for 2008 are not included (corrected $\chi^2$=3.74 and p=0.0531). The comparison between 2005 and 2009 includes all receivers (corrected $\chi^2$=2.98 and p=0.0841).

| | 2005, 2008 and 2009 | | |
|---|---|---|---|
| | Production levels | | |
| Location | <20 % | >20 % | |
| Inside | 4 | 24 | 28 |
| Outside | 27 | 47 | 74 |
| | 31 | 71 | 102 |

| | 2005 and 2009 | | |
|---|---|---|---|
| | Production levels | | |
| Location | <20 % | >20 % | |
| Inside | 6 | 12 | 18 |
| Outside | 27 | 17 | 44 |
| | 33 | 29 | 62 |

If the choice of route that the eels make is influenced by the production level in the wind farm, then the geographical passage of the eels across the transect would be expected to vary in line with production levels.

A comparison between the observed and the expected frequency of the passages of eel inside and outside of the physical boundaries of the wind farm during a period with production greater or lesser than 20 % of the maximum respectively, showed however no significant differences[23] (figure 51 includes all data, table 14 tested two data sets selected from the data).

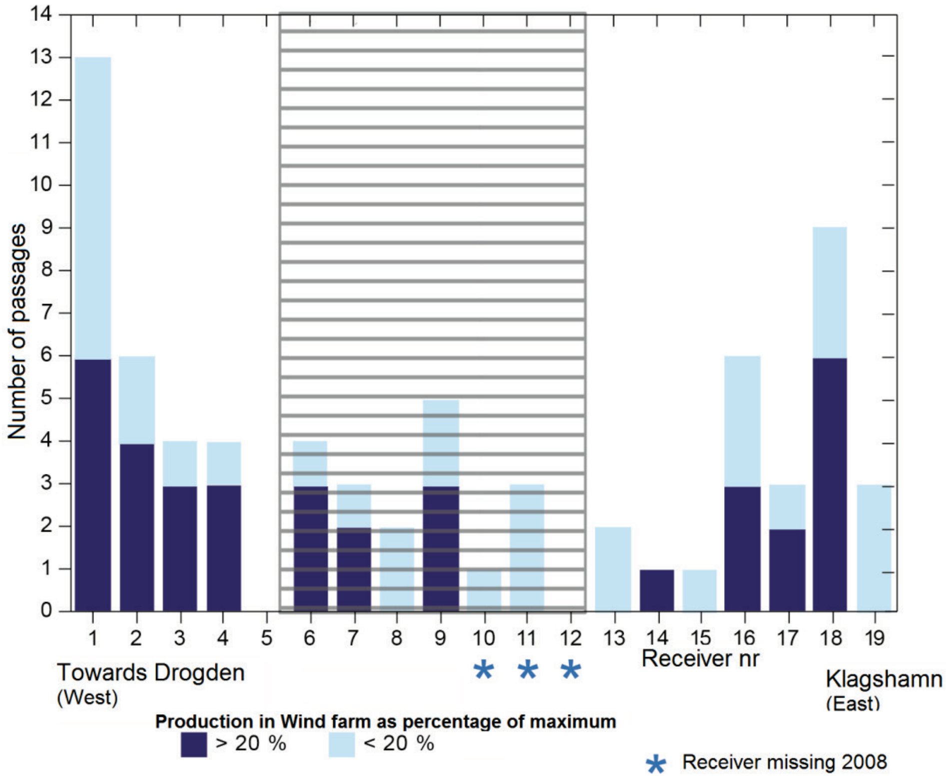


Figure 51. The number of eel passages inside and outside of the physical wind farm boundary during the period when production was greater than 20 % of the maximum (> 20 %) and periods when it was lower than 20 percent of the maximum production (< 20 %). The grey shaded area illustrates the part of the transect which lies within the wind farm. The figure is based on all data (statistical tests with two subsets of the data, with and without results from 2008 or with or without the three missing receivers, are given in table 14).

Table 14. The number of eels recorded within and outside of the wind farm physical boundaries at an average production level of above and below 20 % of the maximum average hourly production respectively. With the comparisons between all three years, the receivers with equivalent positions as those three which were lost in 2008 were not included. (corrected $\chi^2$=0.01 and p=0.9343). The comparison between 2005 and 2009 includes all receivers (corrected $\chi^2$=0.00 and p=0.9831).

| | 2005, 2008 and 2009 | | |
|---|---|---|---|
| | Production levels | | |
| Location | <20 % | >20 % | |
| Inside | 6 | 8 | 14 |
| Outside | 24 | 28 | 52 |
| | 30 | 36 | 66 |

| | 2005 and 2009 | | |
|---|---|---|---|
| | Production levels | | |
| Location | <20 % | >20 % | |
| Inside | 9 | 2 | 11 |
| Outside | 22 | 7 | 29 |
| | 31 | 9 | 40 |

23 $\chi^{2}$-test with Yates correction, p>0.1.

The depth and current are different on both sides of the wind farm. The deeper part on the Drogden side has also frequent shipping traffic close to the wind farm. The AC cable from the wind farm to land runs towards Klagshamn. A more detailed analysis of the information which reflects the asymmetry for the years 2008–2009, with regard to where along the transect the eels passed in relation to production levels, gave no significant differences[24] (figure 52.) In the analysis, the transect has been divided up into four sub-sections, from the central point of the wind farm, with the distances adapted so that there are an equal number of eels in each of the sub-sections; 0.8–3.0 km and -3.5–4.5 km to the east (towards Klagshamn) and 0.5–6.0 km and 6.0–9.0 km to the west (towards Drogden). Eel passages occurred in all four sub-sections during the period when the wind farm was working at full capacity. Measured as a median value and percentiles (25–75 %) more eels passed the western part of the transect, closer to the centre of the wind farm at lower production levels, compared with the equivalent on the eastern side. On the western side, there was only a single passage during the period when the wind farm was not producing anything at the inner sub-section (0.8–3.0 km). For the eastern side of the transect, towards Klagshamn, the situation appeared to be different. Median value of productivity was highest where the eel passed in the transect section between -0.5 and 6.0 km to the east.

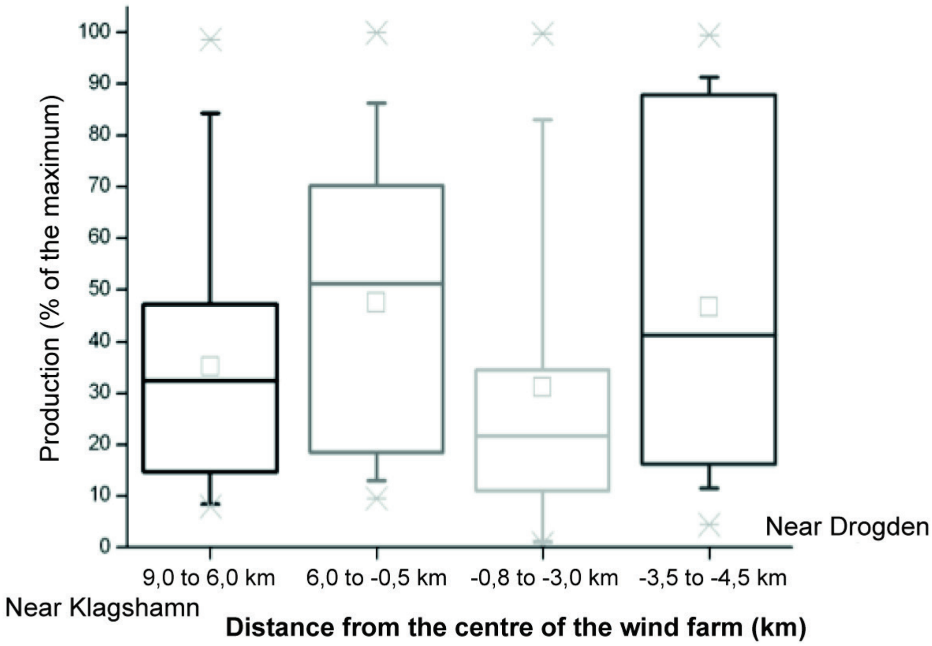


Figure 52. The passage distance of the eels in relation to the production level in the wind farm in 2008 and 2009. The boxes present the median and the quartiles (25 and 75 % percentiles), the bars 5 % percentiles and × 1 % percentiles. — max- and min- and □ average. Compare with figure 54.

[24] One-way ANOVA, log- transformed production value following a test for normal distribution (according to Kolmogorov-Smirnov), mean value p=0.15.

Of the 70 silver eels that were tagged in 2010, 30 were recorded in one of the four transects. Of the 30 recorded eels, seven were recorded from within the area which is covered by the final, most northerly, transect (table 15). One of these had however, not been recorded south of the wind farm and was thus excluded.

In order to characterise the behaviour of the silver eels, the individuals must have been recorded from at least three receivers. The behaviour was divided up schematically into four types of migration pattern in relation to the wind farm:

1. Eel recorded moving south of the wind farm and then later registered in the most northerly transect.
2. Eel recorded moving south of the wind farm with a more or less northerly course, without being recorded north of the wind farm.
3. Eel recorded moving south of the wind farm without having a northerly course and without being recorded north of the wind farm.
4. Eel made a round trip south of the wind farm back to the release site.

Six eels exhibited behaviour that can be characterised according to point one above, i.e. they passed the wind farm or close to it.

The most common behaviour was according to point two above. The movement behaviour of sixteen eels was interpreted according to this pattern. One individual behaved according to point three, as a pure east–westerly migration. One individual behaved according to point four and followed an oval pattern in the area which was covered by the receivers south of the wind farm.

An attempt to present the movement pattern for each individual eel has been made in figure 53. The individual records have been used as points in a diagram, after which a best-fit line (β-spline) has been drawn between the points. The diagram shows eight eels, each of which are ranked according to three levels of maximum average production (calculated over a time period of two hours) in the wind farm: low is below 13 %, intermediate between 13 and 20 % and high is more than 20 %.

Of those eels, which had a course containing a northerly component, but which did not pass the wind farm (point 2 above) there seems to be two different types that are dominant (figure 53). Several individuals exhibited a directly northerly course in the lower left hand corner of the diagram which is equivalent to the deepest part of the area (c.f. maps figures 45 – 46). Other individuals in the lower right hand quarter, had an easterly component in their movement. This is equivalent on a map to the shallower part of the area which is covered by receivers and is bounded to the east by Bredgrund. These individuals end up near to Klagshamn if they follow the coast to the north.

In table 15 below, the behaviour categories were tested against the production levels in the wind farm. No significant difference in behaviour could be established[25]. There was no significant difference in behaviour when the

[25] $\chi^{2}$-test=0.092, p>0.05.

study area was geographically divided into two parts, (table 16), of which one included the wind turbines and the other to the west.

Table 15. Test of the presence of the different behaviour types in 2010 in relation to the Lillgrund are in 2010 at production levels of more than 20 percent of the maximum (>20 %) and below 20 percent (<20 %) respectively in the wind farm. For the different behaviour categories, see the text above.

| | Production | |
|---|---|---|
| Behaviour type | <20 % | >20 % |
| Type 1 | 4 | 2 |
| Type 2 | 7 | 5 |
| Type 3+4 | 5 | 1 |

Table 16. Test of the presence of the different behaviour types in 2010 in relation to the wind farm and to the area west of the wind farm. For the different behaviour categories, see the text above.

| Behaviour type | West of the wind farm | At and through the area of the wind farm |
|---|---|---|
| Type 1 | 3 | 3 |
| Type 2 | 7 | 5 |
| Type 3+4 | 2 | 4 |

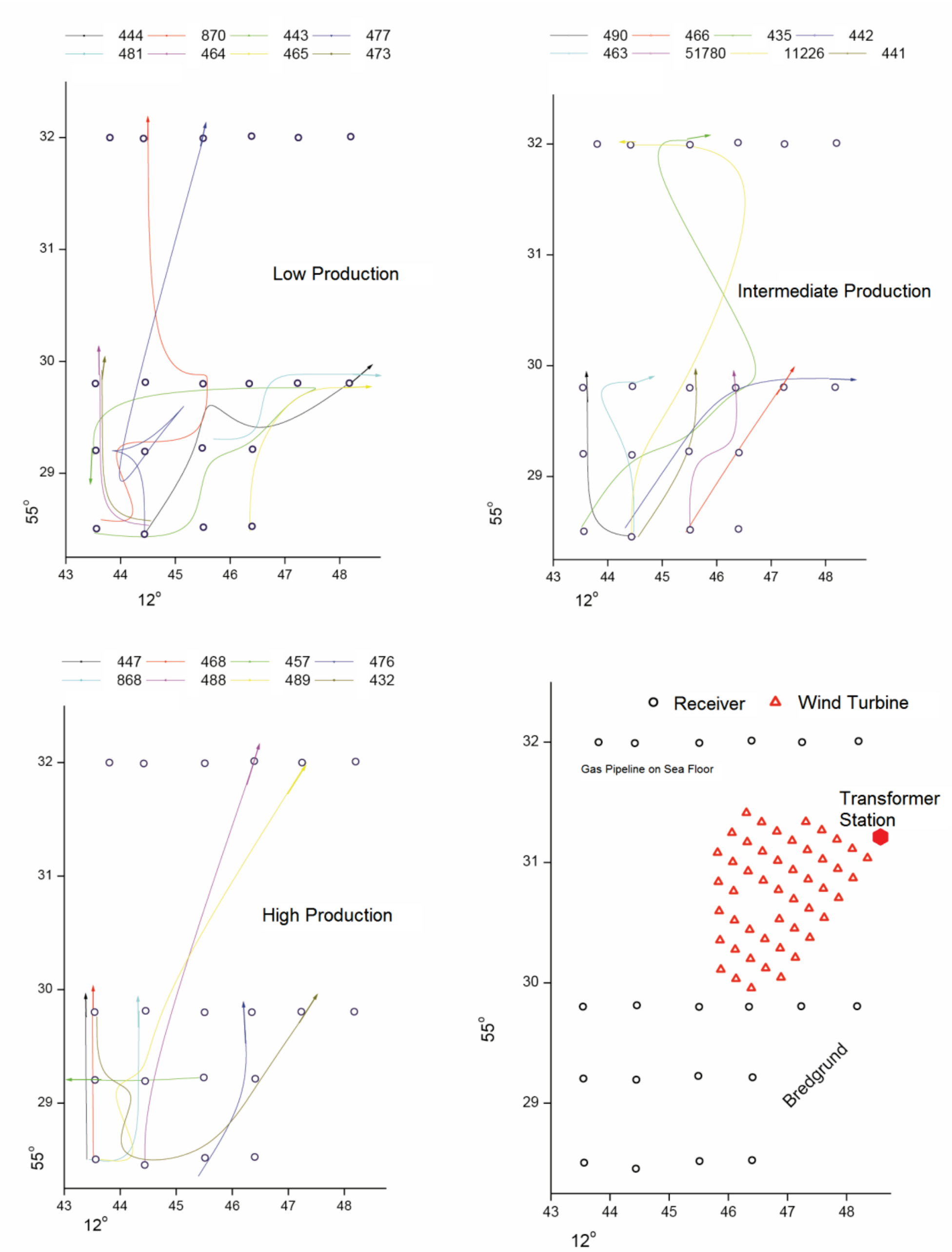


Figure 53. Schematic diagram from the tests in 2010 of the movements of the 24 individual eels that were recorded on at least three occasions each. In each graph, the swimming patterns of eight eels have been illustrated. The division between the different graphs is based on the production levels in the wind farm. The positions of the eels have been put as points after which an adapted (β-spline) line has been drawn between the points to illustrate the movements of the eels. The graph on the bottom right provides a geographic orientation of the area.

## Migration Time

The electricity production in the wind farm varies significantly over time and the variations occur quickly. The difference in average production per hour between two consecutive hour periods can be great.

For 57 eels in the years 2008–2009 there were relatively well defined passage times across the transects. There was a large variation in time from tagging and releasing to passing of the transects with receivers for the different eels. For one of the eels from 2008–2009 the productivity information from the wind farm is missing and for this individual, the wind data has been used to provide the productivity data. The shortest time for passing the transect with a receiver was four hours after tagging and releasing. The longest time recorded was roughly equivalent to a month; more than 1000 hours (figure 55). The eels which travelled towards Drogden passed the transect most quickly. In all three zones (marked on the figure) the passage took more than 385 hours for a quarter of all the individuals. For several individuals, the passage took four to eight days (49–96 hours). The eels which travelled in the deeper parts out towards Drogden moved somewhat quicker than the other eels, but the difference was not significant (figure 54).

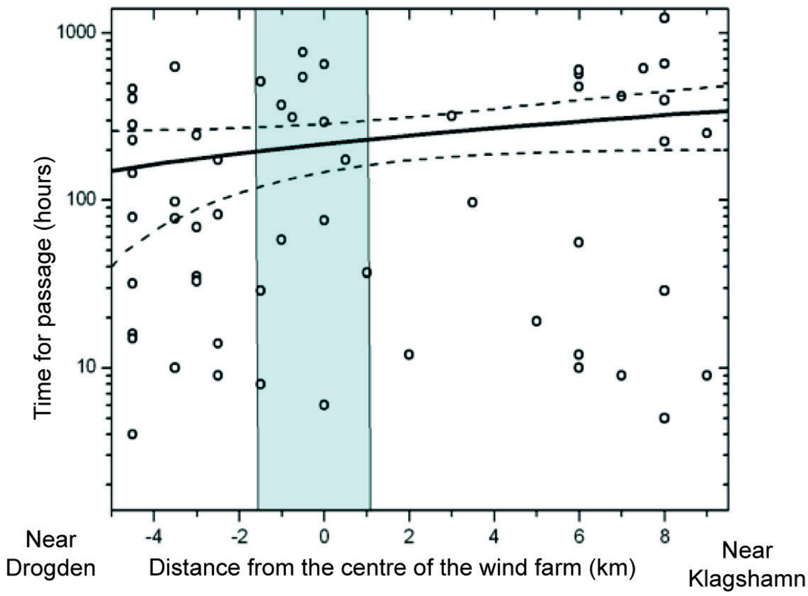


Figure 54. The correlation between distance from the wind farm and the time between release and passage. Data from the years 2008–2009. In order to obtain maximum resolution on the y-axis (time for passage), logarithmic values were used. The horizontal line = linear correlation between the parameters with the confidence interval for the equation (Linear regression r=0.175, n=57, two points coincide, p=0.193.)

The time for passage was compared between three different parts of the transect, due to the fact that these differ in terms of their external conditions (see figure 55). The Drogden side is for example deeper, which influences for example sound propagation, and has frequent shipping traffic nearby, whilst the AC cable from the wind farm to the shore runs towards Klagshamn. Data from the baseline constituted a fourth category. From the year 2005, there were ten silver eels where the time from release to passage was well defined. Data was tested in all four combinations but there was no significant differences found. (ANOVA rank totals, Kruskal-Wallis, H=2.56 and p=0.46.)

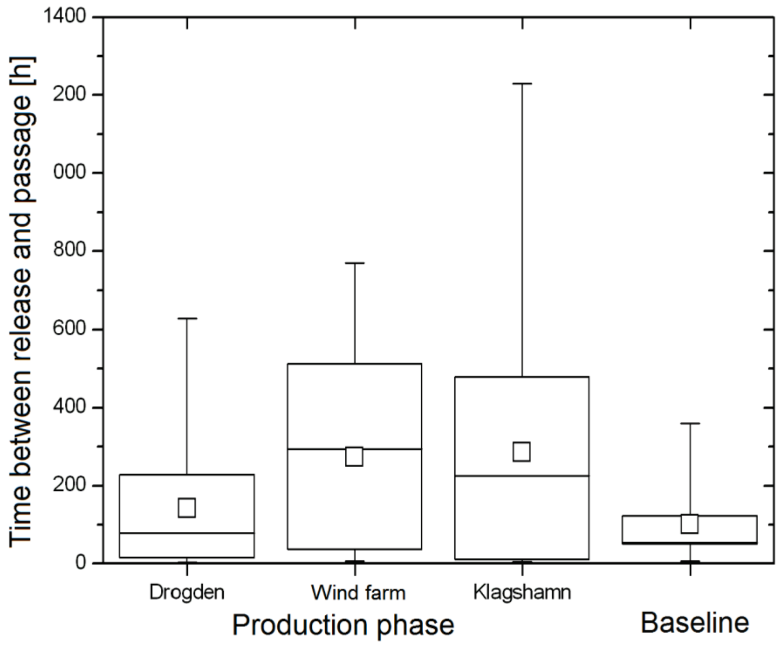


Figure 55. Passage time [hours] from release location to passage of one of the transects with receivers in 2005 (baseline), 2008 and 2009 (production phase). Data from the baseline studies in 2005 are taken from Lagenfelt *et.al.* (2006). The wind farm includes the area from the central line and 1.5 km in both directions. The boxes represent the median and quartile values (25 and 75 % percentiles), the bars 5 % percentiles and × 1 % percentiles.
— max- and min- and □ mean value.

In order to find out if there was any connection between the passage time and the productivity of the wind farm, the passage times were collated in contingency tables with the nominal variables of site (inside or outside the wind farm respectively, defined in figure 54) and productivity (more or less than 20 % of the maximum productivity levels for the wind farm). All eels are included in the tests (figure 56) including those that passed outside of the wind farm where the mechanism behind the delay may be that they first came close to the wind farm (but without being close enough to be recorded, see the discussion) and then passed outside. The limitation for the tests was the number of eels that were recorded from inside the wind farm at production levels of less than 20 % (six individuals). In total, 67 eels are included in the data material, but the number in each of the different analyses varied based on the quality of the data and the issue in question. No significant difference in passage time could be connected to the two different production levels[26] (figure 56 left hand side) The skewed nature of the quantity of data (non-significant) which is reflected in the distance between the median value and the 25 and 75 % percentiles could however, on the basis of previous experience, be interpreted as that a number of eels are actually delayed when the production

[26] t-test log-transformerade värden, medelvärde p=0,83, spridning p=0,10, även ANOVA: Wald $\chi^2$= 1,31, p=0,252.

level is higher than 20 % of the maximum (see discussion). No difference in passage time connected to if passage took place within the wind farm or outside of the wind farm could be seen[27] (The skewed nature of the data quantity is not as marked in this analysis) (figure 56 right hand side).

In figure 56, only the variables Productivity and Site are presented, but tests have also been carried out in relation to the interaction between the variables Productivity and Site (Site Inside and Outside respectively × Productivity < 20 % and > 20 % respectively, four variations in total). The tests did not show any significant interaction effects[28]. The skewed nature of the quantity of data in relation to the median value (illustrated as percentiles 25 and 75 %) which can be seen for the variable Productivity (< 20 % and > 20 %) remain however. It is therefore possible that the wind farm productivity levels may have a greater impact on the passage time for the eels than where in the area (along the transects) they pass.

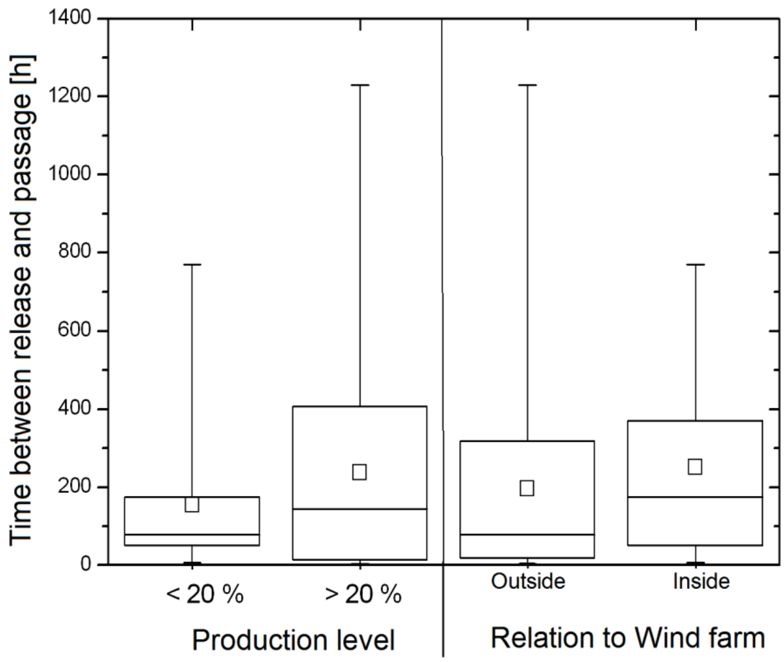


Figure 56. Passage time in relation to two levels of productivity (< 20 % and > 20 % of the maximum) as well as passage time related to if the passage took place inside or outside of the wind farm. Data from 2005, 2008 and 2009. The boxes represent the median and quartiles (25 and 75 % percentiles), the bars 5 % percentiles and × 1 % percentiles. — max- and min- as well as □ mean values.

The spread in terms of passage time (see figure 56, percentiles 25 and 75 %) may mean that a larger proportion of the eels (48 %), at higher productivity levels (greater than 20 % of the maximum) take more than a week to pass,

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27 t-test log-transformed values, mean value p=0.33, distribution p=0,95, also ANOVA: Wald $\chi^2$= 2.04, p=0.154.

28 ANOVA: Wald $\chi^2$= 2.69, p=0.101.

compared with 28 % of the eels at lower productivity levels (less than 20 % of the maximum, from the data in figure 54).

## Passage Time

Silver eels passed the transects with receivers during all productivity conditions in the wind farm. The median value for production for the periods when eels passed was approximately 34 % of the maximum, which is roughly the same as during the other hours, 33 %. For the 40 hours when detection was possible, but no eels passed, the productivity was somewhat lower, just over 20 %. No major differences were observed in maximum average productivity per hour between hours with eels were recorded passing, no eels passed or were detected. There was no clear relationship between the time period from when the eels were released to when they passed a transect with a receiver and the productivity level of the wind farm in 2008 and 2009 (figure 57, table 15).

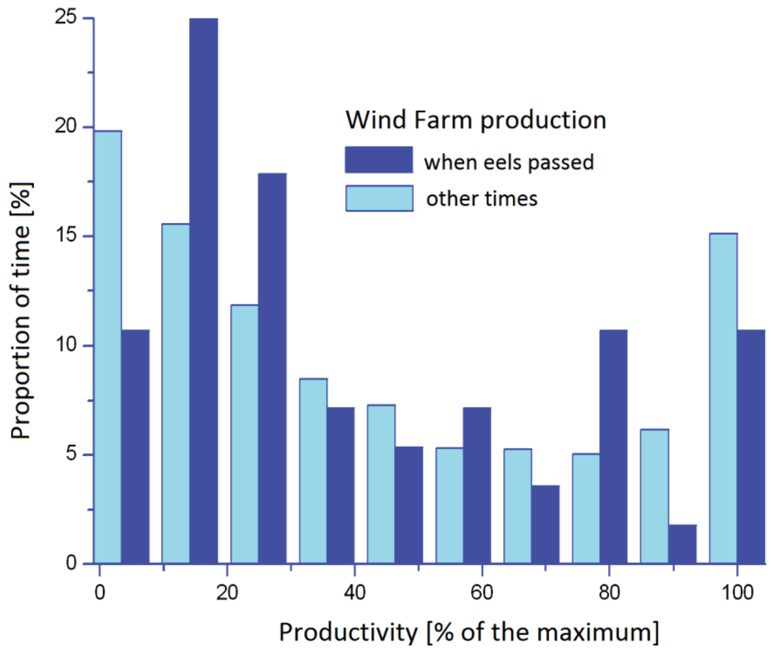


Figure 57. Productivity in the wind farm during the eel migration season in the years 2008 to 2010, calculated on the basis of whole hour mean values (n = 4750 for the wind farm in its entirety and n = 63 for the hours when eels passed). The difference in productivity between periods when eels passed through and other times is not significant ($\chi^2$-test, p=0.492).

## Passage Times
## in Relation to the Length of the Eels and Water Currents.

The speed at which eels migrate has a theoretical connection with the individual's length. The optimal swim speed for an eel according to the literature is 0.77 times the total length of the eel (reference via Cleves tam *et.al.* 2011). In the data from the years 2008–2010 there was a correlation found between the length of eels and their behaviour in relation to the wind farm. The length of the silver eels that were detected without passing, that were detected as passing and the eels not recorded at all was similar (mean value 81.5 cm, 81.5 cm and 83 cm respectively). The largest eel (106 cm long) as well as the smallest (69 cm long) were amongst those that were not detected at all. The migration time from release site by Falsterbo was neither shorter nor longer for the larger individuals as for the shorter ones (table 17).

The dominating *water currents* at Drogden have a direction of 45° (for 42 % of the time) or the complete opposite, 225° (for 26 % of the time). The migration of the silver eels continued independently of the current conditions, even if the migration speed could be expected to be influenced. The current conditions during the periods when eels passed across the transects did not deviate from the current conditions during other periods. The current conditions were similar, also during the periods when eels were detected somewhere along the transects without passing. The northerly component of the current, in other words when the eels experienced that they were swimming against the current, was roughly the same as during the period when eels passed the wind farm as when no eels were recorded at all. The median value for the northerly component during the whole period measured was just over 1.3 m/s.

No clear connection was seen between the time from when the eel was released to the passage of the transects with receivers and the size of the northerly current component in the years 2008 and 2009 (table 17). Data from 2010 is not entirely comparable with previous years but could be recalculated using swimming speed. Even when this data was included, there was no significant correlation between the northerly component of the water current.[29]. The variation was very large regardless of the data that was used.

In order to quantify how the length of the eels, the northerly component of the water current and the productivity of the wind farm combined and individually had an impact on the migration time (time from release to passage of a transect with a receiver through the wind farm), a multiple regression analysis for the years 2008 and 2009 was carried out. The level of explanation (coefficient of determination $r^2$ *100) was low throughout (table 17).

Table 17. Correlation between the migration time (time from release to passage of the transect with a receiver through the wind farm) and the productivity of the wind farm (average production over two hours), the total length of the eels and the northerly component of the water current in the Öresund Strait was analysed using a multiple linear regression as well as a simple linear regression one at a time. Data from 2008 and 2009.

| | Parameters combined | | | Individual parameters | | |
|---|---|---|---|---|---|---|
| | Significance level p= | Correlation coefficient, r = | n | Significance level p= | Correlation coefficient, r = | n |
| Production | 0,670 | 0,0147 | 62 | 0,557 | 0,070 | 73 |
| Length | 0,221 | | | 0,198 | 0,153 | 73 |
| Northerly current | 0,571 | | | 0,473 | 0,091 | 65 |

[29] Linear regression, r =0.0455, n=93, p=0.665

# Discussion

The discussion regarding the potential impact on the migration of eel is based on the acute situation for the species. The fact that a disturbance to the migration of eel cannot be excluded, must be taken seriously, in particular in the context of the fact that more wind farms may be built along the migration routes for eel.

No previous studies, where the tracking of silver eel migration has been carried out close to a wind farm, have been found in the literature. A compilation which includes an assessment of aspects of wind power and the environment was recently produced Wilhelmsson *et.al.* (2010). The risk of impact on fish communities as a whole, from wind power was judged to be low, both in terms of masking of important sound information and electromagnetic fields, but for both of these aspects, the limited amount of current knowledge was highlighted. The lack of information in relation to the long term effects of a wind farm in production and the changed sound environment was particularly identified.

Potential impacts from the wind farm at Lillgrund on migrating silver eels may come from the noise and vibrations which the production and structures generate, or from electromagnetic fields. With regard to the electrical and magnetic fields, there is information regarding the expected reaction of eels to these (see the chapter on the impact of sound and magnetic fields on eel). The published literature (of scientific peer-reviewed quality) regarding the reaction of silver eels to noise and vibrations is virtually missing. Eels may, according to calculations above within the current work, experience noise from the wind farm at Lillgrund at up to a distance of around one kilometre. The distances at which noise will evoke a reaction in silver eels is not yet clear (see introduction). That sound is important for eel is illustrated by the fact they can produce sound themselves via their swim bladder.

In general, the ambient sounds in the sea, constitute an important stimuli for the spatial perception for fish, in order that they can orientate themselves in relation to shores and islands where the sounds from breaking waves and banks provides information about the coastline which can be detected from relatively long distances (Lagardère *et.al.* 1994; Simpson *et.al.* 2005; Fay 2009).

An alternative explanation of the impact from the electrical fields and vibrations could be the impact on the eel's soundscape of their environment. If the eels use the soundscape under water to navigate, changes in this could disturb their navigation during migration. In addition, if the resolution of the silver eel's picture of the surrounding sound environment at distance does not make it possible for them to distinguish individual wind turbines, then the wind farm could act as a point source and thus constitute a hindrance to migration even if the sound pressure is not powerful enough to frighten them. These conditions could occur for example in powerful winds and high productivity. The direction in which the silver eels swim may then change and/or be delayed resulting in the eels using up valuable energy for migration and reproduction which cannot be replaced. Each delay for a migrating eel, leads to a reduced breeding success and the quantity of elvers may reduce in the breeding area. In the worst case, can the combined delays result in that the energy reserves are not enough to complete their migration as the energy margins for the eels from the Baltic Sea are very small, despite the fact that eels are effective swimmers (see Clevestam *et.al.* 2011 regarding the limited energy reserves in eel).

The results show that the wind farm at Lillgrund does not constitute a definitive migration hinder for migrating eels that come into contact with the wind farm. An equally large proportion of the released silver eels, a third, passed the transect lines with receivers in the years 2001 to 2005 (base line period) as did in the years 2008 to 2009 (production phase). To statistically demonstrate an average disturbance was difficult considering the large individual variation in eel migration speed. Taking into consideration that the eel is a very threatened species of fish, it has an extremely long migration route (with many potential hindrances to pass), which needs to be carried out with the same energy reserves (eels stop feeding when they become silver eels) it is important to take into consideration trends towards an impact on their migration.

A comparison between the observed and expected statistical frequency of passages by eels inside and outside of the boundary of the wind farm during periods with a productivity level above and below 20 % of the maximum levels respectively, shows no significance differences (table 14). The low p-values ($0.05 < p < 0.10$) for the number of eels recorded (passages and eels detected which did not pass combined) inside and outside the wind farm indicates/shows that a lower number of eels than expected are present within the wind farm at lower productivity levels (below 20 %) and that a larger number of eels than expected are present within the wind farm at higher productivity levels (above 20 %, table 13).

The interpretation of the results is influenced by how the boundary of the wind farm is defined and of which mechanisms potentially have an impact on the eels. There is a boundary zone with an unknown breadth around the wind farm where eels can perceive for example sound, without reacting. This boundary location can vary with productivity in the wind farm, but also in relation to the general background noise. In the Öresund Strait sound environment, eels can be expected to detect the wind farm at a distance of 250 metres at 60 % productivity and one kilometre at full capacity. The distance between the wind turbines is between 300 m and 400 m.

The uncertainty is in relation to both at what maximum distance the eels can detect and/or react to the wind farm when they approach from the south and at what distance they then pass the wind farm. One speculation may be that the physical structures of the wind farm at low production constitute a point source which the eel can locate whilst at high levels of productivity, the wind farm in its entirety joins together to form a background of noise.

If the eels discover the wind turbine only when they are very close and do not change course, other factors such as current speed across shallow areas may have significance and can make the time spent within the area shorter with consequential fewer registrations from the receivers. At high productivity levels, the eels may hesitate and/or divert and be registered close to or within the area, to then possibly be recorded from the transect outside of the wind farm.

Compare this with the results for benthic fish (see the discussion chapter) where the analyses indicate a correlation between the quantity of fish and the local sound environment, with a reduced frequency than expected of fish at higher noise levels, where the clearest response was seen for eelpout and yellow eel.

The median time for the journey from where they were released to where they passed a transect was the same, regardless of if the wind farm was in production or not. The variation in journey time (illustrated in figures 56, 25 and 75 % percentiles distance from the median value) can however, mean that a larger proportion of the eels (48 %) at the higher productivity level (greater than 20 % of the maximum) used more than a week to travel, compared with 28 % of the eels at the lower productivity levels (less than 20 % of the maximum). The difference in the limited amount of material may be due to chance. Within earlier studies of both different types of cables and by the Öresund Bridge (Westerberg *et.al.* 2008, Westerberg *et.al.* 2006, Appelberg *et.al.* 2005Westerberg, *et.al.* 2000,) there were individual eels, which exhibited a divergent behaviour in relation to disturbance, which meant that the journey time was lengthened. This type of divergence is however, difficult to prove statistically with such a limited number of individuals of less than a hundred. The statistical difficulties with the material are shown for example by the uncorrected $\chi^2$ test where the difference in speed between the different productivity levels was statistically significant. The eel migration (from nursery to breeding areas) takes in total between 5.2–6.5 months (22–27 weeks). One week's delay is equivalent in this context, to an extension of the migration period of just under five percent. Silver eels that are delayed at the end of the migration season may have to wait until the following season and thus lose more of their energy reserves. It would have been ideal, in terms of interpreting the studies on eel migration, if it had been possible as a reference to start and stop the production of the wind farm in addition to using the data from the baseline studies.

Variations in migration behaviour and migration routes which may have an impact on the energy usage for the individual eel occurred within the data, but within each category of variation, there were only very few eels. No statistical difference in the distribution of the eel passages inside and outside of the wind farm area could thus be established. Examples of divergent behaviour during the production phase was that silver eels swan towards land/Klagshamn or that they returned to the release site (four eels of 280 exhibited this latter behaviour, approximately 1.4 %). Even before the wind farm was built, there were however silver eels that passed close to the shore, which is illustrated by the fact that fishing with permanent eel traps has taken place here previously (Appelberg *et.al.* 2005). Catch data from the permanent eel traps does not provide information on how large a proportion of silver eels have chosen this route. Even during the baseline active telemetry tracking study, there were individual deviations from the expected migration behaviour. This includes for examples the fact that one of the 56 eels swam directly south, instead of north.

That there is a large amount of variation between individual migrating eels has been shown in several studies using for example active telemetry of individual eels with a tracking board or with data recording tags (Westerberg & Begout-Anras 2000; Appelberg *et.al.* 2005; Westerberg *et.al.* 2006; Westerberg *et.al.* 2007). A strong migration instinct should mean that eels do not react to disturbance analogous with the fact that fish do not abandon spawning or nursery grounds despite unfavourable environmental conditions (Beale & Monaghan 2004, Bejder *et.al.* 2009). Difficulties in navigating and orientation may well however, result in disturbance, despite this instinct. Repeated disturbance of the eel breeding migration through the Baltic Sea, with lots of offshore DC and AC cables, planned and existing wind farms, shipping traffic and bridges may together result in a large proportion of the eels being delayed on their journey.

The receivers not recovered in 2008 contributed to difficulties in interpreting the results because this affected the specific area, where the statistically limiting numbers of observations were made. Evidence of significant mechanical impact on the seabed where these receivers were placed, was observed from diving at the location. When the data was processed, the potential impact from the wind farm in production was defined as more or less than 20 % of maximum productivity. This meant that the number of observations was acceptable as the results from the periods with low productivity along with the baseline data could be included in the analyses.

# Overarching Discussion

Lillgrund wind farm in the Öresund Strait is located in middle of an important area for fish communities and fishing. The narrow corridor that makes up the Öresund Strait between Kattegatt and the Baltic Sea is an important migration route for a number of fish species primarily eel and Rügen herring.

The greatest environmental impacts from a wind farm are expected to be when it is built, but also the proximity of the actual wind farm and the restriction on other potential stakeholders within the area (such as commercial fishing, shipping etc.) can have an impact. This report focuses on the effects of the wind farm when in production, due to the fact that the building phase is similar to other offshore exploitation activities, and is thus relatively well known.

Previous reviews regarding offshore wind farms have identified the creation of hard substrate on the sea bed, from the foundations and associated scour protection, and an altered sound environment as the most significant effects during the production phase. Direct empirical studies of these impacts are however, relatively few. Effects may also occur as a consequence of changes in the electromagnetic field in the area, but this is less well known given that conduction occurs with AC current, which generates only a weak magnetic field.

**What are the impacts of Lillgrund wind farm and what new information has the montoring programme contributed regarding the impact on fish?**

The studies from the first three years when the wind farm was in operation show that the effects are thus far limited.

One of the most obvious results is the attraction effect (reef effect) that the wind turbine foundations and the associated scour protection have had on bottom-dwelling fish. There are several studies that show that artificial constructions can attract fish (for a summary, see Wilhelmsson *et al.* 2006). The wind turbines can function both as an artificial reef (from the sea bed and upwards) and as *Fish Aggregating Devices* (FADs) (from the surface and downwards), by the fact that the constructions go through the entire water column. An increase in the number of fish on an artificial reef, does not necessarily occur as a consequence of increased productivity, but can be due to the fact that existing fish in the area move to the reef (Bohnsack 1996). The results from Lillgrund most likely reflect a redistribution of the fish from within the wind farm area in its entirety. The response was however relatively weak and limited to the area closest to the foundations (up to 50–160 m from the wind turbine). There are studies which show that artificial reef constructions can have an impact on pelagic (open-water living) fish and larger benthic (bottom-living) fish at a distance of several hundred metres (Grove *et.al.* 1991), up to 400 m (Wilhelmsson *et.al.* 2009).

Experience-based studies from offshore wind farms in production are still very few, even at an international level. Those examples that exist show a fast colonisation by fish and marine invertebrates on the artificial hard-bottom substrate and in accordance with Lillgrund, a more or less pronounced redistribution of the fish community in the wind farm, from a relatively even to a more patchy distribution.

According to Jensen (2002) it takes roughly five years for the stable fauna community to develop after an artificial hard-bottom structure has been built. Studies of invertebrates on an artificial stone reef outside of Göteborg (west coast of Sweden), showed that the species richness on the shallower parts of the reef (12 – 20 m) after five years was equivalent to some 80 % of that found on natural hard-bottom substrates (Egriell *et.al.* 2007). After two months, there were however equally as many fish species on the reef as on natural hard-bottom substrates and after five and a half months the density of the fish was the same on the reef as in natural hard-bottom sea beds.

Studies from the wind farm at Horns rev[30] (Denmark) (Leonhard *et.al.* 2011) seven years after it was built, showed an increased presence of fish species associated with reefs (such as goldsinny wrasse, eelpout and lumpfish) as a consequence of an increase in food (such as amphipoda and mussels), but no attraction effect with regard to large benthic or pelagic fish. The lack of increase in large predatory fish within the wind farm area is thought to be connected to the lack of goby fish which make up an important part of the diet for larger fish, both benthic and pelagic. The wind farm at Horns rev is very exposed to westerly winds, and studies of the foraging behaviour of turbot indicates that goby fish are missing from open, exposed coastal areas (Sparrevohn & Stottrup 2008 in Leonhard 2011). Due to the fact that sample fishing was carried out using 110 m long survey nets, and the catch was integrated across the whole range, this may have contributed to these results.

Acoustic telemetry studies at the offshore wind farm Egmond aan Zee[31] (OWEZ) (Holland) showed that at least a part of the cod population (juvenile cod) were attracted to the foundations (Winter *et.al.* 2010). No large cod were observed within the wind farm area in their studies, which may be explained by the fact that the wind farm had only been in production for just over a year when the telemetry studies began. Tagging and telemetry studies with sole (flat fish) showed in accordance with the studies from Lillgrund, no attraction to the foundations.

Studies (including acoustic telemetry studies) at a Belgian wind farm[32] show that the reef-like environment/good foraging around wind turbines at certain times of the year attract higher densities of fish species such as cod and pouting (Reubens *et.al.* 2010 i Degraer *et.al.* 2011, Reubens *et.al.* i Degraer *et.al.* 2011). The density of both of these fish species was low (few individuals) in the spring, greatest during the summer and reduced once again during the autumn. Improved foraging may also be an explanation for the greater density of juvenile whiting which was observed in the autumn of 2010 adjacent to the wind turbines (Vandendriessche *et.al.* i Degraer *et.al.* 2011). A high density of

[30] Danmark; Horns rev 1, 80 turbines installed at 2 MW, in production from 2003.

[31] Holland; Egmond aan Zee (OWEZ), 48 turbines installed at 3 MW, in production from 2007.

[32] Belgien; Thorntonbank, 6 turbines installed (54 planned) at 5 MW, in production from 2009. Bligh Bank; 56 turbines installed (110 planned) at 3 MW, in production from (2010) 2011.

foraging juvenile whiting has also been observed around the turbine foundations at North Hoyle wind farm (UK) (May 2005).

A significant change at Lillgrund was the increased presence of shore crab during the production phase of the wind farm. A number of studies at other wave and wind farms show that primarily crabs are favoured by the reef-like environments that the foundations and associated scour protection provides; shore crab (*Carcinus maenas*) (Nystedt wind farm, Maar *et.al.* 2009) (wave farm, Wilhelmsson *et.al.* 2009) and thumbnail crab (*Thia scutellata*) (North Hoyle wind farm, May 2005). No equivalent increase in the presence of crabs was observed from the Belgian wind turbines, but it was clearly noted that the individual sizes of flying crab (*Liocarcinus holsatus*) and brown shrimp (*Crangon crangon*) were in general larger in the trawling catches from 2010 within the wind farm area than in the reference areas (Vandendriessche *et.al.* i Degraer *et.al.* 2011). This can be explained either by an increase in access to food or an increased predation pressure on the smaller individuals.

The sound measurements that have been carried out at Lillgrund wind farm show that it significantly contributes to the soundscape in the Öresund Strait both in terms of broadband noise from the wind farm in its entirety and in relation to individual frequencies (from vibrations from the gear boxes). The increased noise levels can lead to an increase in stress levels in fish, even if the fish may choose to remain if access to shelter and food outweigh the disadvantages, but it can also lead to migrating fish species such as silver eel and Rügen herring avoiding the wind farm area. There is nothing from the results from the sample fishing at Lillgrund which indicates stress impacts on the benthic fish species. No analyses however of stress substances (cortisol and glucose levels etc.) in the blood and blood plasma were carried out.

The results from the monitoring programme in relation to the analyses of the commercial fishing catches of herring (pelagic fish), with a significant increase in fishing north of Sjollen and the Öresund Link during the production phase, may suggest that the migration of the Rügen herring is influenced by Lillgrund wind farm. The available data is however, not enough to be certain that this is the case. Spatial variation in the commercial fishing catch of herring also occurred before the wind farm was built, with roughly a fifth of the catch per unit effort south of the adjacent Öresund Link compared with north of it. The echo-sounding work which was carried out during the baseline period (2003–2005) also showed a lower median density of herring in the autumn in the nearby and core area planned for the wind farm, compared to the reference area at Ven in the northern part of the Öresund Strait (Lagenfelt *et.al.* 2006).

No statistically significant difference as a consequence of the wind farm was seen on the journey time for silver eels, from the release area in the south to the passage of the wind farm. Considering the very threatened status of eel as a fish species, even tendencies towards an impact on their migration is important to take into consideration in any further work. A delay in the migration time for individuals (increased journey time at increased production in the wind farm) may contribute to an energy loss and thus a reduction in reproductive success in the eels. Although discrepancies in the distribution of eels recorded, within the area of the wind farm based on the statistical expectations at low (fewer eels than expected) and high (more eels than expected) production, may indicate that individual eels have greater difficulty navigating past the wind farm at higher levels of production. Such variation is difficult to prove statistically and has a limited effect with only individual obstacles, but can lead to effects at a population level if there are additional obstacles and disturbances.

It is difficult to differentiate if any possible impact is due to electromagnetic fields or the soundscape, as the area of impact from both of these may coincide. One condition that differentiates Lillgrund wind farm from several other (existing and planned) wind farms is that the foundations are relatively close together; the distance between the foundations at Lillgrund (2.3 MW) is 300–400 metres compared with for example Horns rev (2 MW) where they are 560 metres apart and Egmond aan Zee (OWEZ) (3 MW) where they are 650 metres apart. The dense placement means that the wind farm has an energy effectiveness of 77 % (compared to what each individual wind turbine combined could generate) (Dahlberg 2009), but may also result in greater difficulties for migrating fish to distinguish the spaces between the individual wind turbine foundations at increasing productivity levels.

Westerberg & Lagenfelt (2008) have shown that silver eels can be delayed on their journey when they pass over AC power cables, however they are unable to provide any physiological explanations for this phenomenon. In their study, there was an average delay of forty minutes when passing a 130 KW cable, and the relative reduction in swimming speed increased with an increase in the electrical current in the cable. As a single construction, neither the above mentioned AC power cable nor Lillgrund wind farm constitute any large obstacles for the 7000 km long migration that eels make to the breeding area in the Sargasso Sea, even if a certain number of eels which pass the area may be delayed on their migration. Cumulatively however, repeated exposure may have an impact on fish such as silver eel, which migrates long distances, primarily for eel from the Baltic Sea, which have to navigate passed a large number of potential obstacles on their way to the Sargasso Sea.

**How important are any potential impacts from Lillgrund wind farm in relation to other factors?**

The impact that a wind farm in production has on the marine ecosystem depends to a large extent on how the local ecosystem structure before and after the construction of the wind farm. In areas where the access to hard-bottom substrates are good, the foundations of the wind turbines will likely result in a more limited effect than in an areas with a sandy bottom (such as is most common in the Öresund Strait).

For the wind farm at Horns rev Leonard & Pedersen (2006) estimated that the availability of food for fish directly surrounding the turbine area increased by a factor of around 50 following the introduction of hard-bottom substrate compared with an existing sandy-bottom substrate. An increased productivity close to the foundation leads to an increase in the deposition of suspended material in the sheltered area behind the wind turbine foundation, where the water movements are stopped, with a risk for local changes in the benthic community structure and biodiversity (Malm & Engkvist 2011, Coates *et.al.* i Degraer *et.al.* 2011).

Studies from the Belgian wind turbines have also shown that the wind turbines artificial reef structures can strengthen the strategic position of invasive species by acting as “stepping stones” in areas where there are otherwise few hard-bottom substrates (Kerckhof *et.al.* in Degraer *et.al.* 2011). This was clearly shown for the obligate intertidal species, where after three years, eight of 17 species were non-native to the southern North Sea.

The issue of how the effects of the wind farm are perceived and judged, such as providing more shelter and foraging opportunities for fish, depends largely on the ecological objectives that have been established for the area. In protected marine areas, the introduction of artificial constructions and the changed soundscape may be perceived as negative in relation to what is supposed to be protected. In other areas, more affected by human activities, a wind farm may provide improvements to the environment. (Inger *et.al.* 2009).

The results from Lillgrund wind farm is one example of what tones and noise levels a wind farm can generate. These results are of course not necessarily valid for another area and another wind farm. The soundscape produced by a wind farm (both in relation to the area and the season) varies for example on the type of foundations, the composition of the substrates, the water depth and the possible presence of a thermocline. With regard to the type of foundation, the material and the size can make a difference as to how much the noise from the gear box is dampened, which leads to a variation in noise levels (Ødegaard & Danneskiold-Samsøe 2000, ÅF-Ingemansson 2007). This has not yet been shown in well-executed, comparable trials, but a study of two different Belgian wind farm constructions, one with 5 MW turbines on gravitational foundations and one with 3 MW turbines on monopile foundations made of steel has shown that the wind turbines on gravitational foundations (like Lillgrund) sounds less than wind turbines on steel foundations (Norro *et.al.* i Degraer *et.al.* 2011). Lillgrund wind farm is also located within one of the busiest shipping areas along the Swedish coast, which means that the noise from the wind farm (excluding the dominant tome which comes from the gear box) at relatively short distances reaches levels equivalent to the background noise. There are either no absolute values for at what distances different fish species can detect the wind farm, rather it is an estimate which is valid for the actual conditions on the site and in relation to the differing hearing ability of different species.

Changes in the ecosystem can also occur due to changes in the stakeholders within a particular area. Changes for example in the commercial fishing pressure can lead to large changes in the ecosystem as a whole. It is primarily the presence of large predatory fish that is important, as they have an important structural role as the top consumer in the Swedish coastal ecosystem (Moksnes *et.al.* 2008, Eriksson *et.al.* 2009). There are no special fishing restrictions within the Lillgrund wind farm other than those which apply to the Öresund Strait in general. The presence of large predators such as cod is however relatively good in the Öresund Strait, as a consequence of the ban on trawling for maritime safety reasons since 1932 (Bergström *et.al.* 2007, Svedäng *et.al.* 2004). To what extent a fish population can benefit from a protected area is dependent on how large a proportion of adult fish come to the area and how large a proportion of the population stay in the area. Although the area of Lillgrund wind farm (covering an area of around 4.6 km$^2$) is not defined as a fisheries closure area within the Öresund Strait, the attraction of fish to the artificial hard-bottom substrate provided by the foundations can result in, for example, that large cod are more easily caught than before.

Offshore constructions for the production of renewable energy may result in a significant anthropogenic impact on marine ecosystems (Inger *et.al.* 2009). The combined impact that we see today is a result of a number of different factors. The impact will also be cumulative if the number of constructions increase. In line with this expansion, the positive and negative effects on the marine environment will interact in a complex way, which may be difficult to predict. It is therefore important in the continued planning and risk assessments that the focus lies on a wider ecosystem perspective, than on the impact of the individual constructions (such as for example Lillgrund).

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There are also others, in addition to the named, rather randomly selected group.

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# Appendices

## Appendix 1

Species composition in terms of numbers per station of the different species caught in the fish sampling using fyke nets at the wind farm (Lillgrund), and the reference areas Bredgrund (southern reference area) and Sjollen (northern reference area) during the base line studies 2002–2005 and after the wind farm was in production 2008–2010.

| Species | LILLGRUND | | | | | | | BREDGRUND | | | | | | | SJOLLEN | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 2003 | 2004 | 2005 | 2008 | 2009 | 2010 | 2002 | 2003 | 2004 | 2005 | 2008 | 2009 | 2010 | 2002 | 2003 | 2004 | 2005 | 2008 | 2009 | 2010 |
| *FISH* | | | | | | | | | | | | | | | | | | | | | |
| Topknot | 0,04 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Silver eel | 0 | 0 | 0,04 | 0 | 0 | 0 | 0 | 0,04 | 0 | 0 | 0 | 0,03 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rock cook | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,17 | 0 | 0 |
| Yellow eel | 0,42 | 0,63 | 0,63 | 0,18 | 1,14 | 0,92 | 0,47 | 0,29 | 0,17 | 0 | 0,14 | 0,56 | 0,28 | 0 | 1,13 | 1,33 | 0,42 | 0,69 | 1,42 | 0,97 | 0,83 |
| Pipefish (undet.) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,04 | 0 | 0 | 0 | 0 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0 | 0,06 | 0 |
| Snake pipefish | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,04 | 0 | 0 | 0 | 0 | 0,03 | 0 |
| Straightnose pipefish | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Longspined bullhead | 0,08 | 0,17 | 0,21 | 0,15 | 0,22 | 0,69 | 0,36 | 0,13 | 0,21 | 0,42 | 0,26 | 0,47 | 1,44 | 2,17 | 0,17 | 0,08 | 0 | 0 | 0,25 | 0,17 | 0,14 |
| Tadpole fish | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Turbot | 0 | 0 | 0,04 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,14 | 0,06 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Shorthorn sculpin | 0,38 | 0,13 | 0,13 | 0,15 | 1,14 | 0,92 | 0,28 | 0,42 | 0,33 | 0,16 | 0,31 | 0,67 | 0,14 | 0,25 | 0 | 0,04 | 0,08 | 0,11 | 0,03 | 0,22 | 0,22 |
| Plaice | 0 | 0,08 | 0 | 0 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0,03 | 0 | 0 | 0,08 | 0,06 | 0 | 0,08 | 0 |
| Dab | 0 | 0 | 0 | 0 | 0,11 | 0 | 0,03 | 0 | 0 | 0 | 0 | 0,11 | 0,03 | 0,03 | 0,04 | 0 | 0,04 | 0,06 | 0,17 | 0,08 | 0,17 |
| Herring | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 |
| Lumpfish | 0,21 | 0,04 | 0 | 0,03 | 0 | 0,03 | 0 | 0,04 | 0,04 | 0 | 0 | 0 | 0 | 0 | 0,25 | 0,13 | 0 | 0 | 0,06 | 0 | 0,03 |
| Sprat | 0 | 0 | 0 | 0 | 0 | 0,0278 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,04 | 0 | 0 | 0,03 | 0,06 | 0,06 | 0 |
| Flounder | 0,04 | 0 | 0,25 | 0,03 | 0,36 | 0,36 | 0,17 | 0,08 | 0,17 | 0,32 | 0,11 | 0,50 | 0,17 | 0,47 | 0 | 0,04 | 0,08 | 0 | 0,03 | 0,14 | 0,08 |
| Hooknose | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0,08 | 0 | 0 | 0 | 0 | 0 | 0 | 0,08 |
| Corkwing wrasse | 0 | 0 | 0 | 0 | 0 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,08 | 0,13 | 0 | 0 | 0 | 0,53 | 0,03 |
| Brill | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Greater pipefish | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 |
| Goldsinny wrasse | 0,13 | 0,13 | 0,17 | 0,15 | 1,64 | 0,61 | 0 | 0 | 0 | 0 | 0 | 0,06 | 0 | 0 | 3,58 | 6,38 | 8,83 | 5,39 | 9,92 | 3,31 | 0,83 |
| Black goby | 0 | 0,04 | 0,29 | 0,03 | 0,53 | 0,58 | 0 | 0,08 | 0 | 0,42 | 0,03 | 0,89 | 0,89 | 0,03 | 0,33 | 0,04 | 1,08 | 1,08 | 5,25 | 2,22 | 0 |
| Rock gunnel | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 | 0,03 | 0,03 | 0 | 0 |
| Sand eel (lesser/small) | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0,03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 |
| Cod | 1,63 | 1,96 | 1,79 | 2,91 | 2,06 | 2,78 | 1,67 | 1,38 | 1,13 | 0,68 | 1,00 | 0,14 | 0,42 | 0,72 | 2,04 | 1,96 | 4,67 | 3,78 | 2,50 | 7,97 | 6,00 |
| Eelpout | 1,63 | 3,08 | 7,25 | 6,67 | 6,39 | 9,94 | 8,83 | 4,54 | 6,92 | 15,47 | 9,94 | 8,75 | 29,17 | 12,11 | 0,04 | 0 | 0,04 | 0,11 | 0,69 | 0,83 | 1,08 |
| Broadnosed pipefish | 0 | 0,08 | 0 | 0 | 0 | 0 | 0 | 0 | 0,08 | 0 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 |
| Fifteen-spined stickleback | 0,46 | 0,21 | 0,33 | 0,15 | 0,44 | 0,39 | 0,47 | 0,54 | 0,46 | 0,16 | 0,14 | 0,53 | 0,56 | 0,50 | 0,79 | 1,13 | 0,46 | 0,14 | 0,28 | 0,47 | 0,08 |
| Sole | 0 | 0 | 0 | 0 | 0 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,03 | 0 |
| *Total fish* | 5,00 | 6,54 | 11,13 | 10,45 | 14,11 | 17,42 | 12,31 | 7,58 | 9,50 | 17,63 | 12,00 | 12,89 | 33,31 | 16,44 | 8,54 | 11,25 | 15,79 | 11,50 | 20,86 | 17,19 | 9,61 |
| *Number of individual fish* | 120 | 157 | 267 | 345 | 508 | 627 | 443 | 182 | 228 | 335 | 420 | 464 | 1199 | 592 | 205 | 270 | 379 | 414 | 751 | 619 | 346 |
| *Number of fish species* | 10 | 11 | 10 | 10 | 12 | 15 | 9 | 10 | 9 | 7 | 9 | 13 | 14 | 12 | 12 | 10 | 10 | 12 | 15 | 17 | 13 |
| *SHELL FISH* | | | | | | | | | | | | | | | | | | | | | |
| Shore crab | 0,75 | 5,88 | 5,75 | 2,15 | 15,61 | 14,69 | 6,31 | 0,13 | 1,83 | 1,74 | 0,46 | 5,08 | 1,94 | 1,89 | 0,50 | 3,08 | 7,71 | 10,36 | 13,56 | 16,39 | 4,31 |
| *Total shell fish* | 0,75 | 5,875 | 5,75 | 2,1515 | 15,611 | 14,694 | 6,3056 | 0,125 | 1,8333 | 1,7368 | 0,4571 | 5,0833 | 1,9444 | 1,8889 | 0,5 | 3,0833 | 7,7083 | 10,361 | 13,556 | 16,389 | 4,3056 |
| *Number of individual shellfish* | 18 | 141 | 138 | 71 | 562 | 529 | 227 | 3 | 44 | 33 | 16 | 183 | 70 | 68 | 12 | 74 | 185 | 373 | 488 | 590 | 155 |
| *Number of shell fish species* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| *Number of stations undisturbed* | 24 | 24 | 24 | 33 | 36 | 36 | 36 | 24 | 24 | 19 | 35 | 36 | 36 | 36 | 24 | 24 | 24 | 36 | 36 | 36 | 36 |

*same species in a different developmental stage

# Appendix 2

Species composition in terms of numbers per station of the different species caught in the fish sampling using gill net series at the wind farm (Lillgrund), and the reference areas Bredgrund (southern reference area) and Sjollen (northern reference area) during the base line studies 2002–2005 and after the wind farm was in production 2008–2009.

| Species | LILLGRUND | | | | | | BREDGRUND | | | | | | SJOLLEN | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 2003 | 2004 | 2005 | 2008 | 2009 | 2002 | 2003 | 2004 | 2005 | 2008 | 2009 | 2002 | 2003 | 2004 | 2005 | 2008 | 2009 |
| *FISH* | | | | | | | | | | | | | | | | | | |
| Perch | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Yellow eel | 0,04 | 0 | 0 | 0 | 0,04 | 0,04 | 0,09 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,04 | 0 |
| Pipefish (undet.) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Longspined bullhead | 0,71 | 1,05 | 0,54 | 1,21 | 0,87 | 1,09 | 0,82 | 1,26 | 0,28 | 0,61 | 0,93 | 3,82 | 0,46 | 0,09 | 0,08 | 0,04 | 0,04 | 0,16 |
| Turbot | 0,04 | 0,11 | 0,04 | 0,17 | 0,04 | 0,04 | 0,18 | 0 | 0,56 | 0,39 | 0,21 | 0,53 | 0,08 | 0 | 0,04 | 0 | 0 | 0 |
| Plaice | 0,13 | 0 | 0,46 | 0,71 | 0,17 | 0,09 | 0,18 | 0,09 | 0,06 | 0,50 | 0,07 | 0 | 0,69 | 0 | 0 | 0,13 | 0,04 | 0,21 |
| Shorthorn sculpin | 0,50 | 1,11 | 3,00 | 1,63 | 1,30 | 0,78 | 0,91 | 3,09 | 4,50 | 5,11 | 1,21 | 1,12 | 1,46 | 0,41 | 0,33 | 0,17 | 0,39 | 2,37 |
| Dab | 0,46 | 0,05 | 0,54 | 0,17 | 0,61 | 0,57 | 0 | 0,04 | 1,56 | 0,11 | 0,64 | 0,24 | 1,00 | 0 | 0,17 | 0,17 | 0,17 | 0,21 |
| Herring | 0,96 | 0,11 | 0 | 0 | 0,17 | 0 | 6,36 | 0,04 | 0,06 | 0,06 | 0,64 | 0,65 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sprat | 0,04 | 0 | 0,04 | 0,13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,15 | 0 | 0 | 0 | 0 | 0 |
| Flounder | 2,33 | 2,32 | 3,13 | 4,96 | 6,96 | 1,83 | 0,64 | 1,70 | 2,94 | 4,22 | 1,43 | 2,88 | 4,23 | 0,82 | 1,13 | 1,71 | 2,26 | 0,84 |
| Hooknose | 0 | 0,11 | 0,21 | 0,04 | 0,13 | 0,26 | 0 | 0,04 | 0 | 0,11 | 0 | 0,12 | 0 | 0,14 | 0,08 | 0 | 0,48 | 0,79 |
| Corkwing wrasse | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,37 |
| Brill | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,04 | 0 |
| Goldsinny wrasse | 0,13 | 0,11 | 0 | 0,21 | 0,04 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,31 | 1,18 | 0,17 | 9,17 | 1,17 | 0,26 |
| Black goby | 0,83 | 0,37 | 0 | 0,50 | 0,26 | 0,04 | 0,27 | 0 | 0,06 | 0 | 0,07 | 0 | 0,69 | 0,32 | 0 | 0,38 | 0,30 | 0,05 |
| Sand eel (lesser/small) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,06 | 0 | 0 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cod | 10,92 | 4,84 | 7,38 | 9,17 | 2,52 | 4,91 | 8,55 | 2,04 | 7,72 | 7,28 | 0,14 | 3,35 | 11,31 | 4,36 | 12,33 | 7,67 | 2,17 | 4,63 |
| Eelpout | 0,04 | 0,11 | 0,25 | 0,21 | 0,13 | 0,04 | 0 | 0,04 | 0 | 0,06 | 0,07 | 0,06 | 0 | 0 | 0 | 0 | 0 | 0,16 |
| Whiting | 0,25 | 0 | 0 | 0 | 0 | 0,04 | 0 | 0,22 | 0,11 | 0,06 | 0 | 0,18 | 0,15 | 0 | 0 | 0 | 0 | 0 |
| Sole | 0,17 | 0 | 0 | 0 | 0,96 | 0,17 | 0,27 | 0 | 0 | 0,06 | 0,36 | 0 | 0,38 | 0 | 0 | 0 | 0,04 | 0 |
| Trout | 0 | 0 | 0,04 | 0 | 0,09 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Total fish* | 17,54 | 10,26 | 15,63 | 19,08 | 14,30 | 9,91 | 18,27 | 8,57 | 17,89 | 18,61 | 5,86 | 13,00 | 21,92 | 7,32 | 14,33 | 19,42 | 7,17 | 11,05 |
| *Number of individual fish* | 421 | 195 | 375 | 458 | 329 | 228 | 201 | 197 | 322 | 335 | 82 | 221 | 285 | 161 | 344 | 466 | 165 | 210 |
| *Number of fish species* | 15 | 11 | 11 | 12 | 15 | 13 | 10 | 10 | 11 | 13 | 12 | 11 | 12 | 7 | 8 | 8 | 12 | 11 |
| *SHELL FISH* | | | | | | | | | | | | | | | | | | |
| Shore crab | 67,29 | 158,74 | 71,75 | 146,21 | 295,35 | 310,57 | 31,82 | 48,65 | 45,78 | 48,33 | 179,57 | 152,88 | 81,15 | 123,77 | 107,96 | 135,50 | 204,00 | 141,37 |
| *Total shell fish* | 67,29 | 158,74 | 71,75 | 146,21 | 295,35 | 310,57 | 31,82 | 48,65 | 45,78 | 48,33 | 179,57 | 152,88 | 81,15 | 123,77 | 107,96 | 135,50 | 204,00 | 141,37 |
| *Number of individual shellfish* | 1615 | 3016 | 1722 | 3509 | 6793 | 7143 | 350 | 1119 | 824 | 870 | 2514 | 2599 | 1055 | 2723 | 2591 | 3252 | 4692 | 2686 |
| *Number of shell fish species* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| *Number of stations undisturbed* | 24 | 19 | 24 | 24 | 23 | 23 | 11 | 23 | 18 | 18 | 14 | 17 | 13 | 22 | 24 | 24 | 23 | 19 |

# Study of the Fish Communities at Lillgrund Wind Farm

## Final Report from the Monitoring Programme for Fish and Fisheries 2002–2010

Lillgrund Wind Farm began operating in 2008 and it is currently the largest investment in offshore wind power in Sweden.

This report deals with the contribution that the wind farm makes to the soundscape in the Öresund Strait, the effects on bottom dwelling and open water fish species, as well as the effects on migrating silver eels. It also contains a literature review within the overarching discussion.

The monitoring programme at Lillgrund has made a valuable contribution to the increase in the understanding of the impact of offshore wind power on fish communities.

The programme has also put focus on the need for studies over a longer period of time and on the cumulative effects on for example migratory fish such as silver eel.

The Swedish Agency for Marine and Water Management hopes that the report will provide an important source of information for environmental impact assessements as well as for the planning and licensing processes for wind power.

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