Final report on the effect of Nysted Offshore Wind Farm on harbour porpoises

Annual report 2005

Technical report to Energi E2 A/S

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Foreword

This report presents results from the monitoring program on harbour porpoises conducted at Nysted Offshore Wind Farm during the period 2001-2005. The study was commissioned by Energy E2 A/S and financed by the Danish Energy Authority (Energistyrelsen). This is the annual report for monitoring in 2005 and at the same time the final report of the monitoring program of harbour porpoises at Nysted. All collected data is thus included in the analysis and this report thus succeeds and replaces annual reports of the previous years. However, some of the technical details and especially the development and justification of the experimental methods and analyses used may require that previous reports are consulted. A complete list of reports related to harbour porpoises at Nysted Offshore Wind Farm is available at www.nystedhavmoellepark.dk.

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Summary

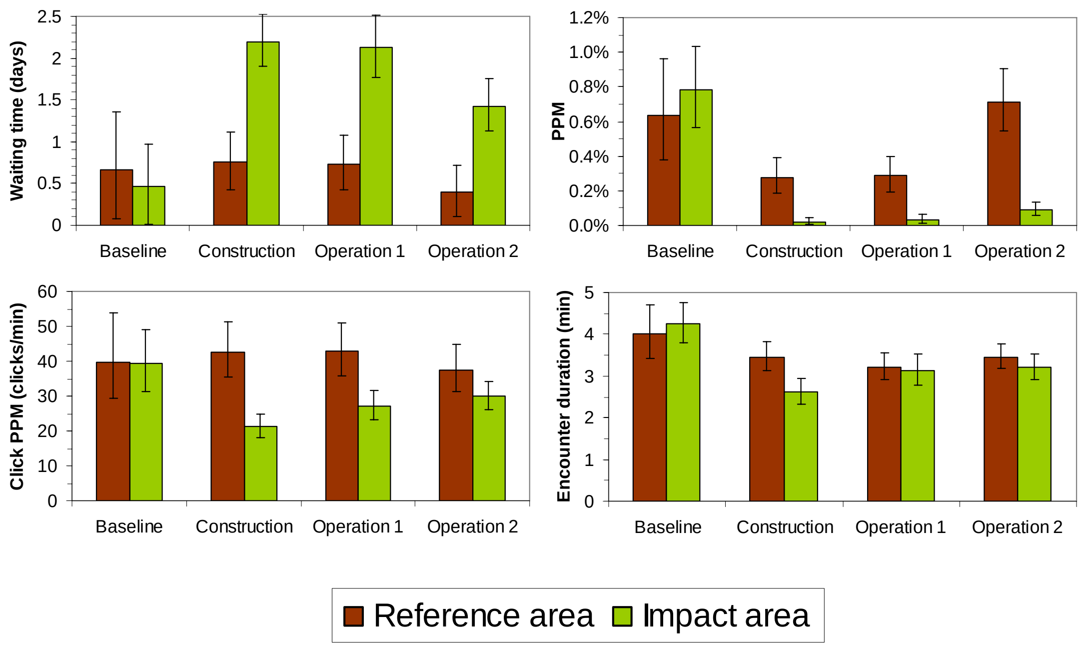
This report describes the setup and result of a four year long investigation of the response of harbour porpoises to the construction and the subsequent operation of Nysted Offshore Wind Farm.

The investigation was conducted with acoustic dataloggers: T-PODs that record and store the time and length of echolocation sounds of harbour porpoises. The first T-PODs were deployed in November 2001 in the area of the proposed wind farm. From April 2002 three PODs were deployed in the wind farm area and further three PODs in a reference area 10 km away. The T-POD data was collected over four years and covers a baseline period, the construction of the wind farm, which started in late June 2002 and ended in December 2003, and two years of operation (2004 and 2005).

Four indicators were calculated on basis of the click recordings and used for the analysis:

- *Porpoise positive minutes* (minutes with porpoise clicks recorded), which is an indication of porpoise echolocation activity.
- *Waiting time* (time between groups of echolocation clicks) indicates how often porpoises enters the area.
- E*ncounter duration* indicates how long the porpoises remain in detectable range of the T-POD.
- *Number of clicks per porpoise positive minute* is an indicator of how intensive the porpoise uses its echolocation when within detectable range.

During the baseline period there was no difference in either *waiting time* or number of *porpoise positive minutes* between the reference and impact area (see figure below). During construction and first two years of operation *waiting time* increased and *porpoise positive minutes* decreased considerably in the wind farm area, indicating that fewer porpoises were present in the wind farm area in these periods. A smaller, yet still significant increase in *waiting time* and decrease in *porpoise positive minutes* was also observed in the reference area, possibly signifying a general effect of wind farm construction on porpoise abundance in the Rødsand area.



Mean values for waiting time, porpoise positive minutes (PPM), Clicks/PPM and encounter duration divided by the reference and impact (wind farm) areas. Error bars indicate 95% confidence limits for the mean values.

Although indicators are still significantly affected two years after completion of the wind farm, there is a tendency towards return to baseline (pre-construction) levels in waiting time and *porpoise positive minutes* in the wind farm area. Activity in the reference area was back to baseline levels two years after end of construction. This likely indicates that porpoises have gradually habituated and returned to the wind farm during the first two years of operation.

Encounter duration and number of *clicks per porpoise positive minute* decreased significantly from baseline to construction period in the wind farm area (see figure above), indicating that not only were there fewer porpoises in the area during construction, their echolocation behaviour was also affected. This effect disappeared in the second year of operation, indicating that the acoustic behaviour of porpoises in the wind farm area returned to baseline levels.

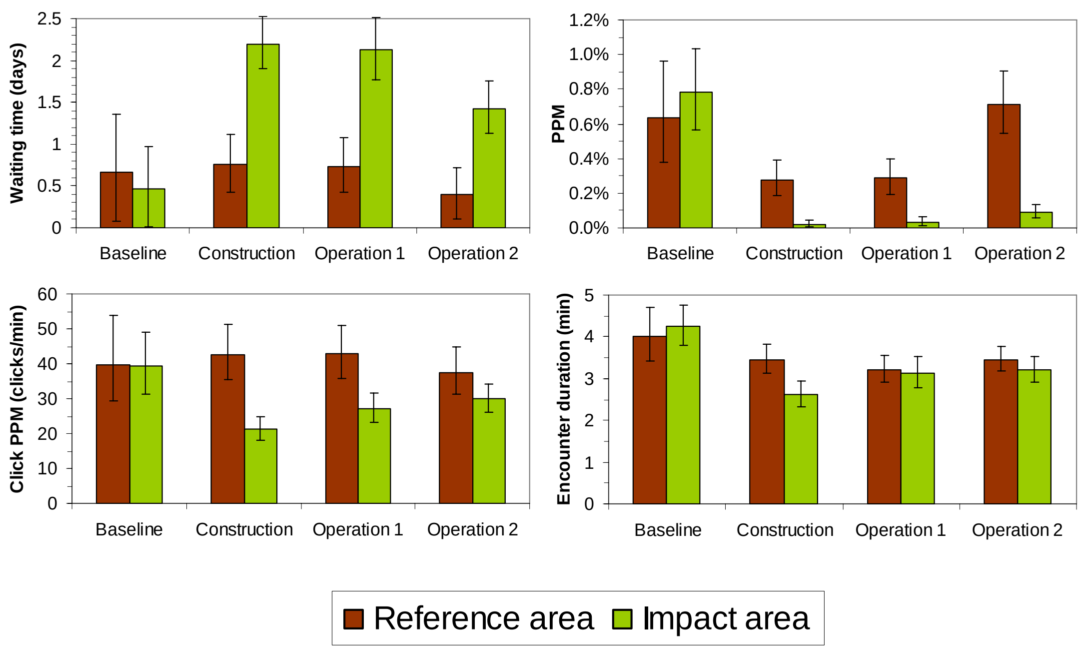
Dansk resumé

Denne rapport beskriver resultaterne af et fire-årigt overvågningsprogram om marsvins reaktioner på bygning og drift af Nysted Havvindmøllepark ved Rødsand, Gedser.

Undersøgelserne blev foretaget med akustiske dataloggere (T-POD), der kan registrere ekkolokaliseringslyde fra marsvin. De første dataloggere blev udlagt i det kommende mølleområde i november 2001. Tre dataloggere blev udlagt i mølleområdet fra april 2002, sammen med tre tilsvarende dataloggere i et referenceområde beliggende ca. 10 km fra mølleområdet. Data blev opsamlet gennem 4 år og dækker en periode før byggeriet startede (baseline), selve byggeperioden fra ultimo juni 2002 til december 2003 og de første to år af havmølleparkens drift (2004 og 2005).

Fire indikatorer blev ekstraheret fra optagelserne af ekkolokaliseringslyde (sonar-klik) og brugt i analyserne:

- *Porpoise positive minutes* (marsvin-positive minutter): minutter per dag hvor klik kunne høres. Dette er et mål for hvor hyppigt marsvin forekommer i området.
- *Waiting time* (ventetid): Tid mellem individuelle grupper af sonar-klik. Indikerer hvor ofte marsvin kommer ind i området.
- E*ncounter duration* (varighed af individuelle grupper af sonar-klik). Indikerer hvor lang tid marsvin forbliver indenfor detektionsafstand af dataloggeren.
- *Number of clicks per porpoise positive minute* (klik per marsvine-positivt minut). Er indikator for hvor meget marsvinene burger deres biosonar når de er indenfor detektionsafstand af dataloggeren.



Gennemsnitsværdier for ventetid (waiting time), marsvine-positive minutter (PPM), klik per marsvine-positive minutter (click PPM) og varighed af klik-grupper (Encounter duration), delt op på referenceområde og havvindmøllepark (impact area). Lodrette streger indikerer 95 % konfidensintervaller på middelværdierne.

I perioden op til bygning af mølleparken var der ikke forskel mellem mølleområde og referenceområde målt på parametrene ventetid og marsvin-positive minutter (se ovenstående figur). Under byggeperioden og de første to år af driften steg ventetiden betragteligt i mølleområdet, mens marsvin-positive minutter faldt, hvilket indikerer at der var færre marsvin i mølleparken under byggeriet end før. En mindre, men stadig signifikant stigning i ventetider hhv. fald i marsvin-positive minutter blev også målt i referenceområdet, hvilket sandsynligvis indikerer en generel effekt af byggeriet på marsvin i Rødsand-området.

På trods af at indikatorerne stadig viser en signifikant påvirkning to år efter byggeriet sluttede, er der en tendens i retning af returnering til niveauer som før byggeriet startede i ventetid og marsvin-positive minutter. I referenceområdet er aktiviteten tilbage til niveauet før byggeriet startede. Begge dele indikerer en sandsynlig gradvis tilvænning og tilbagevenden til havmølleområdet i løbet af de første to år af parkens eksistens.

Varighed af klik-grupper og *klik per marsvin-positivt minut* faldt signifikant fra før til under byggeriet af mølleparken inde i mølleområdet (se figuren). Dette indikerer at der ikke alene var færre marsvin i området under byggeriet, men også at deres ekkolokaliseringsadfærd var påvirket. Effekten forsvandt i andet år efter at byggeriet stoppede, hvilket peger på at den akustiske adfærd af marsvinene i området er returneret til niveauet før byggeriet startede.

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1 Background and Introduction

In 1996 in the wake of the Kyoto summit the Danish government passed an action plan for energy: Energi 21, in which it was decided to establish 5,500 MW of wind power in Denmark before 2030, 4,000 MW of which was to be established as large scale offshore wind farms. This decision was followed by action in 1998 where the Minister for Environment and Energy commissioned the Danish power companies to establish 750 MW of offshore wind power in Danish waters as a demonstration project. The aim of the project was twofold: to test the feasibility and economy of large scale offshore wind power and address potential negative effects on the marine environment by formation of an ambitious environmental monitoring program. After a change in government in 2001 the ambitions of the demonstration project were reduced to only two offshore wind farms (a total power of 318 MW,) one at Horns Reef off the Danish west coast (Horns Rev Offshore Wind Farm) and one at the entrance to the Baltic (Nysted Offshore Wind Farm). This report deals with monitoring of harbour porpoises at Nysted Offshore Wind Farm.

1.1 The sea around Nysted Offshore Wind Farm

Nysted Offshore Wind Farm is situated about 10 km southwest of Gedser in the Femer Belt (Figure 1) and about 4 km south of the sandbar, Rødsand. This narrow sandbar runs about 25 km from Hyllekrog to Gedser and is partly exposed at normal water levels. The sand reef borders a shallow lagoon area (depths 0.5-7 m), which is an important area for fish, birds, seals and coastal fishery.

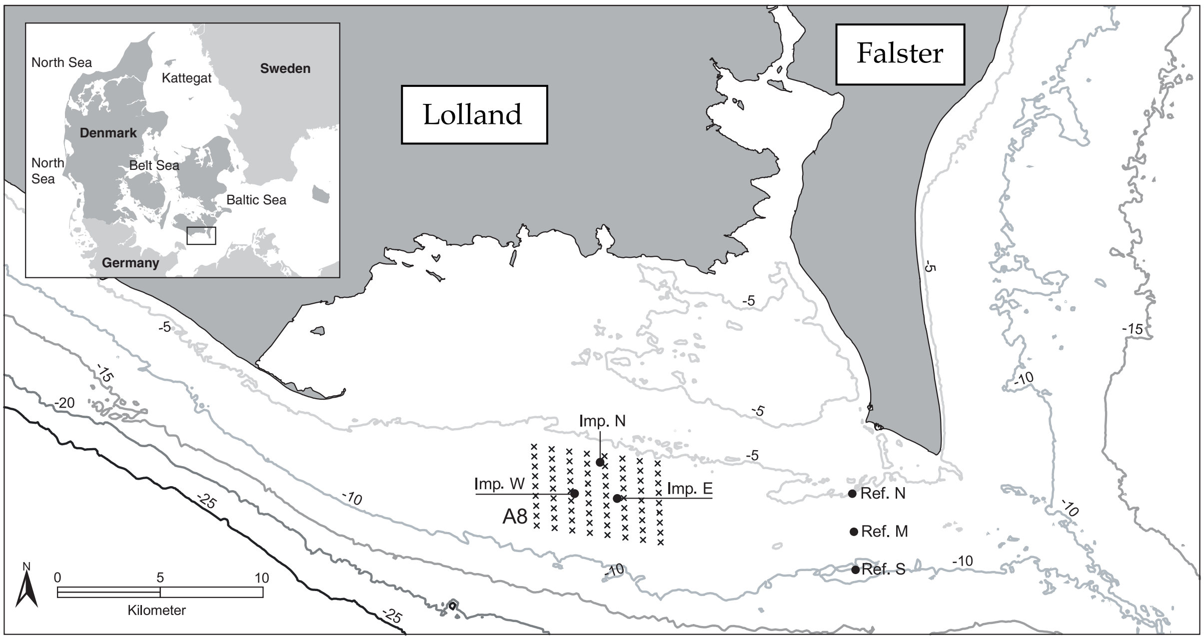


Figure 1. Study area. Wind turbines are indicated with x and T-POD monitoring stations with solid circles. Three stations (Imp. W, Imp. N and Imp. E) are located inside the wind farm and three stations (Ref. N, Ref. M and Ref. S) are located in a reference area about 10 km east of the wind farm.

1.1.1 Geology/geomorphology

Water depth in the wind farm varies between 6 m and 9.5 m and the sea floor consists primarily of glacial depositions (Hansson 2000). The largest part of the area is covered by sand/silt bottom with larger and smaller ridges and with aggregations of pebbles, gravel and shells scattered throughout the area. No reef-like aggregations are found in the area.

1.1.2 Hydrography

The water is brackish and varies with the freshwater surface flow from the Baltic Sea and the more saline water from Kattegat. The tide is weak in the area (less than 0.5 m) and variations in water level are mainly determined by wind.

1.1.3 Human activities

The wind farm is placed between Gedser and Rødby where the two ferry lines to Germany depart. Just south of the wind farm is the heavily trafficked T-route for larger ships going to and from the Baltic harbours. During summer the area is used by recreational boats of all sizes. Intense fyke net fishery and some pound net fishery occur in the lagoon north of the wind farm. Outside the wind farm trawling occurs at irregular intervals. The nearest harbour and town is Nysted, 10 km directly north of the wind farm.

1.2 Nysted Offshore Wind Farm

The wind farm was built in 2002/2003. The construction period began in mid-June 2002 where excavations for the foundations started. The last wind turbine was mounted July 27th 2003 and the last 33 kV cables were covered up in December 2003. The wind farm officially started in normal operation December 1st 2003, which is adopted in this report as the cut-off date between construction phase and operational phase (Figure 2).

The wind farm consists of 72 wind turbines of 2,3MW, placed in 8 rows of 9, forming a trapezoid. The turbine nacelle height is 69 meter and the wings are 41 meters long. The total height is 110 meter. The wind farm covers an area of 24 km².

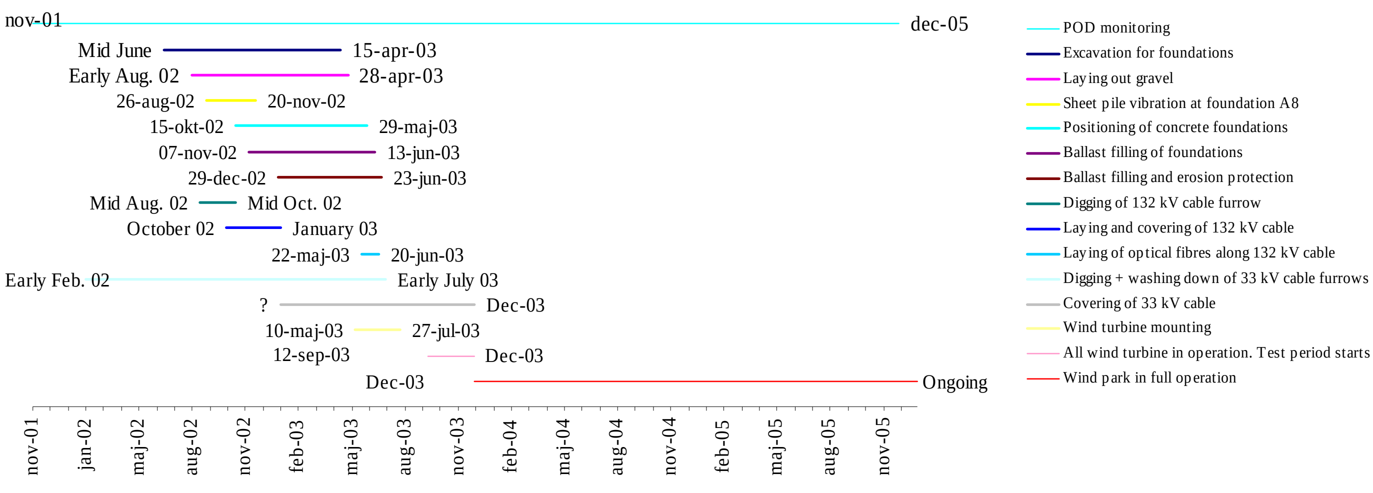


Figure 2. Diagram of major construction activities and their duration at Nysted Offshore Wind Farm.

1.3 Harbour porpoises

Figure 3. Harbour porpoise at the surface.

The harbour porpoise (*Phocoena phocoena*) is one of the smallest odontocetes (toothed whales) and the only cetacean (whale), which breeds in inner Danish waters (Figure 3). It is common in Danish waters, with a population of estimated 37.000 in Skagerrak, Kattegat, the Belt Seas and western Baltic (Hammond et al. 2002). The density of porpoises decreases east of a line between southern Sweden and Rügen and very few porpoises are found in the Baltic proper. Previously, i.e. before the 1950'es, porpoises were abundant in the Baltic. It is unknown exactly what has caused this decrease in distribution range, but factors like bycatch in fishery and pollution probably play important roles.

1.3.1 Reproduction

The breeding period of harbour porpoises begins in late June and ends in late August. Ovulation and conception typically take place in late July and early August (Sørensen & Kinze 1994). The pregnancy period is about 11 months and the females thus give birth to the single calves in early summer. The calves begin suckling immediately after birth and feed by their mother until March the following year and possibly longer. As porpoise cows most often give birth every year, this period can last 12 months at most. The females can conceive when they are 3 or 4 years old (Sørensen & Kinze 1994). If she does not conceive or loose her calf, a porpoise cow must wait until the next year before she can conceive again (Read 1990). Changes in food resources may influence the reproduction of porpoises. The only information that exists on breeding harbour porpoises in Danish waters, are sightings of calves. Calves seem to be sighted throughout their range and there may not be any particular breeding areas (Hammond et al. 1995, Kinze et al. 2003). However, satellite tracking of adult females show that they may have preference for some areas (Teilmann et al. 2004). No specific information exists on calves in the western Baltic.

1.3.2 Foraging ecology

The food sources of harbour porpoises in Danish waters comprise a large variety of fishes: herring, mackerel, cod, saithe, plaice, flounder, gobi, sandeel, garfish and eelpout (Börjesson & Berggren 2003). The daily food intake per adult harbour porpoise is about 1.75kg consisting mainly of fishes of up to 20-25cm in length with a preference for fat fishes like herring, mackerel, eelpout and small individuals of different cod species (Börjesson & Berggren 2003).

Between 1985 and 1990, the stomach contents of 21 harbour porpoises from the southern part of the Belt Seas and the western part of the Baltic Sea were studied. Herring made up 36% while cod made up 41% and eelpout 10% of the fish weight eaten (Börjesson & Berggren 1995). In another study a large proportion of gobies was found in the stomach of porpoises in the Baltic Sea, in particular in smaller individuals (Lick 1993). No exact information exists on the stomach contents of harbour porpoises in the Nysted wind farm area, but it is likely that their food preferences resemble those in the western parts of the Baltic Sea.

1.3.3 Echolocation and hearing

Like other toothed cetaceans harbour porpoises have good underwater hearing and use sound actively for navigation and prey capture (echolocation). They produce short ultrasonic click (130 kHz peak frequency, 50-100 µs duration; Møhl & Andersen 1973, Teilmann *et al*. 2002) and are able to orient and find prey even in complete darkness. Porpoises tagged with acoustic data loggers indicate that they use their echolocation almost continuously (Akamatsu et al. 2005, and Akamatsu et al. subm.).

Odontocetes have no outer ear and their ear canal is vestigial. Sound does not enters the head through the ear canal, but through the surface of the lower jaw and is transmitted via a channel of fat to the tympanic bulla of the middle ear (Norris 1964; Møhl *et al.* 1999; Brill *et al.* 2001). Odontocete inner ears have anatomical specialisations for ultrasonic hearing, such as high thickness to width ratios of the basal (high-frequency) part of the basilar membrane, supplemented by additional stiffening elements along the cochlear duct (Ketten 2000).

The fundamental measure of an animal's hearing ability is the audiogram, expressing the lowest sound pressures detectable by the animal in quiet conditions measured at different frequencies. Odontocete audiograms are as a whole fairly similar in shape, with range of best hearing in the area 10-100 kHz, and best thresholds around 40-50 dB re. 1 µPa. Hearing thresholds increases slowly with about 20 dB per decade for lower frequencies and increases steeply at high frequencies. In general, smaller species like the harbour porpoise have higher upper limits of hearing, around 150 kHz (Andersen 1970; Kastelein *et al.* 2002) than larger species.

Another central characteristic of auditory systems, especially in the context of influence of noise is the bandwidth of auditory filters. Mammalian auditory systems are conventionally modelled as a bank of narrow bandpass filters. In order for noise to interfere with reception of a particular sound it has to fall within the frequency range of that or those particular filters covering the sound. The bandwidth of the auditory filters differs somewhat among species and with frequency within the same species. A general approximation for mammals however, is that the bandwidth is 1/3 octave throughout the hearing range of the animal. This is known as a constant Q filter bank (Q is the ratio of centre frequency to bandwidth) and implies that the width of the filters increase with increasing frequency. A recent study on porpoises (*Phocoena phocoena* and *Neophocoena phocaenoides*) hearing however, has revealed that their filter bank is differently organised than the normal for mammals and that they closely approach a constant bandwidth filter bank (Popov *et al.* 2006). This new information has important implications for the discussion of possible effects of underwater noise from wind turbines. As Popov *et al.* (2006) did not measure filter bandwidths below 20 kHz (i.e. not in the range where turbine noise is) and as the standard mammalian constant Q model does not fit the data, there is uncertainty as to the extent low frequency noise affects the hearing of porpoises..

1.3.4 Vision

Cetaceans have good vision, although odontocetes compared to other mammals have small eyes in relation to their body size. The eyes are completely adapted to water and vision under low light conditions. The spherical lens makes the eye highly myopic (short-sighted) in air and they are not likely to be able to see objects sharply in air beyond a few meters Movement however, such as from rotating turbine wings, should be clearly visible to porpoises, even in air.

Odontocetes, like mysticetes and also seals, are functionally colour blind (Peich *et al.* 2001).

1.3.5 Other senses

Odontocetes have no sense of smell, whereas taste may play a role, not only in relation to tasting prey, but also in terms of collecting information about the surrounding water. Thus, in the context of anthropogenic impact it cannot be ruled out that porpoises can taste and will react to harmful and/or distasteful substances in the water.

A magnetic sense, that is the ability to determine the direction of the earth's magnetic field, has only been demonstrated convincingly in a few vertebrates. However, this ability has turned out to be very difficult to explore experimentally (Wiltschko and Wiltschko 1996) and the weak conclusion is that it remains a possibility that odontocetes, including the porpoise have a magnetic sense, but there is no experimental data to support it.

Until fairly recently it was believed that no mammals had electroreceptive abilities, but it has been conclusively demonstrated that the duckbilled platypus has electroreceptive organs along the edge of the bill and uses these in prey capture (Proske and Gregory 2003). Since then several other mammals have been suspected of possessing electroreceptive capabilities. Although marine mammals seems like good candidates for electroreception, as they like sharks live and find their prey in often dark and murky waters, there is so far nothing that supports this. In contrast to the case for magnetic sense, this absence of evidence should be taken more conclusively. Electroreceptive sensory cells are well known from animals with electric sense and among other features have a characteristic morphology and often special and easily recognisable support structures attached to them, such as the Lorenzinian ampullae of cartilaginous fish (Bullock 1986). No cells with this special morphology and support structures have been identified in any cetacean and it thus seems unlikely that they are sensitive to weak electric fields, or even able to perceive them.

1.3.6 Population and distribution in the area

Rødsand is situated at the edge of the western Baltic Sea and supports a density of 0.1 porpoise per km^2 according to the only survey that have been published on absolute density for the area (Hammond et al. 2002). This number shows that Rødsand is within an area with lower densities of porpoises than many other parts of the Danish waters. It is important to acknowledge that the above mentioned figures are based on one single investigation conducted during July 1994. The great uncertainty implies that the results from the investigated areas cannot be directly transferred to a small area like the wind farm. Results from satellite tracking of 52 harbour porpoises in the Inner Danish waters have revealed that porpoises in the area south of Rødsand is part of the population ranging from the northern Kattegat south to east of Gedser (Teilmann et al. 2004). Nysted Offshore Wind Farm is thus placed at the south-eastern edge of the population bordering the Baltic proper with its endangered porpoise population (ASCOBANS 2002). This makes the area important for future re-colonisation of the Baltic proper, as the Western Baltic population is the closest larger population from which animals can be recruited to the Baltic Proper.

1.4 Scope of investigations

The ultimate question in the context of offshore wind farms and marine mammals is whether the construction and operation of these have a net effect (positive or negative) on the population size in the area and if this is the case whether this change in population size is acceptable or not. In the end, the latter question is political rather than biological and will not be discussed here.

Even if the ultimate goal may be to address impact at the population level, this is rarely possible to do directly. It is then helpful to address the issue through an overview of the significant factors affecting the porpoises and their ultimate impact on the population (figure 4). Effects are divided into negative (red) and positive (green). The net effect is thus broken up into a number of individual contributions from different factors that can be assessed individually. The focus of the study is thus the proximate question of whether the abundance and behaviour of porpoises is affected by construction and operation of an offshore wind farm and the ultimate question of impact at population level will only be touched upon in the discussion.

1.4.1 Physical presence and visual impact

It is conceivable that the physical presence of the turbines has a negative effect on porpoises, i.e. that porpoises will be reluctant to enter an area with new large structures such as the turbine foundations and be deterred by the rotating wings. Such effects are very difficult to assess experimentally and no studies have demonstrated such effects in any marine mammal.

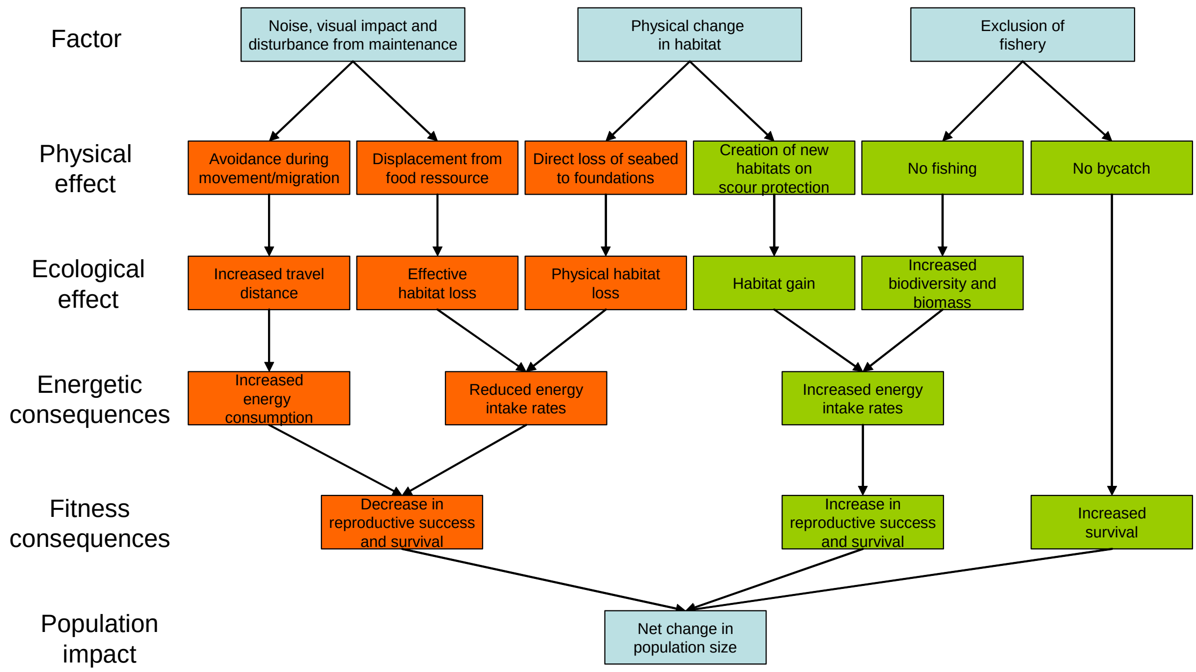


Figure 4. Potential effects of offshore wind farms on harbour porpoises. Factors with negative effect are shown in red; factors with positive effects are shown in green. Adapted from Fox *et al.* 2004).

1.4.2 Noise from operating wind turbines

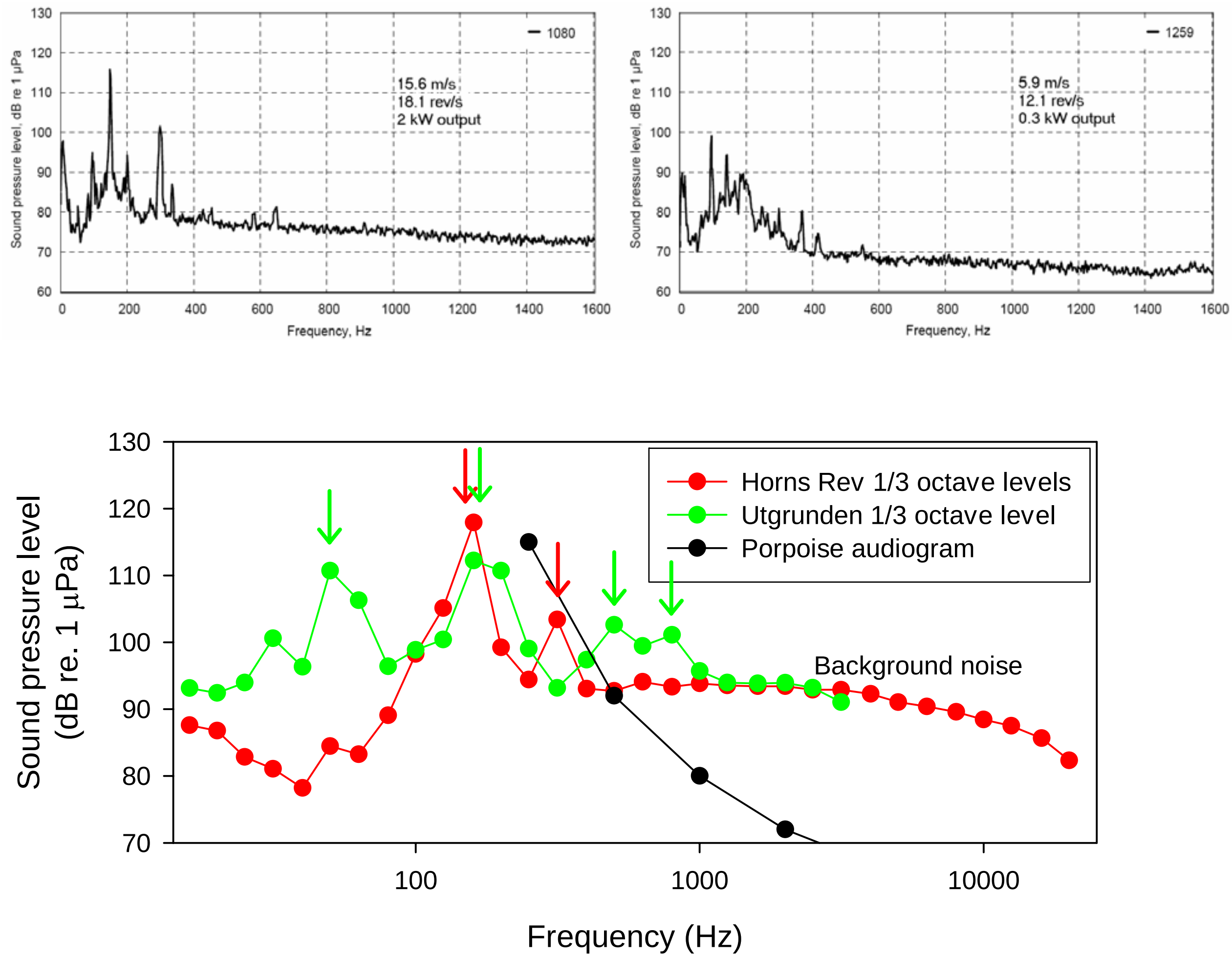


Figure 5. Top: Frequency spectra of noise recorded from a turbine in Horns Rev offshore wind farm running at maximum power (left) and reduced power (right). Turbine noise consists of multiple peaks at discrete frequencies, which rise above the background noise. From Betke (2006). Bottom: Noise from Horns Rev and Utgrunden Wind Farms, expressed as third-octave levels at 100 meters distance from turbines and plotted together with threshold curve of a porpoise (audiogram). Arrows indicate the prominent peaks in the spectrum where the turbine noise exceeds the background noise. Noise above 800 Hz and 1250 Hz for Horns Rev and Utgrunden respectively, is background noise unrelated to the turbine noise. Adapted from Betke (2006).

Noise radiated from the turbine foundations into the water could potentially have an effect on porpoises. Based on measurements of other offshore wind turbines, the noise from the wind turbines is expected to be of relatively low intensity and frequency (Madsen et al. 2006). Calculations and field experiments indicate that harbour porpoises are able to hear individual turbines at distances up to about hundred meters (Henriksen 2001). These calculations however, are based on a 1/3 octave filter bank model and as mentioned above (section 1.3.3), there is recent experimental evidence showing that this assumption does not hold for porpoises (Popov *et al.* 2006). At present, it is thus difficult to estimate the range at which the turbines are audible to the porpoises, although the generally low levels of noise emitted, combined with the relatively poor hearing abilities of porpoises at low frequencies makes it unlikely that they should be audible beyond a few hundred meters at best. Figure 5 shows noise from a single 1.4 MW turbine at Utgrunden Wind Farm (Ingemansson Technology AB 2003), the noisiest turbine measured to date. Absolute third-octave levels measured at 83 meters distance from the turbine foundation are low, with a maximum of 126 dB re 1 µPa at 180 Hz, measured at a wind speed of 13 m/s. This level roughly coincides with the extrapolated audiogram of the porpoise, indicating that it should be just audible to a porpoise

83 m from the turbine, where the measurement was made. A second, smaller peak around 800 Hz is present in the turbine noise. This peak is considerably above threshold level for the porpoise at 800 Hz and 10-15 dB above background noise level, and should be clearly audible to the animal at 83 meters. The distance at which this peak disappears below the background noise can be calculated given knowledge of the transmission loss in the waters around the turbine. Measurements from Ingemansson (2003), recalculated by Madsen *et al.* (2006) indicate a transmission loss of 30 dB per 10-fold increase in distance. Using this value, the peak at 800 Hz reaches the background noise level at a distance of 260 m from the turbine.

No measurements of noise from the turbines at Nysted Offshore Wind Farm are available. A number of measurements from other turbines are available and all share common features of low absolute sound levels and no significant energy at frequencies above 500-1000 Hz. The noise from Utgrunden wind farm deviates from the remaining measurements (Vindeby, Middelgrunden, Horns Rev and Bockstigen-Valar) in being considerably higher in intensity (approx 10 dB) and with considerable energy at higher frequencies than the other wind farms. The reason why these turbines differ from the rest is unknown, but may have to do with the foundation on solid bedrock, in contrast to the hard sand in the other wind farms. The foundations at Nysted are similar to the foundations at Middelgrunden and although the turbines at Nysted are larger, they are of similar size as the turbines at Horns Rev. In the absence of measurements from Nysted it thus seems reasonable to assume that noise levels are comparable to e.g. Horns Rev, and that then measurements from Utgrunden can be used as a worst case estimate.

One complicating factor in extrapolating from other turbines is that the turbines at Nysted have two gears and thus two different speeds of rotation. As the main components of the noise (the prominent peaks in the frequency spectrum) are likely to correspond to the frequency at which the teeth of the individual gearwheels engage, a change from one gear to another will change this frequency and hence also the spectrum of the noise. In addition to this, there will be a transient noise from the gear change itself, the spectrum and intensity of which is unknown. The change from low to high gearing occurs at wind speeds around 6 m/s.

When it comes to reactions of the porpoises to the noise, we are left with qualified guessing. Sound pressure levels where behavioural reactions are observed are likely to be considerably higher than levels of audibility and may vary considerably from individual to individual. A high dependence on context is also likely, as animals engaged in important activities, such as feeding or mating, may be more tolerant to increased noise levels. The extent of the zone of responsiveness (*sensu* Richardson *et al.,* 1995) is thus likely to be considerably smaller than the zone of audibility and reactions may thus be expected to occur only in the very vicinity of the turbine foundations.

Besides being a disturbing factor in itself, noise has the potential to interfere with detection of other sounds, known as masking. This may occur when there is an overlap between the frequency ranges of the noise and the sound in question. The low frequency emphasis of the turbine noise makes it very unlikely that it will mask any sounds of importance to the porpoises under any conditions. The echolocation signals of porpoises contain virtually no energy below 100 kHz and are thus completely outside the frequency range of the turbine noise. There may be other sounds, such as from potential prey, which contains significant energy at lower frequencies and thus potentially could be masked by the turbine noise. However, it is well established that the audiogram of a particular animal reflects the frequency content of the sounds of importance to the particular animal. Porpoises have poor low frequency hearing, poorer than e.g. seals and considerably poorer than low frequency hearing specialists, such as fish. Thus, by this indirect inference, it seems unlikely that they listen for sounds below 1 kHz on a regular basis and any masking by the turbine noise in this frequency range is thus unlikely to be significant to harbour porpoises.

1.4.3 Noise from service and maintenance activities

The third potentially disturbing factor is service operations on the turbines, where small, fast boats commute between land and the wind farm, as well as between the wind turbines. Such boats are known to be very noisy especially at cruising speeds above 15 knots (Richardson et al., 1995, Erbe 2002) and the pure presence of these boats are likely to have a deterring effect on harbour porpoises. In contrast to the noise from the turbines, the boat noise is of intermittent nature and overall disturbance will depend on the duration of each visit and intervals between visits. The wind farm area was previously used mostly for recreational traffic to and from Nysted harbour (Figure 1). A regular presence of service vessels in the area will be a marked increase in boating activity, especially outside the summer season where the leisure traffic to Nysted is negligible.

The effects of boat traffic on presence of harbour porpoises are poorly documented and while there is a general agreement that porpoises will evade individual fast motor vessels, there is no basis for concluding that high boat traffic levels in general correlate with low abundance of porpoises. Some of the highest densities of porpoises in inner Danish waters are in fact found in the most heavily trafficked areas, Storebælt and Lillebælt (Kinze *et al.* 2003; Teilmann *et al.* 2004).

1.4.3.1 Changes in habitat

The construction of an offshore wind farm on hard sandy bottom as at Nysted will inevitably cause changes to the habitat. First of all is the direct loss of habitat to foundations and scour protection, which unquestionable is negative to the organisms inhabiting the sandy seabed, lost to the foundations. This loss is clearly insignificant to porpoises as it comprises a loss of not more than about 2,000 m^2 per turbine or 0.01% of the total area of the wind farm (24 km^2). The introduction of new hard substrates (foundation tower and scour protection), will be colonised by algae and filter feeding epifauna. These will in turn attract fish and crustaceans and thus increase the biodiversity in the area and potentially increase the potential prey available for top predators as porpoises.

1.4.4 Exclusion of fishery

For reasons of safety (to fishermen and installations) no trawl fishery is allowed in the wind farm and there are restrictions on set net fishery. This may benefit porpoises directly due to a reduction of bycatch, which is by far the largest anthropogenic cause of increased mortality in porpoises in the North Sea (Vinther & Larsen 2004) and likely also in the inner Danish waters. The effect of restricting fishery in a small area like the wind farm is likely small however. A second, and perhaps more beneficial effect of restrictions in fishery is the greater availability of prey to the porpoises and likely also an increase in diversity of prey. However, these changes in the fish community are difficult to assess both for technical reasons and because they add on top of changes in the fish community caused by the introduction of hard substrates.

1.4.5 Hypotheses regarding effects

In the Environmental Impact Assessment (EIA) conducted prior to permission to build the park was granted, two main predictions regarding effects on harbour porpoises were stated:

- Activities during construction would create disturbance in the area, mainly in the form of underwater noise, increased ship and boat traffic and disturbance to the bottom sediment. All factors would likely cause porpoises to leave the wind farm area partly or totally during construction

- Operation and normal maintenance activities in the completed wind farm would not cause significant disturbance to the porpoises and porpoise abundance would return to baseline levels.

2 Methods

During the environmental impact assessment only few harbour porpoises were sighted during ship and aerial surveys for birds (Bach et al. 2000). Therefore visual surveys were considered to be ineffective in addressing questions of impact of the wind farm on harbour porpoises. Instead a design relying on passive acoustic detection of porpoises by means of long term deployment of dataloggers was adopted.

2.1 Acoustic dataloggers (T-PODs)

The T-POD or POrpoise Detector is a small self-contained data-logger that logs echolocation clicks from harbour porpoises and other cetaceans. It is developed by Nick Tregenza (Chelonia, UK). It is programmable and can be set to specifically detect and record the echolocation signals from harbour porpoises. Detailed descriptions and discussions of the methodology of using T-PODs in monitoring effects of wind farms can be found in previous reports (Teilmann *et al.* 2001; Henriksen *et al.* 2003).

2.1.1 Principle of operation and characteristics

The T-POD consists of a hydrophone, an amplifier, a number of band-pass filters and a data-logger that logs echolocation clicks. It processes the recorded signals in real-time and only logs time and duration of sounds fulfilling a number of acoustic criteria set by the user. These criteria relate to click-length (duration), frequency spectrum and intensity, and are set to match the specific characteristics of echolocation-clicks.

The T-POD relies on the highly stereotypical nature of porpoise sonar signals. These are unique in being very short (50-150 microseconds) and containing virtually no energy below 100 kHz (Figure 6). Main part of the energy is in a narrow band 120-150 kHz, which makes the signals ideal for automatic detection. Most other sounds in the sea, with the important exception of echosounders and boat sonars, are characterised by being either more broadband (energy distributed over a wider frequency range), longer in duration, with peak energy at lower frequencies or combinations of the three.

The actual detection of porpoise signals is performed by comparing signal energy in a narrow filter centred at 130 kHz with another narrow filter centred at 90 kHz. Any signal, which has substantially more energy in the high filter relative to the low and is below 200 microseconds in duration, is highly likely to be either from a porpoise or a man-made sound (echosounder or boat sonar).

Some spurious clicks of undetermined origin (e.g. background noise and cavitation sounds from high-speed propellers) may also be recorded. These, as well as boat sonars and echosounders are filtered out by analysing intervals between clicks using the associated T-POD software. Porpoise click trains are recognisable by a gradual change of click intervals throughout a click sequence, whereas boat sonars and echosounders have highly regular repetition rates (almost constant click intervals). Clicks of other origin tend to occur at random, thus with highly irregular intervals.

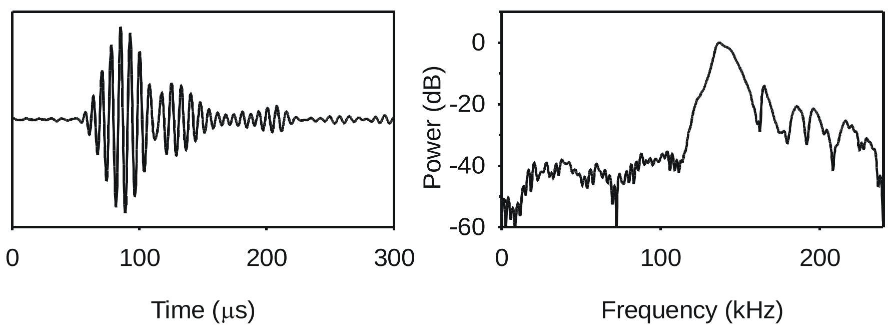


Figure 6. Porpoise click time signal (left) and power spectrum (right). There is virtually no energy present below 100 kHz (the curve below 100 kHz represents background noise of the recording).

No other cetacean regularly found in the Baltic has sonar signals that can be confused with porpoise signals.

The T-POD operates with six separate and individually programmable channels. This allows for e.g. one channel to log low frequency boat activity while the remaining channels log porpoise echolocation activity. However, in this study all channels had identical settings (Table 1).

Table 1. T-POD filter settings used during deployments.

A filter frequency	130 kHz
B filter frequency	90 kHz
Ratio A/B	5
A filter sharpness (arbitrary unit)	5
B filter sharpness (arbitrary unit)	18
Minimum intensity (arbitrary unit)	0

Each of the six channels records sequentially for 9 seconds, with 6 seconds per minute assigned for change between channels. This gives an overall duty cycle of 90% (54 seconds per minute), 15% for each channels (9 seconds per minute). In order to minimise data storage requirements only the onset time of clicks and their duration are logged. This is done with a resolution of 10 μs. The absolute accuracy of the timing of each recording is much less, due to drift in the T-PODs clock during deployment (a few minutes per month). This drift however, is only of concern when comparing records from two T-PODs deployed simultaneously. Clicks shorter than 10 μs and sounds longer than 2550 μs were discarded.

The hydrophone of the T-POD has a resonance frequency of 120 kHz and is cylindrical and thus in principle omnidirectional (equally sensitive at all angles of incidence) in the horizontal plane. T-PODs are insensitive to temperature changes within the normal operating range between 3ºC and 25ºC, except from a reduction in battery life at lower temperatures. Battery-voltage does not influence sensitivity as the electronics in the T-POD receive a stable voltage until the battery is drained below 5.1 V, where the electronics turn off.

Figure 7. An open T-POD connected to a computer. The hydrophone can be seen as a small attachment in the lower end of the T-POD. A prefabricated 6xD-cell Li-Ion battery pack is seen behind the T-POD.

The T-PODs used (version 1) are equipped with 8 MB RAM and powered with 49.5Ah, 7.2V lithium batteries (six 3.6V D-cells), which gives a maximum logging period of about 60 days. The memory will normally fill in 2-4 month depending on echolocation activity, background noise and software settings.

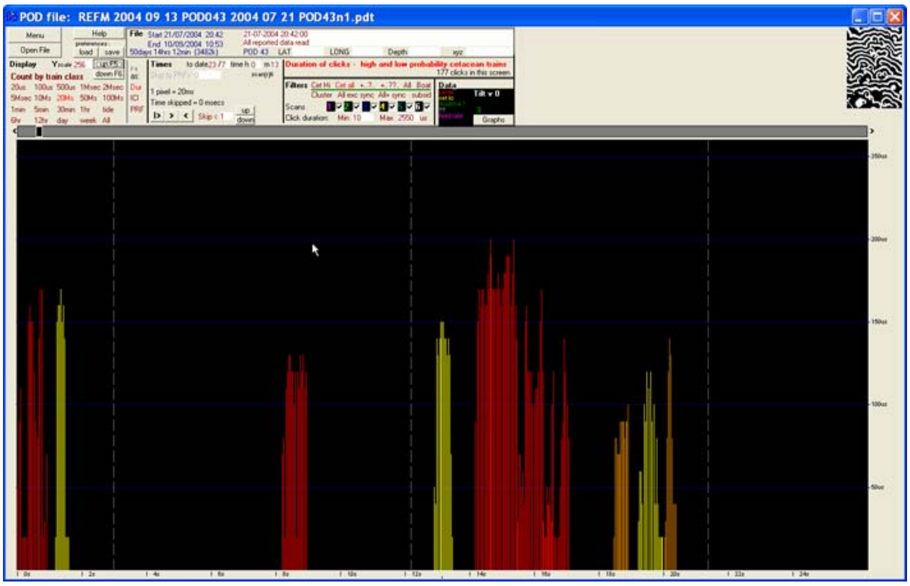


Figure 8. Screen snapshot from the T-POD.exe software. Several series of porpoise clicks can be seen as vertical bars. Time in seconds is shown on the X-axis, and the duration of each click is shown on the Y-axis.

Data from the T-POD can be downloaded in the field with a parallel cable for storage on a PC (Figure 7). Data was downloaded with the T-POD.exe program designed for communication with the T-POD and subsequent analysis of data. Figure 8 shows an example of downloaded data. Harbour porpoise echolocation clicks were extracted from the background noise using a filtering algorithm that filters out non-porpoise clicks such as cavitation noise from boat propellers, echo sounder signals and similar high frequency noise. This filter has several classes of confidence of which the second highest class ("cetaceans all") was used. Data were exported in ASCII format for statistical analysis after filtering

See appendix A for description and results of T-POD calibration.

2.1.2 Mooring of T-PODs

Field experiments have shown that T-PODs deployed near the bottom records a higher level of harbour porpoise echolocation activity than those deployed simultaneously near the surface (Nick Tregenza pers. comm.). The T-PODs in this study has all been moored about 1-2 m above the bottom. The mooring method is shown in Figure 9.

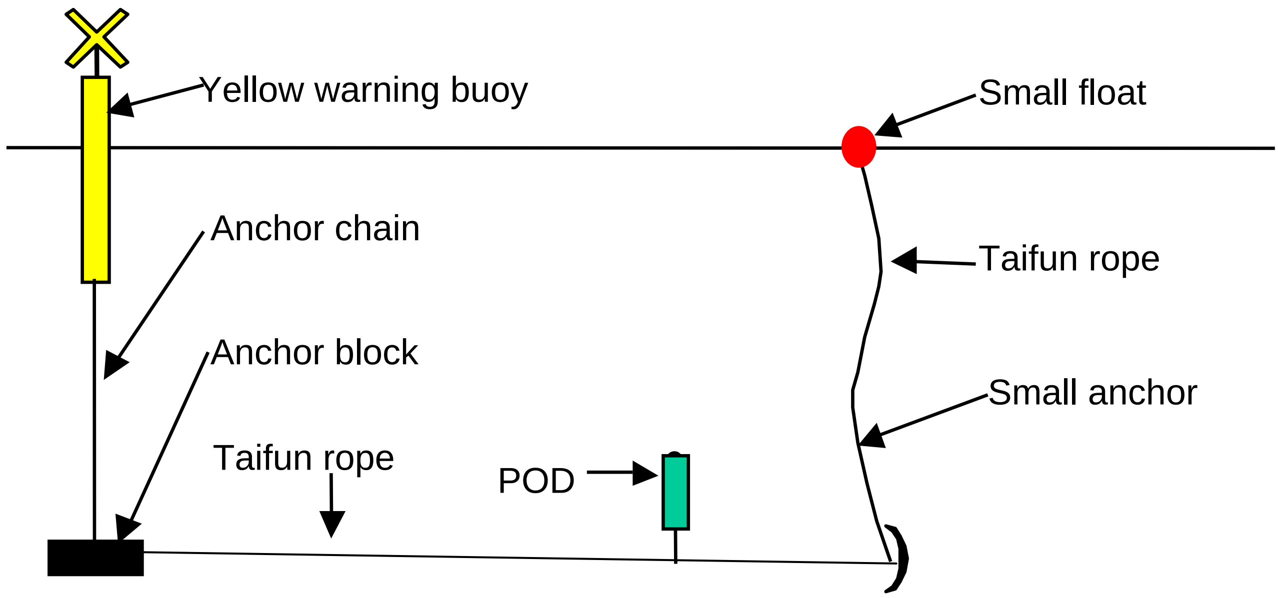


Figure 9. The deployment technique used for mooring T-PODs at Nysted Offshore Wind Farm.

The set-up has been designed so the T-POD, the small anchor and the red float can be lifted to the surface by hand. In case that the float is lost the large anchor block can be lifted with a winch or a crane from the service boat, and the POD and the rest of the gear can be retrieved.

2.1.3 Deployment of T-PODs

The natural inter-annual variations in ecosystems always make it difficult to evaluate the reason for biological changes in an area where e.g. a wind farm is constructed. By looking at the relative change in harbour porpoise activity from baseline to construction and operation periods in both the impact and a reference area the effect can be evaluated.

It is important that the reference locations are selected in an area that is affected by the same natural variations in the environment (e.g. hydrography and food availability) as the impact area. It is not required that conditions are similar, as long as any variation in conditions over time occurs in parallel in the two areas. Since data on all natural factors that may affect harbour porpoises were not available, the reference locations were chosen to resemble the depth, currents, and expected porpoise density of the wind farm area.

The Rødsand area consists of the Nysted Offshore Wind Farm area where three T-PODs were deployed. Three reference locations were placed in a north-south going row approximately 10 kilometres east of the construction site (Figure 1).

2.2 Data analysis

2.2.1 Indicators from T-POD signals

T-POD data were analysed in the same manner as previously reported (Skov *et al.* 2002; , Teilmann *et al.* 2001). Four indicators were extracted from T-POD signals, based on the logged number of clicks per 1-minute interval. This signal, denoted x_t, consists of many observations of zero (periods with no clicks) and relatively few observations with click recordings. The recorded clicks per minute were aggregated into daily observations of porpoise positive minutes (PPM, in previous reports called "click frequency") and clicks per porpoise positive minutes (clicks/PPM, in previous reports called "click intensity") calculated as:

$$PPM = \frac{\text{Number of minutes with clicks}}{\text{Total number of minutes}} = \frac{N\{x_t > 0\}}{N_{total}} \qquad (1)$$

$$\text{Clicks/PPM} = \frac{1}{N\{x_t > 0\}} \sum_{x_t > 0} x_t \text{Click PPM} = \frac{1}{N\{x_t > 0\}} \sum_{x_t > 0} x \qquad (2)$$

Another approach to analysis was to consider recorded clicks as the outcome of a point process, i.e. separate events occurring within the monitored time span. We considered x_t as a sequence of porpoise encounters within the T-POD range of detection separated by silent periods without any clicks recorded. Porpoise clicks were often recorded in short sequences consisting of both minutes with and without clicks. Such short sequences were considered to belong to the same encounter (i.e. same porpoise). We decided to use a silent period of at least 10 minutes to separate two different encounters from each other. This threshold value was determined from graphical investigation of different time series of x_t. Thus, two click recordings separated by a 9-minute silent period would still be part of the same encounter. The conversion resulted in two new indicators for porpoise echolocation activity:

Encounter duration = Number of minutes between two silent periods longer than 10 minutes

Waiting time = Number of minutes in a silent period lasting more than 10 minutes

The definitions imply that waiting time has a natural lower bound of 10 minutes, as well as the possibility of encounters potentially including periods with zero clicks between periods with clicks spaced less than 9 minutes apart. Encounter duration and waiting times were computed from data from each T-POD deployment. Consequently, each deployment resulted in one more observation of encounter duration, since the silent periods at the beginning and end of deployment were truncated (interrupted) observations of waiting times. Encounter duration and waiting time observations were temporally associated with the time of the midpoint observation, e.g. a silent period starting 30 September at 12:14 and ending 1 October at 1:43 was associated with the mean time of 30 September 18:59 and categorised as a September observation.

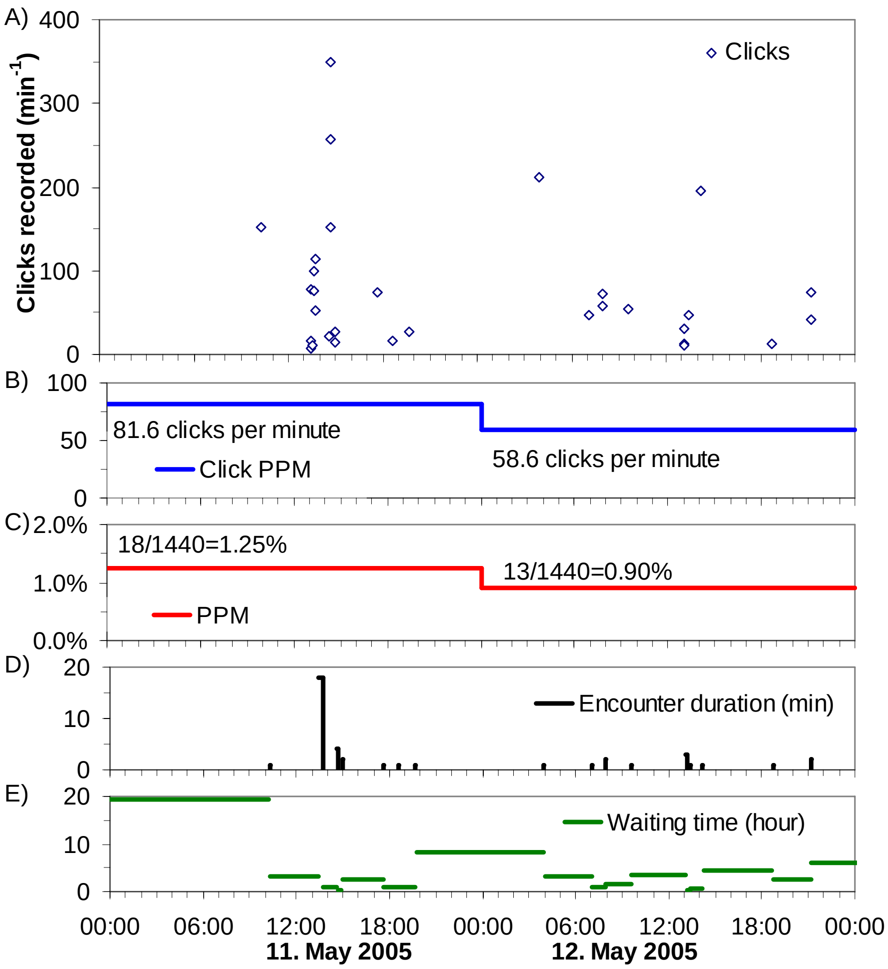


Figure 10. Calculation of the 4 indicators (B-E) from clicks (A) exemplified using two randomly chosen days at station Imp. W inside the wind farm. The values for clicks/PPM (B) and PPM (C) for the two days are listed above the lines. Encounters (D) are shown as vertical lines fat the time of occurrence with a length equal to the duration of the encounter in minutes. Waiting times (E) are shown as vertical lines between two encounters with a level showing the duration in hours.

Of the four indicators, waiting time and PPM values indicate the abundance of animals while encounter duration and clicks/PPM indicate aspects of the present animals' behaviour. Figure 10 shows recordings from the 11th and 12th of May 2005 and gives an example of how the parameters are extracted from the T-POD recordings and used in the analysis. For each day there were 18 and 13 minutes with porpoise clicks out of a total of 1440 minutes, respectively, corresponding to a PPM of 1.25% and 0.90%, respectively. The average number of click recordings during the 18 and 13 minutes were 81.6 and 58.6 per minute. During the two days 14 distinct encounters were identified ranging from 1 minute to 18 minutes in duration. Waiting times between these 14 encounters ranged from 13 minutes to 496 minutes, whereas the waiting time prior to the first encounter on May 11th was close to 20 hours.

2.2.2 Interpretation and statistical modelling

The four indicators vary according to presence and behaviour of porpoises in the vicinity of the T-PODs. The indicators PPM and waiting time between encounters are indicative of porpoise presence. A higher daily PPM and a lower average waiting time between encounters compared to another T-POD recording are indicative of a relative higher abundance of porpoises. Daily mean clicks/PPM and average encounter duration are little affected by the number of animals in the area. Instead they provide information on the acoustic behaviour of porpoises, when these are present. The exact interpretation of these two indicators is difficult, as no behavioural observations concurrent with T-POD recordings are available. A high mean clicks/PPM means that more clicks are recorded, whenever animals are close to the T-POD. This could simply be a reflection of the animals physically being closer to the T-POD, or it could be caused by the animals actually emitting more clicks. The latter would be the case for foraging animals, or animals actively investigating objects close to the T-POD. High average encounter duration is likely to be caused by animals spending more time in the area close to the T-POD, again indicating a higher interest in the area (caused by food or something else).

The four indicators were assumed to be potentially affected by the following factors *Area* (wind farm or reference), *Station(area)* (difference between stations within areas), *Podnr(area station)* (differences among different T-PODs deployed at the same station), *Period* (baseline, construction, first or second year of operation), *Area×Period* (BACI effect, describing different response to impact in wind farm and reference areas in the four periods), and *Month* (variation across the year).

Variations in the indicators, after appropriate transformation (see appendix B), were assumed Normal-distributed with a mean value described by the equation:

$$\mu = area + station(area) + month + period + area \times period \qquad (3)$$

Besides answering general questions on differences between wind farm area and reference areas, seasonal variation, variation among T-PODs etc., the main purpose of the analysis is to address differential changes in abundance and behaviour of porpoises in the wind farm area during construction and operation. Thus, the BACI-test addresses whether a decrease (or increase) in porpoise abundance in the wind farm e.g. during construction is higher than what can be expected based on changes observed concurrently in the reference areas. In addition to the main hypothesis analysed by means of the model above (equation 3), echolocation activity in relation to time of the day and wind speed was also investigated.

Further details on the statistical analysis of T-POD data can be found in appendix B.

3 Results

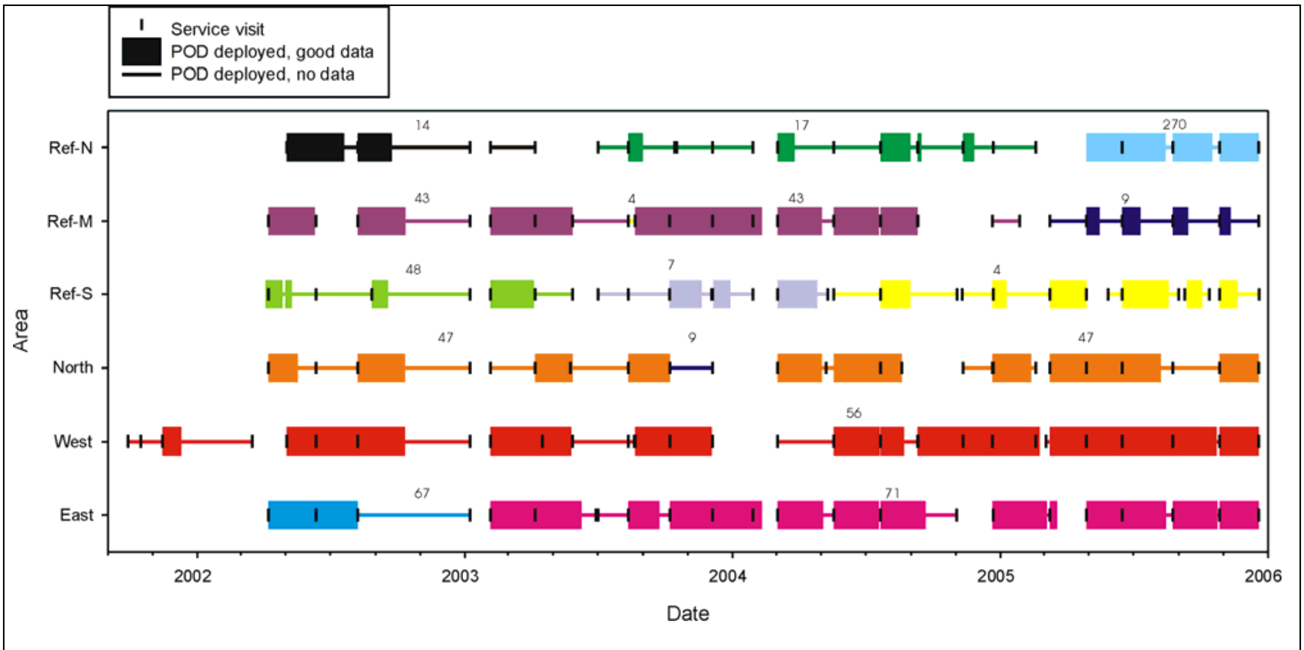


Figure 11. Deployment of T-PODs in the entire monitoring period from 2001 to 2005. Stations North, East and West were in the wind farm and stations Ref-N, Ref-M and Ref-S were in the reference area. Each colour indicates the use of a specific T-POD, whose serial number is indicated above the line. Narrow lines indicate that the T-POD was deployed and thick bars indicate that useable data were collected.

From November 14th 2001 to December 19th 2005, a total of 12 different T-PODs were deployed in the impact and reference area. Due to loss or damage of T-PODs more than one instrument was used at most stations.

Table 2. Summary of deployments and data collection at the six stations used in the monitoring program.

	North	West	East	Ref-N	Ref-M	Ref-S	Total
Deployment (days)	1132	1364	1189	1057	1089	1187	7018
Data (days)	623	944	906	443	665	453	4034
Deployment/total time	84.0%	88.6%	88.2%	78.4%	80.8%	89.7%	85.0%
Data/deployment time	55.0%	69.2%	76.2%	41.9%	61.1%	38.2%	57.5%
Data/total time	46.2%	61.3%	67.2%	32.9%	49.3%	34.2%	48.9%

T-PODs were deployed on average for 1170 days on each station, corresponding to 85% of the total time from onset of baseline in 2001 to end of the monitoring program in December 2005. This resulted in on average 672 days of useful data from each station, corresponding to 57.5% of the deployment time and close to half of the total duration of the program. There is some variation among stations, as seen in Table 2, with most data collected from the stations inside the wind farm. The stations in the reference area were more exposed, due to their proximity to the channel leading into Gedser harbour and suffered more losses of equipment (Figure 11). Only one T-POD was replaced inside the wind farm during the entire monitoring period (T-POD 67 exchanged with T-POD 71 in 2002) adding considerable strength to the conclusions of the subsequent analysis. Although many T-PODs detached from their mooring during the study, most of the T-PODs were subsequently recovered in fishing gear or from the coastline in the surrounding area.

During the study 2572 daily values of clicks/PPM, 4096 daily values of PPM and almost 10000 encounters and waiting times were recorded. These indicators were almost equally distributed between stations (Appendix C).

There were relatively few deployments prior to the construction and therefore fewer observations in the baseline (368 stations x days) compared to the construction period (1249 stations x days) and the 2 years with operation (1119 and 1360 stations x days, respectively). Fortunately, monitoring during the baseline occurred during months with relatively high echolocation activity resulting in 1734 encounters compared to 1995 during construction period, 1902 during the first operation period, and 3948 during the second operation period. Thus, the shorter time of deployment during baseline was partly compensated by relatively high echolocation activity. The total number of observations and time series plots of the 4 indicators for all 6 stations covering the entire period are given in Appendix B.

Despite the very large number of 1-minute recordings (>5.8 million minutes) there were too few 1-minute observations (24,276) containing clicks to consistently estimate the diurnal patterns for each month in both areas separately and for each of the considered periods.

Monthly averages of the four indicators for the reference and impact areas are shown in Figure 12. Average numbers of clicks per porpoise positive minute (clicks/PPM) during baseline were almost identical in the two areas, whereas it was generally lower in the wind farm area during construction and operation periods (Figure 12A).

Daily PPM was highest in the impact area during baseline and decreased to a low level during the construction period and then slowly increased again (Figure 12B). This tendency was also seen to a lesser degree in the reference area. Average encounter durations showed similar trends in the two areas with slightly lower levels during construction and first year of operation (Figure 12C). During baseline the longest median waiting times were measured in the reference area (Figure 12D), but this changed after start of construction concurrent with a dramatic increase in median waiting times (from a scale of hours between encounters to days between encounters). Waiting times generally became shorter in the course of the two years of operation compared to levels in the construction period, but at the end of monitoring in December 2005, waiting times in the impact area were still considerably higher than both baseline levels and levels in the reference area.

3.1 Trends in impact area relative to reference area

Echolocation activity in the impact and reference area during baseline showed similar variation with time, when data from station Ref. N were removed from the analysis (Carstensen et al. in press, Henriksen et al. 2003). Consequently, the BACI analysis was carried out using all three stations in the impact area and the two most southern stations in the reference area. The random effects of the model showed a significant correlation between successive observations ($p<0.0001$ for all indicators) and a non-significant variance contribution from different T-PODs ($p>0.05$ for all indicators). The model was simplified by pooling the T-POD specific variation with the residual variation, i.e. treating all T-PODs as being identical in sensitivity.

The fixed factors of the model were mostly significant for all indicators (*Table 3*). Spatial variation between the two areas was significant for all indicators, i.e. there were systematic differences between impact and reference areas, whereas significant differences among stations within areas were only observed for encounter duration and waiting time. Variation among periods (baseline, construction, operation1 and operation2) was significant for all indicators except daily clicks/PPM, and all indicators except encounter duration showed significant seasonal variation. Finally, the

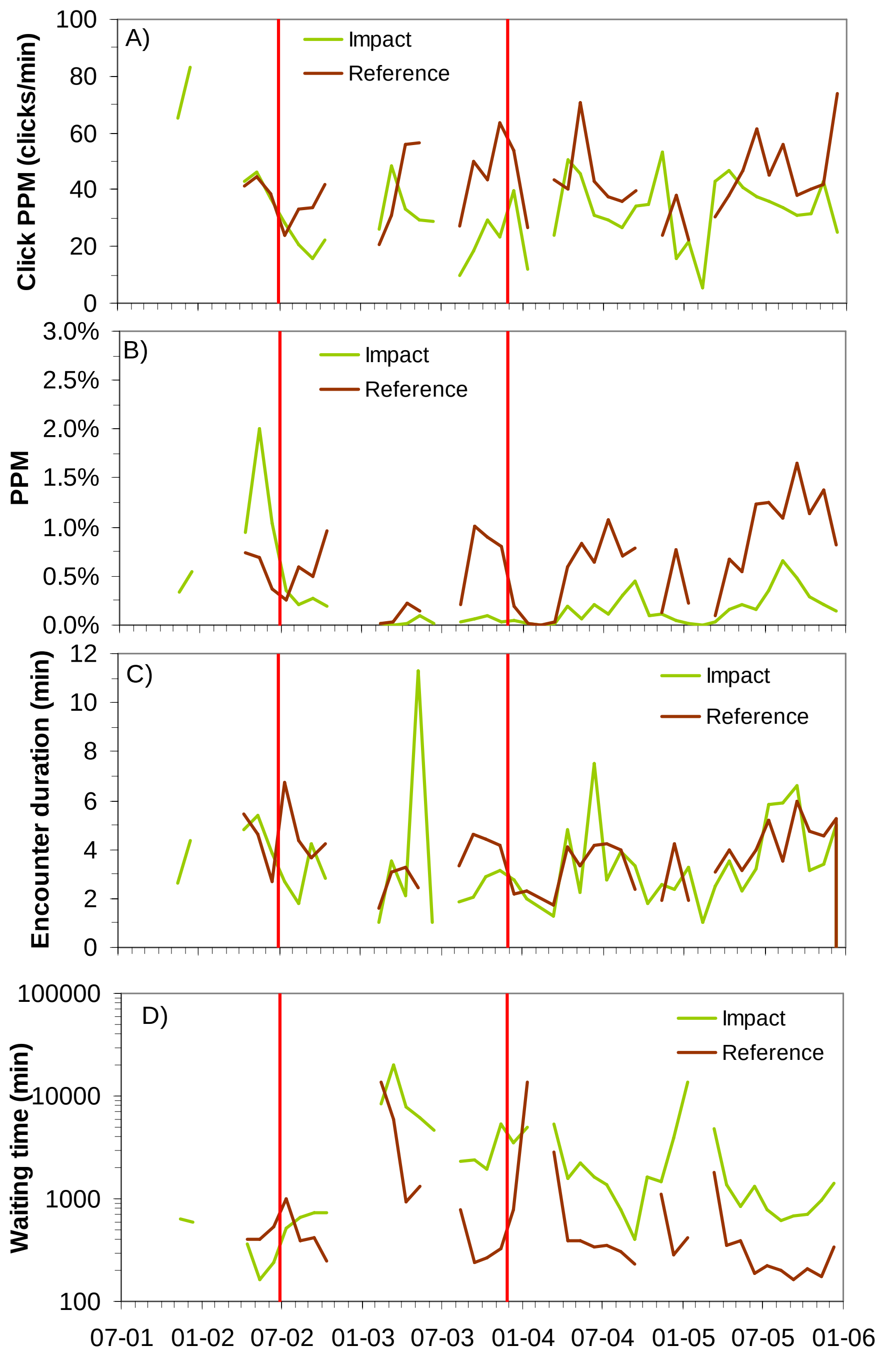


Figure 12. Monthly averages of the 4 indicators for the control and reference area. From top to bottom is shown average number of clicks per porpoise positive minute; average porpoise positive minutes (in % per day); average encounter duration and median waiting time. Note the log-scale on the y-axis for waiting time. Red vertical lines indicate beginning and end of construction period.

Trends between periods were significantly different for the two areas, signifying that changes in indicators among periods were different for the two areas (the BACI effect)

Table 3. *Test of fixed factors in the model for the four indicators of porpoise echolocation activity. Data from station Ref. N was excluded from the analysis. Significant factors (p<0.05) are highlighted in bold.*

Indicator variable	Test for fixed factors in model				
	Area	*Station(area)*	*Period*	*Month*	*Area×period*
Daily clicks/PPM	**<0.0001**	0.0529	0.1325	**0.0002**	**0.0056**
Daily PPM	**<0.0001**	0.3776	**<0.0001**	**<0.0001**	**<0.0001**
Encounter duration	**0.0172**	**0.0167**	**<0.0001**	0.2937	**0.0069**
Waiting time	**<0.0001**	**0.0157**	**<0.0001**	**<0.0001**	**<0.0001**

3.2 BACI-analysis

3.2.1 Daily clicks/PPM

The daily clicks/PPM was at the same level (~40 clicks per minute) for both the reference and the impact area during the baseline period, but in the construction period the daily clicks/PPM in the impact area was reduced by almost 50%, whereas a small increase was observed in the reference area (Figure 13). From the construction period to the first year of operation the daily clicks/PPM increased by 27% in the impact area, whereas no change was observed in the reference area. A further increase of 11% in clicks/PPM was seen in the impact area from first to second year of operation, compared to a decrease of 13% in the reference area.

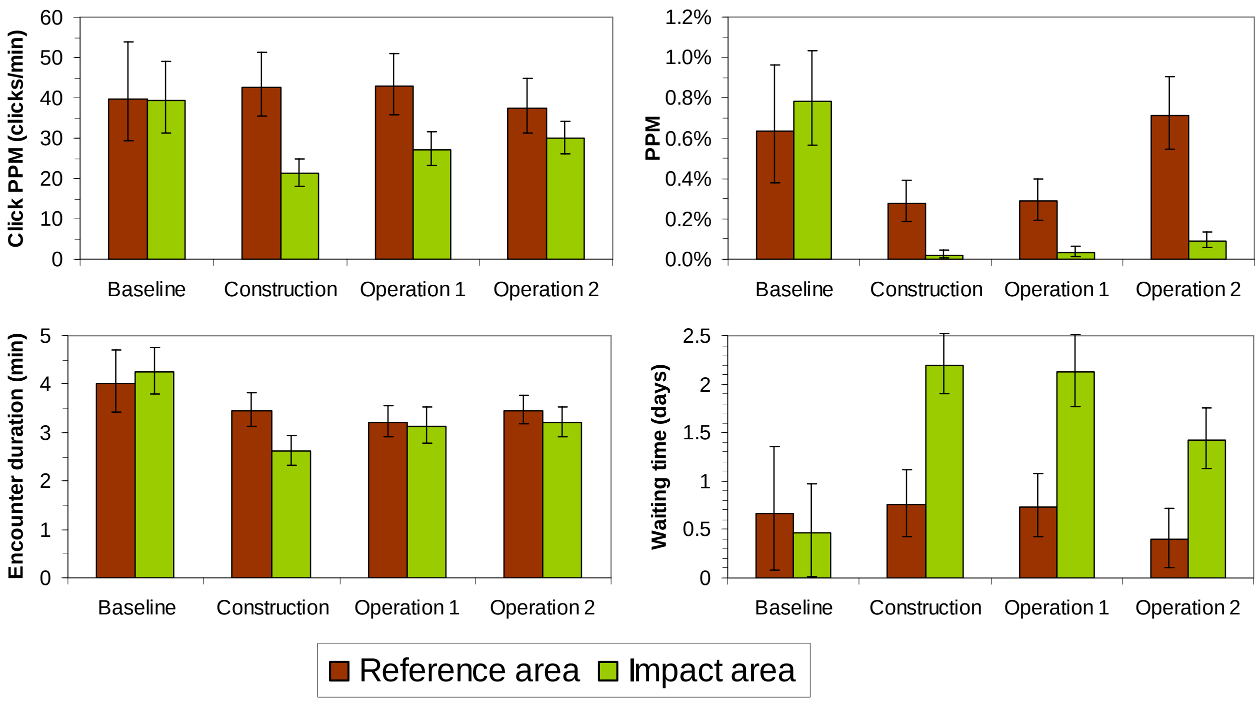


Figure 13. Mean values for combinations of area and period back-transformed to the original scale for combinations of the two areas (reference and impact) and the four periods (baseline, construction, first and second year of operation). Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in *station* and *month* have been accounted for by calculating marginal means. Data from station Ref. N were not included.

Looking at the BACI-effect (Table 4) it is seen that the contrasts between baseline and construction; baseline and operation 1; and construction and operation 2 were all significant, whereas there was no significant BACI effect from baseline to second year of operation. This signifies that construction had a significant negative effect on clicks/PPM in the wind farm, and that this effect persisted in first year of operation but that during the second year of operation clicks/PPM is back to the baseline level.

3.2.2 Porpoise positive minutes (PPM)

The daily PPM was slightly lower in the impact area during the baseline period (mean of 11.3 minutes with porpoise clicks per day), but it declined to a mean of 0.25 minutes with porpoise positive minutes per day (Figure 13), i.e. a decrease of approximately a factor of 45. The daily PPM also decreased for the two stations in the reference area, although this decrease was considerably less (factor of 2.3). From the construction period to the first year of operation the daily PPM increased slightly in both areas, whereas it more than doubled from first to second year of operation. As a result the daily PPM in the reference area had the same level as during baseline in the reference area, but the PPM in the impact area was still lower during second year of operation than during baseline by a factor of 8. Consequently, the BACI effect was significant for all comparisons between baseline on one hand and construction, first and second year of operation on the other hand, indicating a significantly higher impact of construction and operation on PPM inside the wind farm that in the reference area (Table 4). However, there was also a significant negative BACI effect when moving from first to second year of operation, despite the fact that daily PPM levels actually increased in the impact area. This occurs since PPM increased proportionally more in the reference area than in the impact area (Table 4). Thus, PPM has increased steadily in the impact area since the construction period, but it has increased more rapidly towards baseline levels in the reference area.

Table 4. Test of contrasts from the BACI analysis for combinations of periods (baseline, construction and two years of operation). Data from station Ref.N was not included in the analysis. Significant contrasts ($p<0.05$) are highlighted in bold.

BACI contrast		Significance of contrasts for indicators			
Period 1	Period 2	Clicks/PPM	PPM	Encounter duration	Waiting time
Baseline	Construction	**0.0022**	**0.0002**	**0.0013**	**<0.0001**
Baseline	Operation year 1	**0.0404**	**0.0006**	0.4058	**<0.0001**
Baseline	Operation year 2	0.3214	**<0.0001**	0.1649	**<0.0001**
Construction	Operation year 1	0.1346	0.6116	**0.0085**	0.9949
Construction	Operation year 2	**0.0048**	0.1012	**0.0163**	0.3189
Operation year 1	Operation year 2	0.1351	**0.0309**	0.5779	0.3152

3.2.3 Encounter duration

Encounter duration was similar in the control and impact area during the baseline and operation periods, whereas it was about 25% shorter in the impact area during construction (Figure 13). The overall encounter duration decreased from 4.1 minutes during baseline to 3.0 minutes during construction, then increasing to 3.2 and 3.3 minutes during first and second year of operation, respectively. In the first year of operation the encounter duration continued to decrease in the reference area, whereas it increased in the impact area to the same level as the control area. From first to second year of operation the encounter duration increased in both areas by 0.1-0.2 minutes. The BACI contrast showed a significant relatively larger decrease in the impact area from baseline to construction, followed by a significant relatively larger increase from construction to operation (both years), suggesting that the relatively largest effect on encounter duration occurred during construction (Table 4). However, it should be stressed that the mean encounter duration during the second year of operation is still 20% lower than during baseline.

3.2.4 Waiting time between encounters

For waiting times the reference and impact area were at similar levels (11-16 hours) during the baseline, and in both areas waiting times increased during the construction period. The increase was much larger in the impact area, however (Figure 13). During construction, the median waiting time was 18 hours in the reference area and 53 hours in the impact area, i.e. almost three times larger. In the first year of operation the median waiting times decreased only marginally to 18 and 52 hours for the reference and impact area, respectively, but during the second year of operation shorter waiting times than during baseline were observed in the reference area (~10 hours), whereas waiting times were still about 3 times longer in the impact area compared to baseline. Waiting times increased significantly more in the impact area relative to the reference area from baseline to all other periods, whereas the proportional decrease in waiting times from construction to operation was similar for the reference and impact area (Table 4), noting that waiting times in the impact area was still significantly longer.

3.3 Seasonal variation

All indicators except encounter duration displayed a significant seasonal variation (*Table 3*). The estimated seasonal variation was used to analyse variations between the different periods such that observations were compared across the same months. Mean clicks/PPM varied from 20 to 45 clicks per minute across the year with the lowest values in January-March. Mean PPM was also low in January-March (ca. 0.05-0.07%) peaking in September with a mean of 0.57%. Encounter duration was low from January through March (means between 2.3 and 3.2 minutes), whereas it was around 3.5-4.0 minutes for the rest of the year although means were not significantly different among months. Median waiting times were >1 day in December-March with the highest median value observed in February (11.0 days). From June to November the median waiting time was less than half a day with the shortest mean waiting time observed for September (7.4 hours). In general, the highest echolocation activities were observed in late spring, summer and autumn, whereas the lowest echolocation activity was found in winter and early spring.

3.4 Echolocation activity in relation to wind

The potential covariation of the indicators to wind was investigated from time series of wind speed, obtained from the wind gauges located in the wind farm area and in Gedser (Danish Meteorological Institute). Since the wind changes over time, even on very short time scales, and porpoise click recordings are not instantaneous, it is not possible to compare wind and click activity directly. Instead one must compare averages over some suitable interval. Daily averages of the wind speed were thus combined with daily means of PPM and clicks/PPM, whereas encounter duration was combined with the average wind during the specific hour of the encounter. Waiting times were not combined with the wind data, since it was difficult to characterise wind speed with a single number for long silent periods. Moreover, averaging wind speed over long periods has an adverse effect resulting in average values for wind only, i.e. long waiting times (several days) will be associated with average wind conditions. Including wind as an additional variable (including *area×period×wind* as a covariate) it was investigated if the echolocation activity was related to wind speed and if the relationship differed between areas and periods. The wind speed was partitioned into 7 different categories (0-2 m/s, 2-4 m/s, 4-6 m/s, 6-8 m/s, 8-10 m/s, 10-12 m/s, and >12 m/s).

There was no effect of wind on clicks/PPM (p=0.8242 for *area×period×wind*), whereas PPM had significant relationships to wind that differed for areas and periods (p=0.0034). However, the relationship to wind was only significant for PPM in the impact area during construction and second year of operation (Figure 15). Encounter duration also showed significant relationship to wind (p=0.0280), albeit not as significant as for PPM, but the significance was entirely driven by observations from the first year of operation in the reference area (Table 5). This could be an artefact from relatively few, but long encounters observed at wind speed 0-2 m/s in the reference area during this specific period. Probabilities of the other factors (*Table 3*) only changed marginally by including wind into the model.

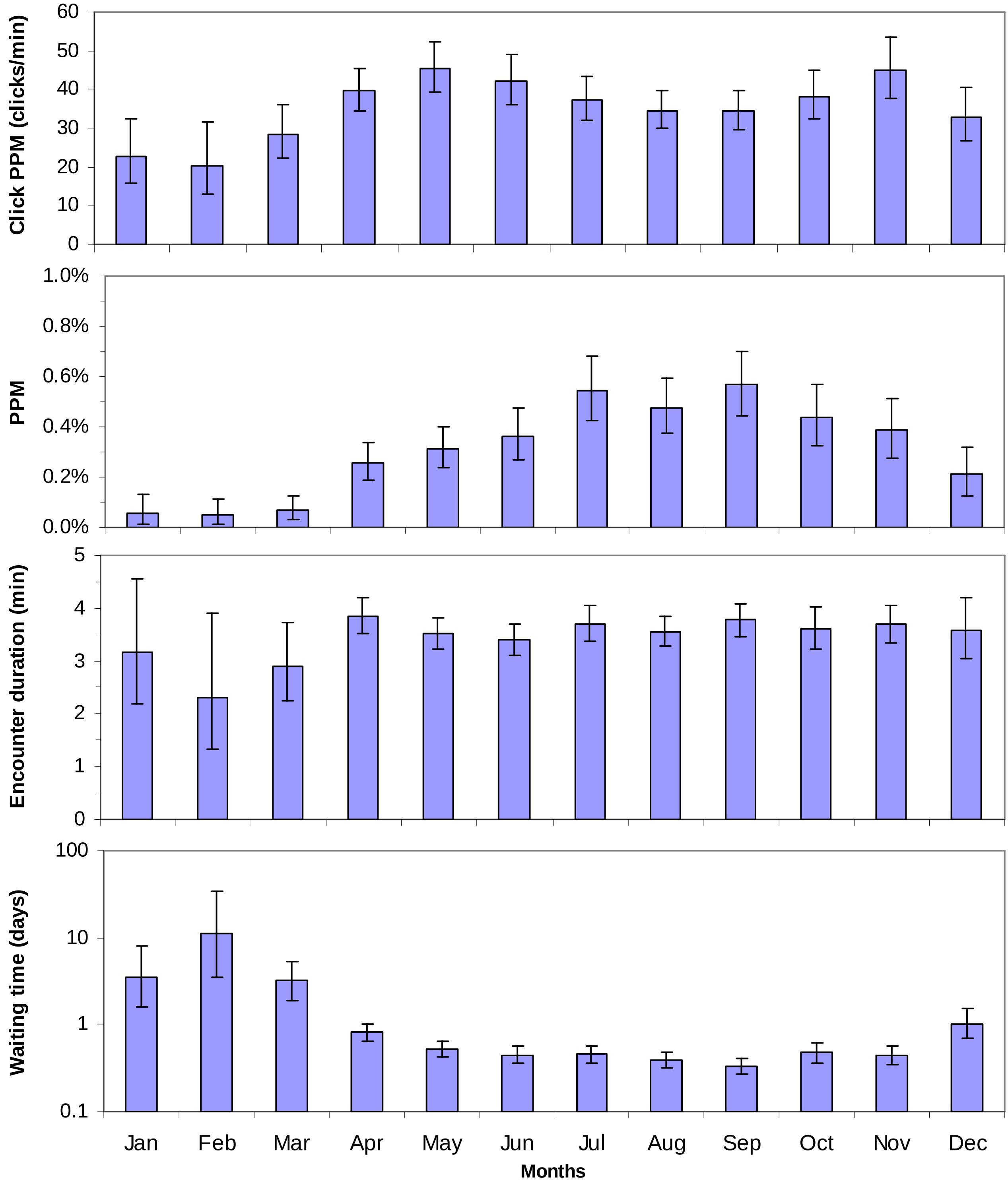


Figure 14. Seasonal means for the four indicators after back-transformation. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in *area*, *station*, *period* and *area*×*period* have been accounted for by calculating marginal means. Data from station Ref. N were not included.

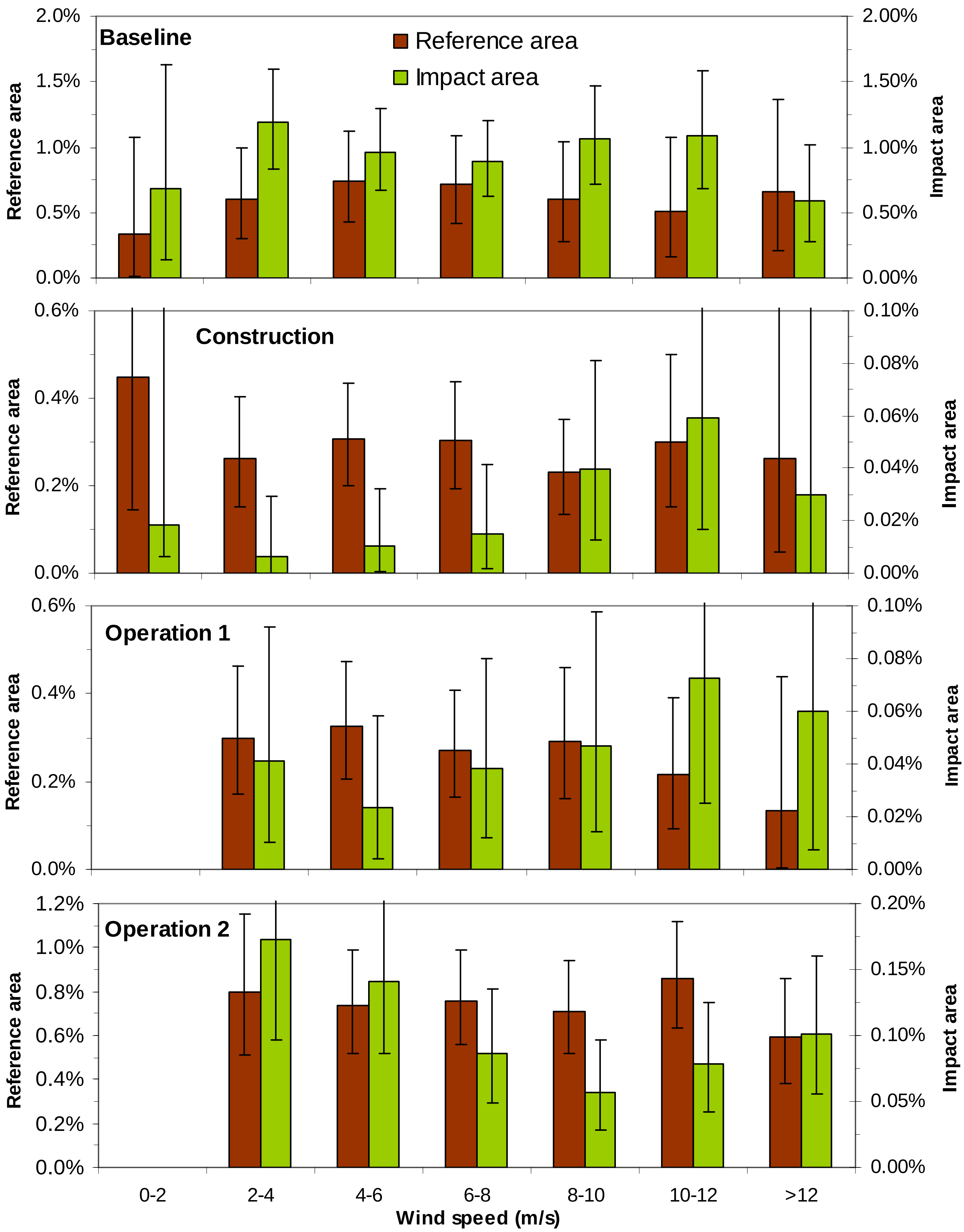


Figure 15. Distribution of daily PPM for different wind speeds in the reference and impact areas during the four periods. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in area, station, period, month and area ×period have been accounted for by calculating marginal means. Data from station Ref. N were not included. Note the different scales used for the reference (left y-axis) and impact areas (right y-axis).

Table 5. Test for wind-specific relationship of porpoise positive minutes (PPM) and encounter duration for the four periods and two areas. Data from station Ref. N was not included in the analysis. Significant relationships (*p*<0.05) are highlighted in bold.

Period	Reference area		Impact area	
	PPM	Encounter duration	PPM	Encounter duration
Baseline	0.7911	0.2480	0.0877	0.4366
Construction	0.6183	0.2588	**0.0133**	0.2315
Operation year 1	0.5569	**0.0195**	0.2637	0.3091
Operation year 2	0.4206	0.1767	**0.0003**	0.2586

It should be noted that none of the three indicators (waiting time not analysed) showed any relationship to wind during baseline. PPM was generally higher in the impact area during baseline but no distinctive pattern to wind was observed for any of the two areas (Figure 15). During construction a marked response to wind was found in the impact area with low PPM for winds below 8 m/s, when 3-4 times less clicks were recorded per day compared to winds above 8 m/s. In the impact area the highest PPM was observed for wind speed between 10 and 12 m/s during construction as well as for the first year of operation, although the relationship between PPM and wind was not significant for the first year of operation. The most significant pattern to wind (Table 5)) was found during the second year of operation in the impact area, where PPM gradually declined by a factor of 3 with increasing winds up to 8-10 m/s, and then increased for wind speed above 10 m/s. In the reference area the PPM patterns had no systematic variation to wind at all.
The changes observed in the impact area from construction to the two years of operations showed that the porpoise response to wind speed in the first year of operation was similar to the construction period with the largest increase in PPM for wind speed between 2 and 4 m/s (Figure 16). The overall increase in PPM from first to second year of operation was mainly due to increasing PPM for wind speeds below 8 m/s and above 12 m/s, whereas increases in PPM for wind speed between 8 and 12 m/s were moderate.

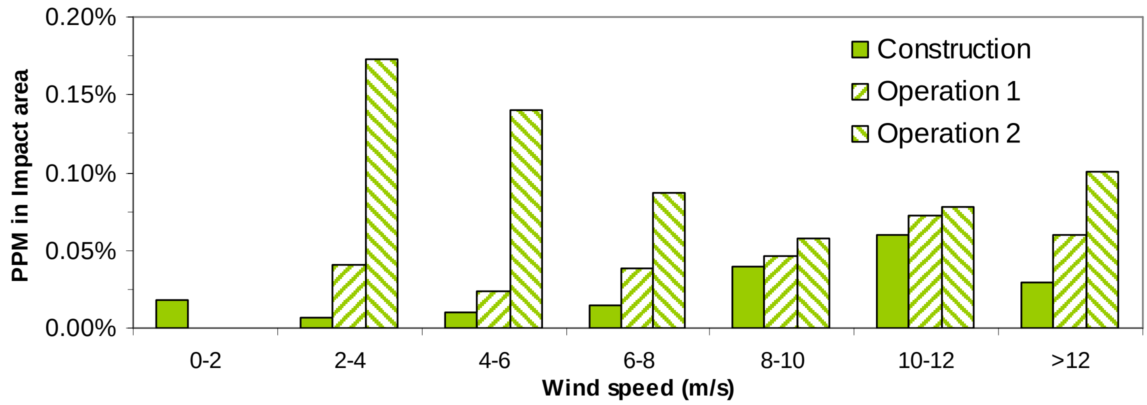


Figure 16. Porpoise positive minutes (PPM) in the impact area in response to wind speed during construction and operation... Baseline levels were 5-10 times higher and were thus excluded for clarity. Reiteration of the same data as in Figure 15, where baseline data can also be found.

3.5 Encounter distribution

Harbour porpoise encounters probably occur when environmental conditions are favourable. In the following section the distribution of encounters during the day and for various wind speeds is investigated for the different areas and periods.

During baseline, encounters were equally distributed between hours of the day, but during the construction a significant diurnal pattern with relatively fewer encounters during daytime was observed for both the reference and impact area (Figure 17). This pattern was more or less replicated and significant during the first year of operation in both areas, and also during the second year of operation in the impact area only. The diurnal pattern was most significant during the construction period in the impact area where the 3-4 times more encounters were observed during night hours than during daytime. During the second year of operation a uniform distribution of encounters was found in the reference area, similar to the patterns observed during baseline in both reference and impact area. The T-PODs were logging continuously for long periods and the different hours of the day were therefore monitored equally well.

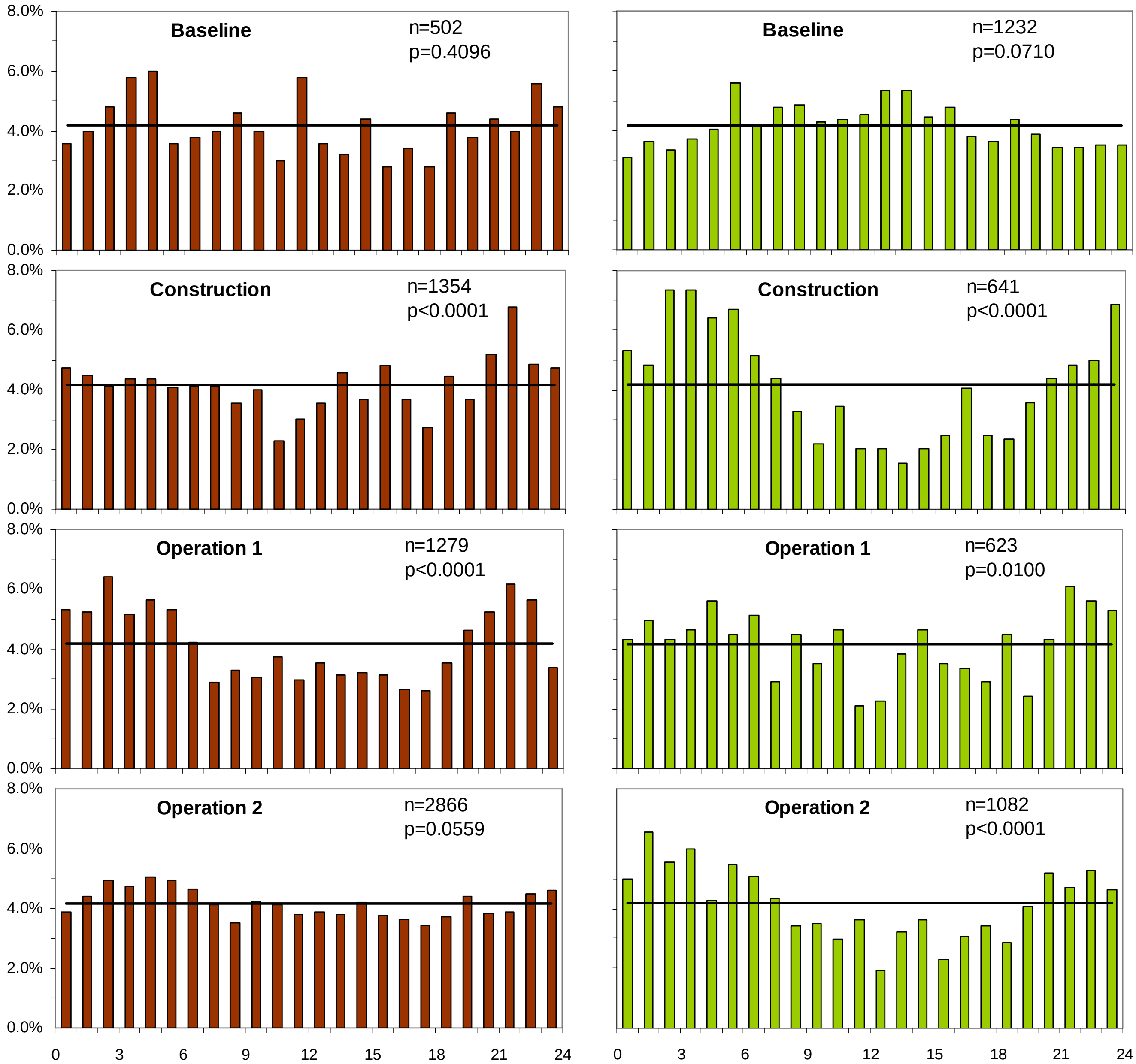


Figure 17. Distribution of encounters over the day in the reference area (left panel) and impact area (right panel) for the four periods. For each graph n=number of encounters and p=probability of equal distribution over all hours of the day. Vertical lines show the uniform distribution of encounters for comparison.

The wind distribution when encounters were logged by the T-PODs did not deviate significantly from the overall wind distribution in neither the reference nor the impact area during baseline (Figure 18). In the reference area encounters also occurred independently of the wind distribution during the operation period, whereas there were relatively fewer encounters during the construction period for wind speed between 6 m/s and 10 m/s and relatively more encounters at wind speed 10-12 m/s. The most significant changes in wind distribution for encounters were observed in the impact area during construction and the two years of operation (p<0.0005 for these three periods). During construction relatively fewer encounters were observed for wind speeds between 2 m/s and 6 m/s and relatively more encounters were observed for wind speeds above 8 m/s. During the first year of operation there were relatively more encounters for wind speeds of 0-2 m/s, relatively fewer encounters for wind speeds of 2-10 m/s, and relatively more encounter for wind speeds >10 m/s. During the second year of operation there were relatively more encounters for winds below 4 m/s, and relatively fewer encounters for wind speed between 8 m/s and 10 m/s. For wind speed above 10 m/s the two distributions were similar (Figure 18).

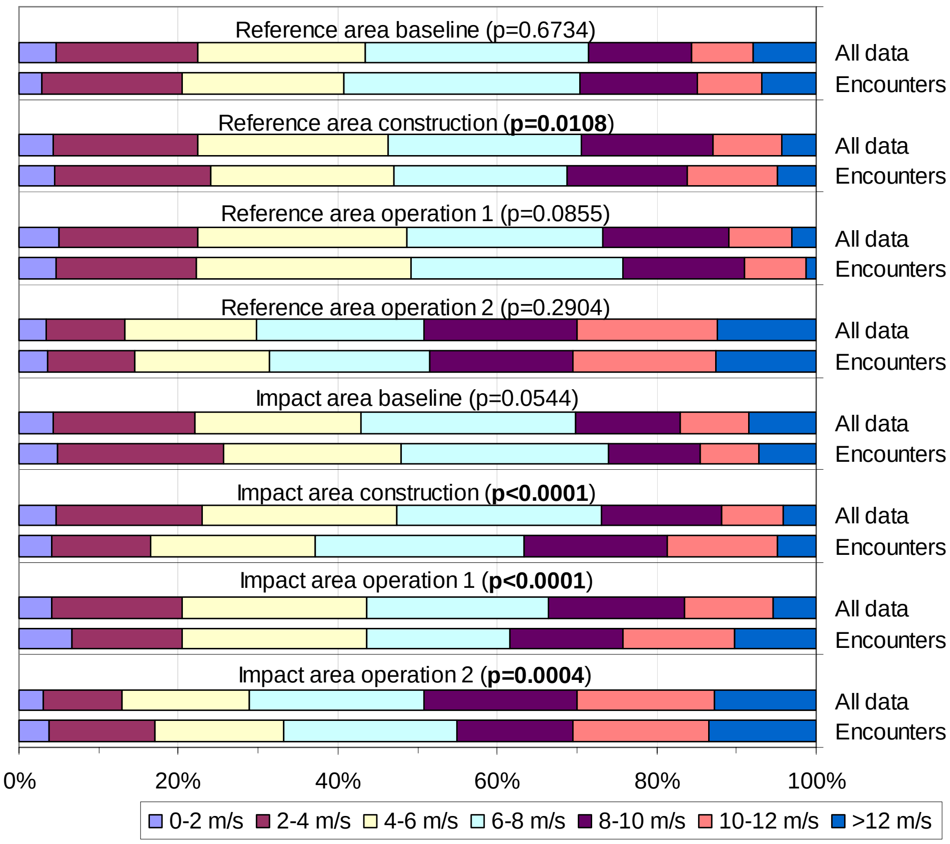


Figure 18. Distribution of wind speed during the whole period (All data) and wind speed during encounters for each area and period. Only wind speed data and T-PODs recordings during May-November were used, i.e. excluding winter and early spring months with few encounters. P-values for testing if the wind distribution during encounters was equal to the overall wind distribution for the specific period and area is listed above each set of bars.

3.6 Effect of pile driving activities

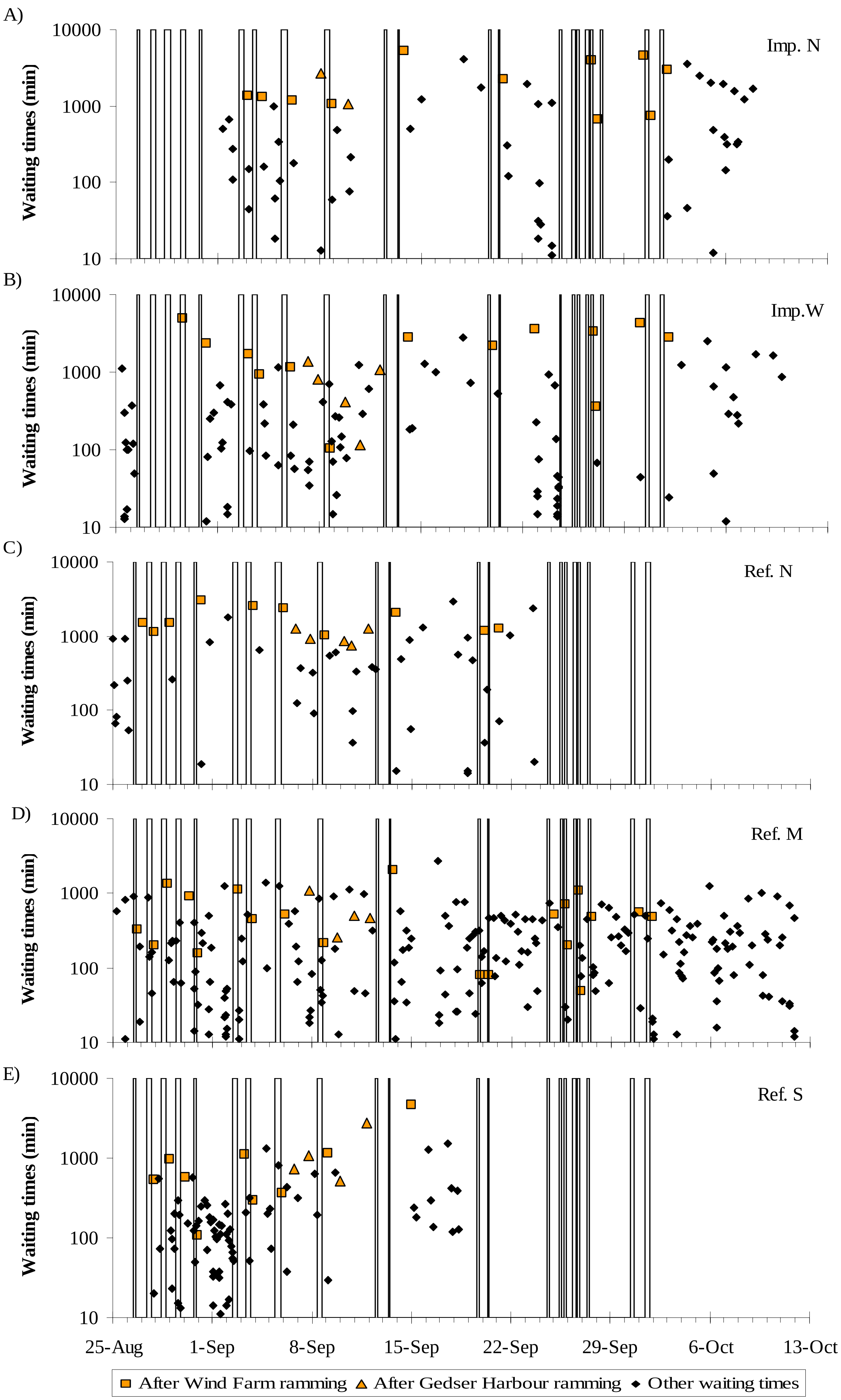
Between August 25th and October 12th 2002, the period with pile driving activity, five out of the six T-PODs were logging harbour porpoise echolocation activity, and all these five T-PODs were operational during the short pile driving activity at Gedser Harbour from September 5th to 12th 2002. The waiting time after pile driving activities was approximately the same for pile drivings taking place at the A8 foundation within the wind farm and pile drivings at Gedser Harbour (Figure 19). There was a significant variation in waiting times at four of the five stations (exception was station Imp. N that recorded only two waiting times following pile driving at Gedser Harbour) depending on whether pile driving activity had taken place prior to the observation (Table). For all of the remaining four stations there was a significant increase in waiting times when pile driving took place, irrespective of the pile driving location (the eight contrasts for pile driving versus no pile driving were all significant, Table 6). For three of the four stations there was no difference in waiting time when comparing pile drivings in the wind farm and pile drivings at Gedser Harbour. Only at station Ref. N were the waiting times longer when pile driving took place in the wind farm compared to pile driving at Gedser Harbour, although a similar result, on the verge of being significant, was observed for station Imp. W as well.

Waiting times after pile driving activity in the wind farm area increased significantly by 19.4, 42.3, 16.2, 4.6 and 14.1 hours for stations Imp. N, Imp. W, Ref.N, Ref.M, and Ref.S, respectively. Waiting times after pile driving activity at Gedser Harbour increased significantly by 7.1, 3.6, 3.8, and 17.4 hours for stations Imp. W, Ref.N, Ref.M, and Ref.S, respectively. The increases in mean waiting time ranged from 27% at station Ref.N to 491% at station Imp. W. The smallest change during pile driving at Gedser Harbour actually occurred at the T-POD deployed closest to the harbour.

Table 6. Variation in waiting times analysed by F-test for the three pile driving categories (No pile driving, pile driving at Gedser Harbour, pile driving in the wind farm) at the five stations. Contrasts (t-tests) between the three categories are listed below the overall test. No data were available from station Imp. E in this particular period. Significant p-values are highlighted in bold.

Test	Station				
	Imp. N	Imp. W	Ref. N	Ref. M	Ref. S
Piling category	0.1297	**<0.0001**	**<0.0001**	**0.0001**	**0.0002**
Contrasts					
- Gedser Harbour ~ No piling	0.0718	**0.0212**	**<0.0001**	**0.0103**	**0.0030**
- Wind Farm ~ No piling	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0005**
- Wind Farm ~ Gedser Harbour	0.9837	0.0860	**0.0076**	0.4667	0.3769

Figure 19 (opposite). Waiting times (symbols) at the five stations in the period of pile drivings. Note the logarithmic scale. Pile driving/vibration activities at foundation A8 are indicated by vertical grey lines.


A)
Imp. N
B)
Imp.W
C)
Ref. N
D)
Ref. M
E)
Ref. S
Waiting times (min)
10000
1000
100
10
25-Aug
1-Sep
8-Sep
15-Sep
22-Sep
29-Sep
6-Oct
13-Oct
After Wind Farm ramming
After Gedser Harbour ramming
Other waiting times

4 Discussion

Nearly five years have passed since the monitoring program on harbour porpoises at Nysted started and large amounts of data has been collected, distributed over a baseline period, the construction of the wind farm and the first two years of operation. Despite the fact that baseline data covers only a short period immediately prior to construction commenced, the number of porpoise recordings is large. Data is available for almost 50% of the total time between start of monitoring in November 2001 and end in December 2005, which is sufficient for strong statistical conclusions.

4.1 Natural patterns in distribution and abundance

Before effects of the wind farm can be addressed, it is important to identify and deal with natural factors, which can influence the abundance and behaviour of porpoises and hence influence the results. Given that the fundamental assumption of correlation between natural fluctuations in the reference area and the impact area, the BACI-design is robust to variation unrelated to the impact from the wind farm. This means that natural fluctuations in porpoise abundance are handled by the BACI analysis, which addresses only differential changes between reference and impact areas, and hence changes which can be directly attributed to the impact from the wind farm. However, when it comes to more detailed analyses of what mechanisms underlie significant changes caused by the impact, it becomes essential to take natural fluctuations into consideration.

4.1.1 Annual variation

A robust annual variation in most of the statistical indicators has been evident from the first analyses of the data and conclusions have been strengthened as more data has entered the analysis. Thus, there seems to be a natural variation in abundance of porpoises in the study area, with few porpoises in winter (January through March), followed by an increase during early April and high presence throughout the rest of the year, possibly with a peak in late summer. This variation is site specific, as other patterns in annual variation have been observed at other locations, such as Horns Reef (presence year round, with peak in summer (Tougaard et al. 2005) and in the Netherlands (high peak in winter and almost complete absence in summer (Brasseur et al. 2004). The biological reason behind the observed decrease in abundance in winter is unknown. Controlling factors are likely to be lower prey availability and perhaps the risk of sea ice in winter. It is noteworthy however, that the disappearance of porpoises in winter is consistent with the historical account of a large migration of porpoises out of the inner Baltic and up through the Danish Belts in late autumn and their return again in spring.

4.1.2 Inter-annual variation

Variation from year to year cannot be properly addresses because the baseline period only covered one year and because both impact and reference area were affected by construction and operation of the wind farm.

4.1.3 Diurnal variation

No diurnal pattern was found in the distribution of encounters in the baseline period, in contrast to the situation during construction and operation (see below). Although the baseline period is comparatively short, this conclusion is nevertheless strengthened by the absence of diurnal patterns in encounters in the reference area in the second year of operation, where there are other indications that activity was returned to undisturbed levels (see below).

4.2 Effects of wind farm

4.2.1 General effect of construction and operation

The BACI-test on the T-POD data showed a pronounced effect of construction on abundance of porpoises in the area, not only measurable in the wind farm, but also at the reference site. All four statistical indicators analysed were affected. The two indicators porpoise positive minutes (PPM) and waiting time between encounters, which are likely to be directly linked to the abundance of porpoises were affected more strongly than the indicators clicks/PPM and encounter duration. The latter two indicators are probably more linked to the behaviour of animals when present, rather than abundance of animals. The overall results can be summarised schematically, showing development in indicators from baseline, over construction to the second year of operation.

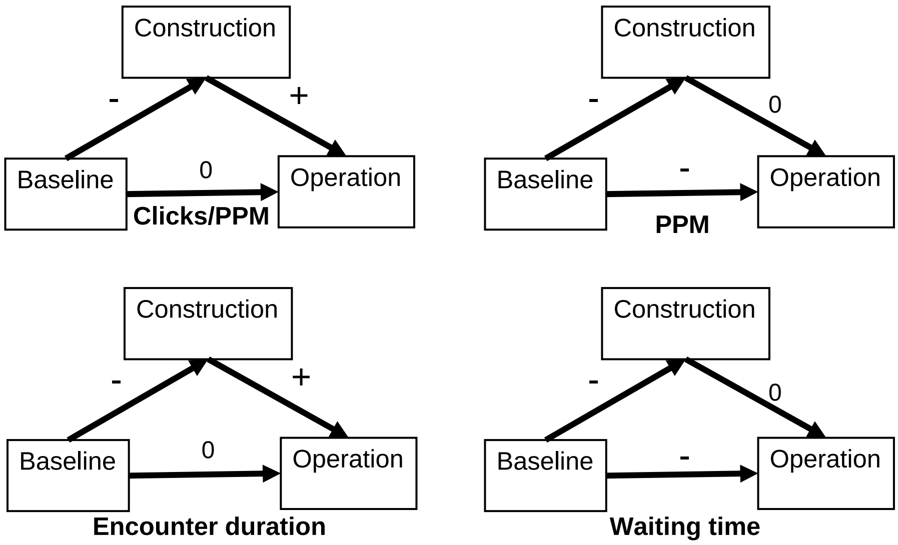


Figure 20. Schematic overview of development in statistical indicators in the wind farm from baseline to construction period and second year of operation. Minus indicates a change in the indicator in a direction signifying a negative impact on porpoises, plus indicates a positive change and 0 indicates no significant change.

PPM and waiting time between encounters are both indicators of how often porpoises are near the T-POD and hence visit the area. Both indicators showed large changes from baseline to construction and both in a direction indicating that there were considerably fewer porpoises in the wind farm area during construction (lower daily PPM and higher median waiting time). Clicks/PPM and encounter duration are both indicative of the behaviour of the porpoises when present. These indicators changed significantly during construction, but returned to baseline levels in the second year of operation. This means that not only were there very few porpoises in the area during construction, those that were there also had am acoustic behaviour which was different from the natural behaviour. Following end of construction the number of porpoises in the area has returned towards baseline levels, although only in the reference area has baseline levels been reached. Their behaviour however, as judged from clicks/PPM and encounter duration is back to normal, as defined by the baseline, in both wind farm and reference area.

4.2.2 Factors affecting porpoises during construction

The results clearly show that porpoises left the general area during construction, but there are few indications as to why they did so and whether particular activities during construction played a larger role than others. Some factors may be direct, such as noise from construction activities, ships and boats, whereas others may be indirect through effects on the prey of porpoises. The latter includes noise too, but also sediment spill and disturbance to the seabed.

In order to pinpoint the important factors it is necessary to monitor these closely and if possible quantify them continuously through e.g. continuous measurements of underwater noise. This constitutes a major task and assessment of mechanisms behind disturbances was not part of the objectives of the monitoring program when it was designed prior to construction. Hence little information is available to base conclusions on. In fact, the only factor which can conclusively be linked to a disturbance is the pile driving operations at foundation A8. These pilings occurred as discrete events in time and the behaviour of porpoises before and after individual pilings could be assessed. The data clearly demonstrated that porpoises left the area during piling and returned again after a period of up to several days. The reaction is probably less dramatic than it seems from the figures, as the absolute number of porpoises in the region during construction was very low and the number of animals directly affected by the pilings thus likewise was low. An unintentional opportunity to conduct a control experiment occurred with the pile drivings at Gedser harbour, which occurred concurrently with the pilings in the wind farm. These pilings turned out to have an effect on the porpoises similar to the pilings at foundation A8. Thus, while it is evident that the pilings at A8 had a significant and considerable effect on porpoises, this impact was no greater than what can be expected to occur in connection with sheet pile drivings in harbours and other marine areas throughout the inner Danish waters.

Another important conclusion from the pile driving data is that although animals disappeared following onset of a pile driving operation and only returned after a considerable time, once they were back, their behaviour seemed unaltered when compared to the level of the construction period as a whole. This has the important implication that it was probably not the pile drivings, which caused the general decrease in porpoise abundance during construction, even though they most certainly represent the strongest single sources of disturbance. Other factors, one way or the other linked to the general activities in the area, must have played an important role in deterring the porpoises. These factors could be general elevation of underwater noise levels and disturbance to the seabed with associated sediment resuspension. The fact that a clear diurnal pattern in porpoise encounters appears during construction with fewer porpoises during the day than during the night is suggestive of construction activities and ship traffic as significant contributing factors. The reason for fewer encounters in the day during construction of the wind farm is probably due to the construction activities taking place during daytime. The effect in the reference area may be due to both an increase in shipping activities passing close by the reference area and that construction noise in the wind farm may be heard by the porpoises at the reference area.

4.2.3 Factors affecting porpoises in the operating wind farm

As was the case with the construction period, the fundamental design of the monitoring program was not aimed at determining specific mechanisms behind observed effects on abundance. Thus, although a strong decrease in abundance has been observed in the wind farm area, as well as the reference area during the first two years of operation, it is not possible to present firm answers to the question of why fewer than expected porpoises has returned to the area. Some indications are present, however.

The presence of the wind farm clearly affects the porpoises, directly or indirectly through e.g. effects on fish prey. This is seen by the changes that have occurred in the diurnal activity of the animals and the correlations with wind speed. Further support comes from results of a completely independent study with T-PODs in Nysted Offshore Wind Farm, conducted in 2005, the second year of operation (Blew *et al.* 2006). In that particular study five T-PODs were placed on a line perpendicular to the outer edge of the wind farm and thus along a line going from about 1 km outside the wind farm to well inside it. Along this line a gradient in observations of porpoises was ob-

served, with fewer animals inside the wind farm than outside, supporting a local effect of the turbines.
The fact that no diurnal pattern in encounters was found during the baseline period suggests that the change to a clear significant diurnal pattern during construction and operation periods is related to the wind farm. This is furthermore supported by the more pronounced diurnal pattern seen in the wind farm area compared to the reference area and the return to baseline pattern during the second year of operation in the reference area. The cause of this pattern, with more animals at night compared to day is unclear. One may speculate whether porpoises learned to avoid the wind farm area in daylight hours during the construction and have continued with this habit even two years after end of construction. Such a memory effect has not been documented in any cetacean and it would furthermore require that the porpoises present in the area today to a large degree are the same as were there three years ago. Porpoises move over large distances during the year (Teilmann *et al.* 2004) and although they may well return to the Nysted area the following year, the large exchange of animals means that the behaviour of a very large number of animals should still be affected two years after end of construction in order for this memory effect to show up in diurnal patterns. It thus seems more likely that the effect is due to some persistent feature of the wind farm, i.e. that the response is due to an immediate reaction of the animals and not their memory of an impact in the past.
Explanations for the appearance of a diurnal pattern in the operating wind farm could include 1) visual impact from the rotating wings, 2) noise and other disturbances from service vessels and 3) a change in diurnal activity of prey species of fish inside the wind farm. Our data do not allow for a more thorough assessment of these effects (and possibly others) and they are thus left as ideas for further investigations.

4.2.4 Variation with wind

There was no effect of wind speed on any parameter during baseline. This indicates that porpoise behaviour is not affected by wind itself. The correlations observed during construction and operation of the wind farm must thus be due to changes in other environmental parameters related to wind speed. No effects of wind were found inside the wind farm area on the indicators clicks/PPM and encounter duration. As these indicators are more linked to porpoise behaviour than abundance as such, this relation suggests that the effect of wind was a reduction in the number of animals entering the wind farm area rather than causing a change in acoustic behaviour of the animals inside the wind farm.

The significant effect of wind speed on PPM in the wind farm during construction revealed that 3-4 times fewer clicks were recorded for wind speeds below 8 m/s, which is readily explainable by the fact that construction activities mostly took place in good weather and was paused when the wind speed exceeded about 10m/s (Charlotte Boesen pers. comm.).

During first year of operation, the same pattern was seen as during construction, with fewer porpoises during low wind speed, although this effect was not statistically significant. A similar, but statistically significant picture was found during the second year of operation in the impact area, where PPM gradually declined by a factor of 3 with increasing winds up to 8-10 m/s. In the reference area the PPM patterns showed no systematic variation to wind at all. The number of encounters was significantly and differentially affected by wind speed, both during construction and operation. During construction more encounters than average were observed for wind speeds above 8 m/s, readily explainable as with PPM by the shut down of construction activities at high wind speeds. During both years of operation there were more encounters than average for low wind speeds (<4 m/s), and more encounter for strong wind speeds (>10 m/s).

Thus during operation there are indications that more porpoises are recorded at low wind speeds and possibly also high wind speeds, compared to medium wind speeds (4-10 m/s). The first observation, but not the last is supported by the results of Blew *et al.* (2006), which also recorded more porpoises at low wind speeds compared to moderate and high wind speeds. These relations could be related to the increasing noise from the wind farm with increasing wind speed, indicating that porpoises at least to some degree avoid the turbines when they are running and thus produce noise. This interpretation is not without problems and needs further investigations to be verified or replaced by a better explanation. The most important problem is to understand how the noise, which is weak by any standard, only has energy at very low frequencies and hence barely audible to the porpoises at a distance of 100 m from the turbine can cause a measurable effect. As mentioned in the introduction (section 1.4.3) some open questions remain with respect to the turbine noise and the porpoises' perception of it. Thus either a) the noise from turbines at Nysted is different and/or more intense than what has been measured on other turbines so far, or b) the hearing of porpoises at very low frequencies is better than previously assumed and hence their susceptibility to noise higher than expected. The change from low to high gears at moderate wind speeds and the associated changes in noise spectrum as well as the sound of the change itself also call for quantification. Despite the difficulties in understanding its nature, the relation between abundance and wind speed, within the wind farm persist however, and calls for an explanation which one way or the other involves the wind turbines.

5 Conclusion

The purpose of this study was to investigate whether the construction and operation of Nysted Offshore Wind Farm affected the abundance of harbour porpoises in this area.

Based on acoustic recordings the abundance and behaviour of porpoises was affected significantly during construction and operation of Nysted Offshore Wind Farm in relation to the baseline period and a reference area. Compared to the baseline period, the effect was not only measurable in the wind farm, but also at the reference area 10 km from the wind farm.

The frequency of porpoise positive minutes (PPM) and waiting time between encounters, are both directly linked to the abundance of porpoises and were affected more strongly than the two indicators clicks/PPM and encounter duration, which are related to the behaviour of animals when present. The strong negative impact on waiting time and number of porpoise positive minutes from baseline to the construction period, decreased gradually during the two years of operation. This indicates that porpoises gradually seem to adapt to the presence and noise from the wind farm and use the area more frequently. For the two behavioural indicators there was a significant decrease from baseline to construction and first year of operation in the wind farm area, this effect disappeared in the second year of operation. This indicates that the porpoises entering the wind farm area either habituated to the presence of the wind farm and thus returned to baseline behaviour, or that the porpoises started to hunt for prey in the same way as previously.

We have found that the construction and operation of Nysted Offshore Wind Farm had an impact on the abundance and behaviour of porpoises in the area lasting at least until the second year of operation. The reason for this effect is likely due to disturbance from the construction and operation noise either directly on the porpoises or indirectly by affecting their prey.

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Appendix A: T-POD calibration

T-PODs were calibrated in a laboratory test tank where the absolute sensitivity was measured. The set-up is shown in Figure 21. The small tank is a highly reverberant environment, but usable for threshold measurements, as the duration of the calibration signals are short. There is thus no time overlap and hence interference between the directly transmitted signal and echoes from tank sides and the water surface. Echoes are recorded by the T-POD however, but as the directly transmitted signal has the highest intensity threshold measurements will relate only to this signal. Echoes will always be below threshold of the T-POD and hence undetectable when the intensity of the directly transmitted signal is at threshold.

The signal used for calibration was a porpoise signal recorded about 1 m in front of a captive porpoise and digitally sampled at 12 bit, 480 samples/second. This signal was transferred to an arbitrary waveform generator (Agilent 33250) that was used as signal source. The signal from the generator was fed through a computer controlled attenuator (see below), amplified by a custom build amplifier and projected from a Brüel & Kjær 8104 hydrophone placed 25 cm from the T-POD and at the same depth as the hydrophone of the T-POD. A Reson TC4034 measuring hydrophone placed at the position of the T-PODs hydrophone (T-POD was removed) measured the sound level prior to each calibration.

Signals were presented to the T-POD at intensities ranging from well above to well below threshold. Signal levels were adjusted by the digitally controlled attenuator, which stepped down in steps of 1 dB. Duration of each step was 9 seconds and adjusted to coincide with the six channels of the T-POD. T-POD files were inspected and the signal level where approx. 50% of the presented clicks were determined. This level is referred to as the absolute sensitivity of the T-POD. The thresholds were in all cases very sharp, with 1-3 dB between the lowest level with 100% detection and highest level with 0% detection and threshold determination thus unambiguous. Settings of the T-POD filters during calibration were identical to the settings used for deployment.

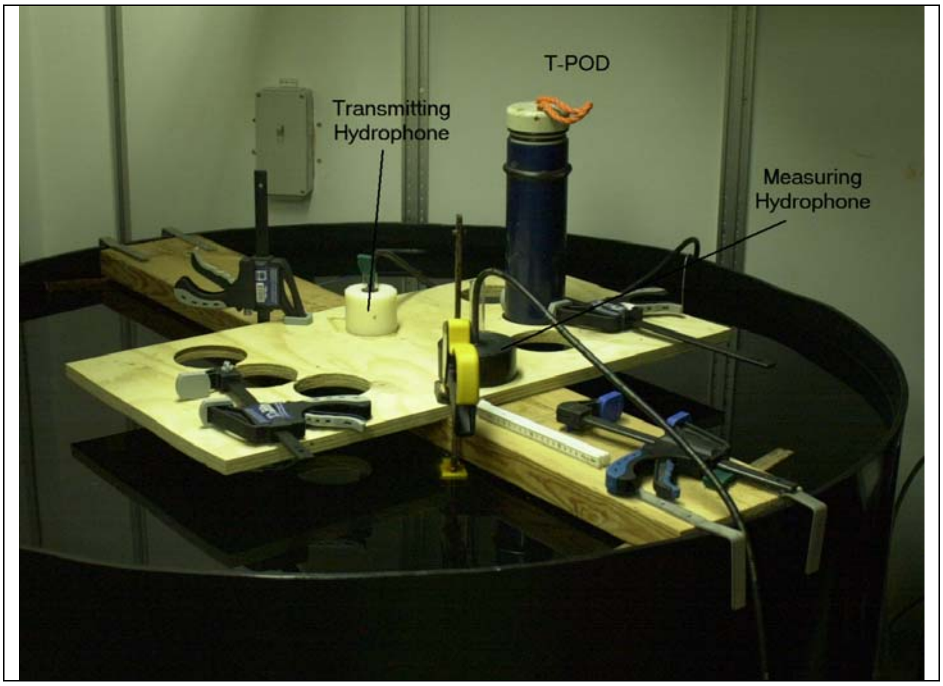


Figure 21. T-POD calibration test tank. One T-POD (out of six possible) is mounted for calibration. Transmitting hydrophone is placed in the centre of the tank. Water depth is approx. 90 cm.

The horizontal directionality of T-PODs was measured by sequentially measuring the T-POD sensitivity at four different angles of incidence, separated with 90 degrees.

T-POD sensitivity and directionality

The directional variation in sensitivity of the T-POD hydrophone in the horizontal plane is specified by a horizontal directivity index, DI_H equation **1**. This index is derived from Urick 1983 and Au 1993 and reduced from the usual three dimensional index to only the horizontal plane, relevant for the T-POD hydrophone. The three-dimensional directivity index expresses the difference between the intensity received by the hydrophone in an isotropic[1] sound field and what would be received by a hydrophone perfectly omnidirectional in the horizontal plane with sensitivity equal to what is measured at the most sensitive angle of incidence. The horizontal directivity index developed here cannot be interpreted in a way as simple as the three-dimensional counterpart without some rather restrictive assumptions. It is nevertheless a convenient single measure of departure from omnidirectionality.

$$DI_H = -10\log\int_0^{2\pi}\left(\frac{p(\phi)}{p_{\min}}\right)^2 d\phi \approx -10\log\left(\frac{1}{n}\sum_n\left(\frac{p}{p_{\min}}\right)^2\right) \qquad (1)$$

p(ϕ) is the horizontal receiving sensitivity at angle of incidence *ϕ*. This is reduced to *n* measurements spaced evenly in the horizontal plane (*n* = 4 for the current measurements).

A maximal detection distance *r* for porpoises can be calculated if the sensitivity (DT, or detection threshold) of the T-POD is known. This distance is determined from the source level (SL) of the porpoise echolocation clicks and the angle from porpoise to T-POD, through the transmission loss, TL equation **2**

$$DT = SL - 20\log\left(\frac{p(\varphi)}{p_0}\right) - TL, \quad TL = 20\log r + \alpha r \qquad (2)$$

p(φ) is the transmission beam pattern of the porpoise signal and α is the sound absorption coefficient of sea water. In order to calculate the maximal possible range at which a porpoise can be detected, we consider only the situation where the animal is facing directly towards the T-POD (*φ* = 0), which reduces equation **2** to:

$$DT = SL - TL = SL - 20\log r - \alpha r \qquad (3)$$

DT is the sensitivity from the calibration and SL is assumed to be 170 dB re. 1 μPa (rms) Teilmann *et al.* 2002, which leaves *r* as the only unknown. Unfortunately, the equation can only be solved numerically. The relation between T-POD sensitivity and maximal detection distance is illustrated in Figure 22.

As the T-POD is not equally sensitive in all directions, the maximal detection distance for several angles of incidence is calculated and the RMS average, r_e is calculated as

$$r_e = \sqrt{\frac{\int_0^{2\pi} r(\phi)d\phi}{4\pi}} \approx \sqrt{\frac{\sum_n r^2}{n}} \qquad (4)$$

where *r(ϕ)* is the maximal detection distance at angle of incidence *ϕ*.

The distance r_e expresses the radius of a circle with the same area as the actual area around the T-POD inside which a porpoise can be detected (see Figure 23). In other words, the area actually sur-

[1] An isotropic sound field is a uniform sound field without directional properties, i.e. the sound intensity is the same from all directions of space.

veyed by the T-POD is equal to the area surveyed by a perfect omnidirectional T-POD (DI = 0) with maximal detection distance r_e.

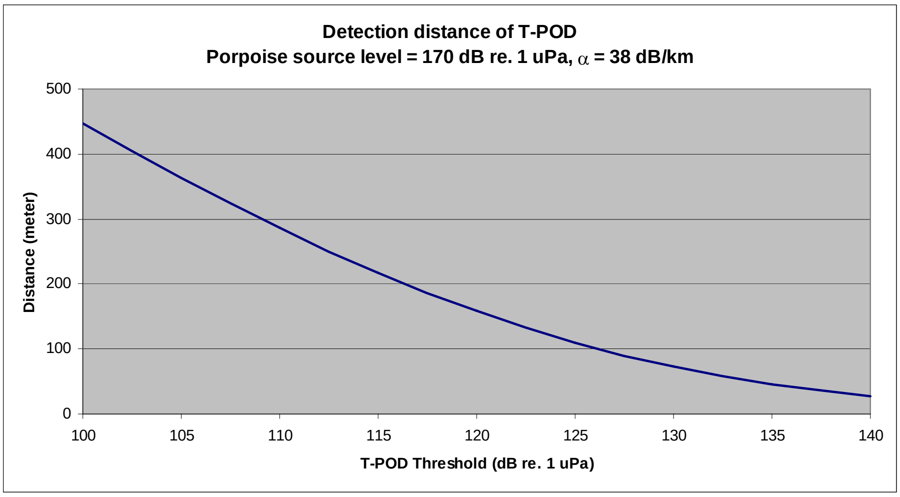


Figure 22: Relation between T-POD sensitivity (expressed as lowest sound pressure needed to detect a porpoise signal) and theoretical maximum distance at which a porpoise can be detected by the T-POD.

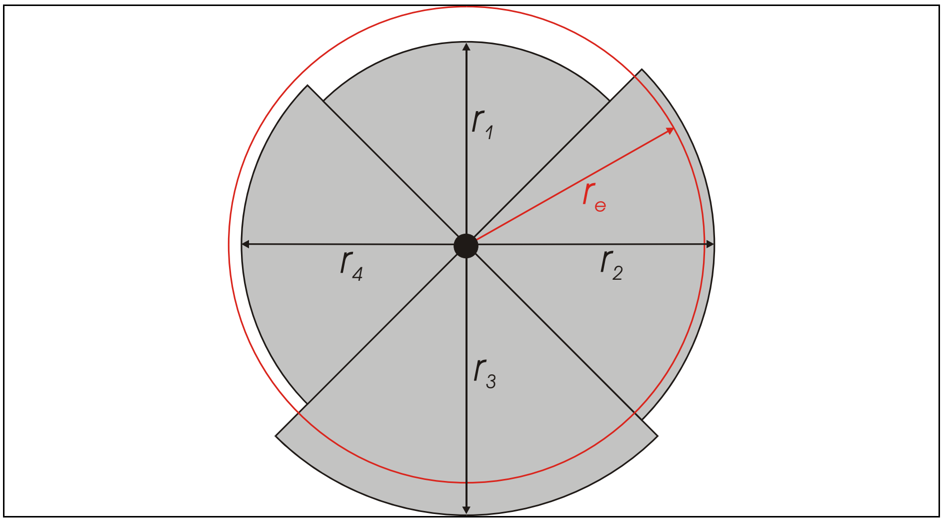


Figure 23. Average detection distance (r_e), calculated from four measurements of detection distances at 0, 90, 180 and 270 degrees angle of incidence. Area of red circle equals sum of the four grey sections.

T-POD Calibration result

The calibration results are given in Table 7. Sensitivity is given as a mean value over all four angles of incidence measured, as described in Figure 23. The directivity index (DI) describes how directional each T-POD is, compared to a hydrophone perfectly omnidirectional in the horizontal plane (DI = 0). The larger the DI the more directional the hydrophone is.

The average maximum detection distance describes the maximum distance from the T-PODs where a harbour porpoise pointing its echolocation beam directly towards the T-POD theoretically can be detected, averaged across the four angles of incidence where measurements were made.

Table 7. Calibration data for T-PODs.

T-POD number	4	9	43	47	56	71	270
Sensitivity (dB SPL RMS)	124.2	117.0	122.0	116.7	120.1	128.7	120.5
Directivity index, DI (dB)	1.6	0.8	0.6	1.6	0.8	1.1	
RMS maximum detection distance (meters)	117	192	138	196	157	82	162

Average maximum detection distances for T-PODs used in this study were 82-196 meters. The exact origin of the variation between the T-PODs is unknown, as they are identical in design. Likely sources are differences in hydrophone sensitivity (inherent differences between crystals and differences due to soldering and plastic housing) and differences in amplifier and self noise of the electronics.

The design of the study at Nysted Offshore Wind Farm and the statistical model used in the data analysis was selected for its insensitivity to differences in POD sensitivity. The calibration has been used to verify the functionality and performance of the individual T-POD.

Appendix B: Statistical analysis of T-POD data

Models for indicators

The indicators were analysed according to a modified BACI-design (Green 1979) that included station-specific and seasonal variation as well. Variation in all four indicators reflecting different features of the same porpoise echolocation activity were assumed to be potentially affected by the following factors:

- *Area* (2 levels) describes the spatial variation between control and impact area.
- *Station (area)* (6 levels) describing the station-specific variation nested within the two areas.
- *Podnr(area station)* (12 levels) describes the T-POD specific variation for the three stations where the equipment was replaced
- *Period* (4 levels) describing the stepwise changes in the activity level during the baseline, the construction and two post construction period (first and second year of operation).
- *Area× Period* (8 levels) describing differences in the 4 periods between the control and impact area.
- *Month* (12 levels) describes the seasonal variation by means of monthly values.

All factors, except *podnr(area station)*, in the model were modelled as fixed effects, assuming their variations to be systematic. The deployment of different T-PODs introduced an additional source of variation that was not considered systematic and therefore modelled as a random factor. Thus, variations in the indicators, after appropriate transformation, were assumed Normal-distributed with a mean value described by the equation:

$$\mu = area + station(area) + month + period + area \times period \qquad (1)$$

The factor *area× period*, also referred to as the overall BACI effect, described a step-wise change in the impact area different from that in the reference area. Marginal means for the different factors of the model were calculated and back-transformed to mean values on the original scale. BACI effects for comparing the relative change for the two areas between two periods (e.g. baseline and construction, or baseline and second year of operation) were calculated explicitly as contrasts, each having 1 numerator degree of freedom, of the marginal means in the model, and their significance tested. For log-transformed indicators such contrasts can be interpreted by calculating

$$\exp(\text{BACI contrast}) = \frac{E[\text{Impact, construction}]}{E[\text{Impact, baseline}]} \cdot \frac{E[\text{Reference, baseline}]}{E[\text{Reference, construction}]} \qquad (2)$$

i.e. the exponential of the contrast describes the relative change from the baseline to the construction period in the impact area relative to the reference area. Similar calculations were carried out for the BACI contrasts for any two selected periods.

The potential effect of wind speed on echolocation activity was investigated by including an additional factor (*area× period × wind)* for describing variations in the indicator means in (5-5).Wind speed was included as a categorical factor using 7 intervals of 2 m/s (i.e. 0-2 m/s, 2-4 m/s, 4-6 m/s, 6-8 m/s, 8-10 m/s, 10-12 m/s and >12 m/s). Including wind speed as a categorical factor allowed for analysing a wide range of different responses to wind as opposed to formulating a parametric relationship. For each combination of area and period differences in the indicators for different wind speeds were investigated by calculating contrasts between wind categories (contrasts with 6 degrees of freedom to test differences between the 7 categories).

The temporal variation in the indicators was assumed to follow an overall fixed seasonal pattern described by monthly means, but fluctuations in the harbour porpoise density in the region on a shorter time scale may potentially give rise to serial correlations in the observations. For example, if a short waiting time is observed the next waiting time is likely to be short as well. Similar arguments can be proposed for the other indicators. In order to account for any autocorrelation in the residuals we formulated a covariance structure for the random variation by means of an ARMA(1,1)-process Chatfield 1984 subject to observations within separate deployments, i.e. complete independence was assumed across gaps in the time series. Thus, this model included an extension to the general linear theory (e.g. McCullagh and Nelder 1989) by mixing fixed and random effects.

Transformations, distributions and back-transformations were selected separately for the different indicators by investigating the statistical properties of data (Table 8). The data comprised an unbalanced design, i.e. uneven number for the different combinations of factors in the model, and arithmetic means by averaging over groups within a given factor may therefore not reflect the "typical" response of that factor because they do not take other effects into account. Typical responses of the different factors were calculated by marginal means Searle *et al.* 1980 where the variation in other factors was taken into account.

Waiting times has a natural lower bound of 10 minutes imposed by the encounter definition, and we therefore subtracted 10 minutes from these observations before taking the logarithm in order to derive a more typical lognormal distribution. Applying the log-transformation had the implication that additive factors as described in equation 2 were multiplicative on the original scale. This meant that e.g. the seasonal variation was described by monthly scaling means rather than additive means. Variations in the four indicators were investigated within the framework of generalised linear models , McCullagh and Nelder 1989, and the significance of the different factors in equation 1 was tested using F-test (type III SS) for the normal distribution (SAS Institute 2003). The normal distribution was chosen for encounter duration as opposed to the Gamma distribution used in (Tougaard *et al.* 2003) in order to employ a covariance structure describing temporal correlation in the observations.

Table 8. List of transformation, distributions and back-transformation employed on the four indicators for harbour porpoise echolocation activity.

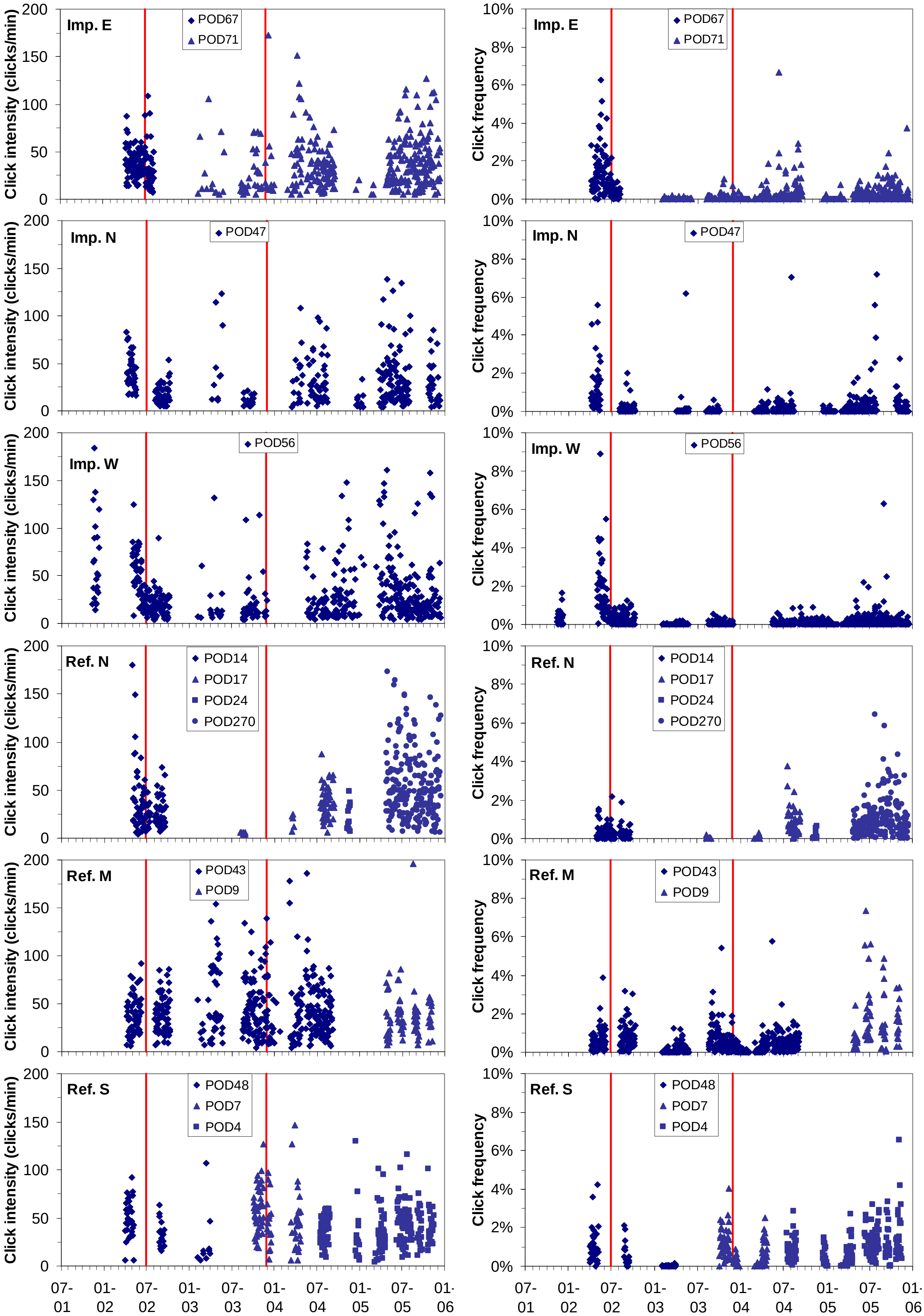
Indicator	Transformation	Distribution	Back-transformation
Clicks per PMM	Logarithmic – log(y)	Normal	$\exp(\mu + \sigma^2/2)$ [1]
Porpoise positive minutes (PPM)	Angular – $\sin^{-1}(\sqrt{y})$	Normal	Table 6 (Rohlf and Sokal 1981)
Encounter duration	Logarithmic – log(y)	Normal	$\exp(\mu + \sigma^2/2)$ [1]
Waiting time	Logarithmic – log(y-10)	Normal	$\exp(\mu + \sigma^2/2)$ +10[1]

The statistical analyses were carried out within the framework of mixed linear models (Littell *et al).* 1996 by means of PROC MIXED in the SAS system. Statistical testing for fixed effects (F-test with Satterthwaite approximation for denominator degrees of freedom) and random effects (Wald Z) were carried out at a 5% significance level (Pearl and Fenton 1996,Searle et al. 1980). The F-test for fixed effects was partial, i.e. taking all other factors of the model into account. In addition to analysing variations of the indicators, the distribution of encounters with respect to time of the day and wind speed were investigated, and for each period within each area it was tested by means of chi-square tests if the diurnal distribution of encounters was uniform and if the wind conditions of encounters was different from the overall wind conditions.

Appendix C: T-POD data

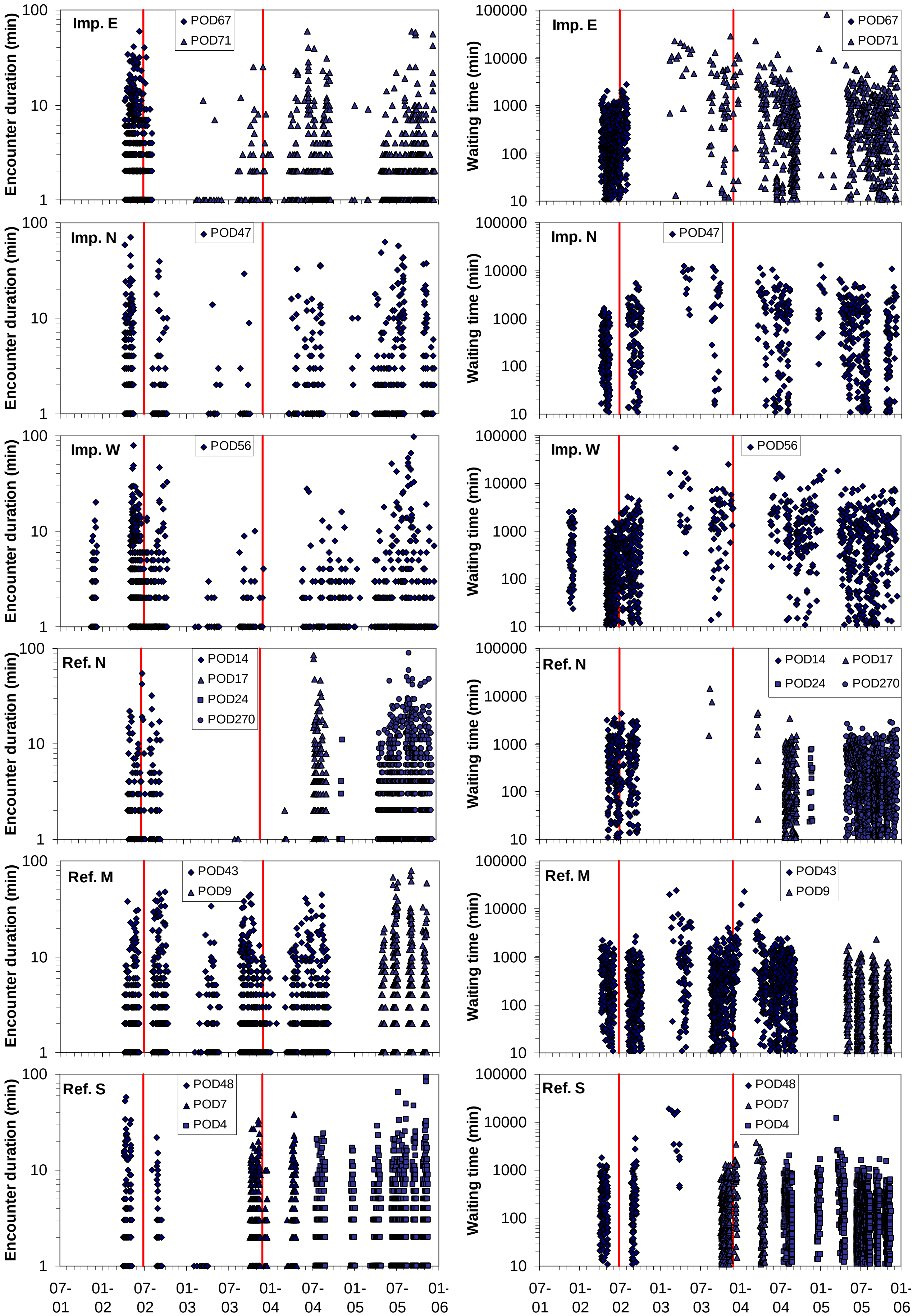
Table 9. Number of observations for the 4 indicators derived from deployments of 13 different T-PODs at the 6 stations in the wind farm (Impact) and in the reference area.

Station	Period	Pod #	Daily indicators		Encounter indicators	
			Click/PPM	PPM	Encounters	Waiting times
Impact E	Baseline	67	83	84	546	545
	Construction	67	37	39	118	117
		71	44	222	69	66
	Operation year 1	71	129	272	69	66
	Operation year 2	71	172	301	425	421
	Entire period		465	918	1494	1482
Impact N	Baseline	47	41	41	174	173
	Construction	47	74	175	131	129
	Operation year 1	47	73	165	130	126
	Operation year 2	47	139	250	290	289
	Entire period		327	631	725	717
Impact W	Baseline	56	83	86	512	509
	Construction	56	143	316	323	319
	Operation year 1	56	102	214	157	155
	Operation year 2	56	178	337	367	364
	Entire period		506	953	1359	1347
Impact all	Entire period		1298	2502	3578	3546
Reference N	Baseline	14	51	59	138	138
	Construction	14	56	67	129	127
		17	7	21	4	3
	Operation year 1	17	52	72	243	240
		24	10	16	18	17
	Operation year 2	270	213	218	1077	1074
	Entire period		529	676	1609	1599
Reference M	Baseline	43	63	64	222	220
	Construction	43	204	281	809	807
	Operation year 1	43	179	248	562	558
	Operation year 2	9	83	83	636	633
	Entire period		389	453	2229	2218
Reference S	Baseline	48	33	34	142	141
	Construction	48	29	83	103	101
		7	44	45	309	308
	Operation year 1	7	45	79	160	158
		4	53	53	296	295
	Operation year 2	4	152	171	1153	1149
	Entire period		356	465	2163	2152
Reference all	Entire period		1274	1594	6001	5969
All data			2572	4096	9579	9515



Imp. E
POD67
POD71
Imp. N
POD47
Imp. W
POD56
Ref. N
POD14
POD17
POD24
POD270
Ref. M
POD43
POD9
Ref. S
POD48
POD7
POD4
Click intensity (clicks/min)
Click frequency
07-01
01-02
07-02
01-03
07-03
01-04
07-04
01-05
07-05
01-06

Figure 24. Daily clicks/porpoise positive minute (click intensity, left panel) and porpoise positive minutes (click frequency, right panel) extracted from T-POD data collected at Nysted from November 14th 2001 to December 19th 2005. Different symbols mark observations derived from different T-PODs. The two vertical lines indicate the start and end of the construction period. Eleven daily cliks/PPM and two daily PPM values exceeded the plotting range (not shown).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Ref. S
POD48
POD7
POD4
Encounter duration (min)
Waiting time (min)
07-01
01-02
07-02
01-03
07-03
01-04
07-04
01-05
07-05
01-06

Figure 25. Encounter duration (left panel) and waiting time (right panel) extracted from T-POD data collected at Nysted from November 14th 2001 to December 19th 2005. Different symbols mark observations derived from different T-PODs. The two vertical lines indicate the start and end of the construction period. Six encounters exceeded the plotting range (not shown). Note the log-scale on the y-axis.