Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds

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European legislation requires Strategic Environmental Assessments (SEAs) of national offshore wind farm (OWF) programmes and Environmental Impact Assessments (EIAs) for individual projects likely to affect birds. SEAs require extensive mapping of waterbird densities to define breeding and feeding areas of importance and sensitivity. Use of extensive large scale weather, military, and air traffic control surveillance radar is recommended, to define areas, routes and behaviour of migrating birds, and to determine avian migration corridors in three dimensions. EIAs for individual OWFs should define the key avian species present; as well as assess the hazards presented to birds in terms of avoidance behaviour, habitat change and collision risk. Such measures, however, are less helpful in assessing cumulative impacts. Using aerial survey, physical habitat loss, modification, or gain and effective habitat loss through avoidance behaviour can be measured using bird densities as a proxy measure of habitat availability. The energetic consequences of avoidance responses and habitat change should be modelled to estimate fitness costs and predict impacts at the population level. Our present ability to model collision risk remains poor due to lack of data on species-specific avoidance responses. There is therefore an urgent need to gather data on avoidance responses; energetic consequences of habitat modification and avoidance flights and demographic sensitivity of key species, most affected by OWFs. This analysis stresses the importance of common data collection protocols, sharing of information and experience, and accessibility of results at the international level to better improve our predictive abilities.

INTRODUCTION

Clean renewable energy from offshore wind power offers the prospect of some relief from reliance upon fossil fuels. Offshore wind power avoids some of the problems presented to landbirds (e.g. raptors Orloff & Flannery 1992, 1996, Thelander & Rugge 2001, Barrios & Rodriguez 2004) and is free from 'Not In My Back Yard' protests on land. Since the first European marine wind farms were constructed in the early 1990s (Larsson 1994), at least 13 000 offshore wind turbines are currently proposed (ICES 2003), potentially making a major contribution towards achieving national targets for sustainable development under the Kyoto Protocol of 1997. This constitutes Europe's most dramatic marine industrial development to date. Current plans to develop offshore wind resources will require an area of 13 000 km^2 by 2030 in German marine waters alone (BMU 2001, Garthe & Hüppop 2004).

By virtue of their aerial mobility, high public profile and the existing international and national legal frameworks relating to the specific protection of migratory species, birds feature prominently in the environmental impact assessment (EIA) process associated with wind farm developments, both on land and at sea. There is a burgeoning literature relating to the interactions between land-based wind turbines and birds (Anonymous 2002, Langston & Pullan 2003, Hötker *et al*. 2004, Percival 2005). However, with only nine offshore wind farms currently operational in European waters, few case studies exist upon

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which to develop well-founded EIAs for future marine developments. Only four of these projects (Tunø Knob, Nysted and Horns Rev in Denmark and Kalmar Sound in Sweden) have provided good quality data on the effects on birds, since post-construction investigations are far from standard. In this review, we present the Danish experience of developing EIAs and results from post-construction monitoring in the context of the existing international legislation. We attempt to establish ideal objectives for offshore wind farm (OWF) EIAs in terms of assessing local effects (defined as proximate local changes in abundance and distribution) and large-scale impacts (defined as ultimate changes at the population level). In addition, we assess the constraints on achieving such objectives. It is necessary to distinguish between local effects and population impacts, to assess cumulative consequences for long-distance migratory birds. Finally, we provide guidance on the methods currently available, and make recommendations for improving data collection, collation and analysis.

BACKGROUND AND THEORETICAL FRAMEWORK

Factors associated with offshore wind farms affecting birds

Wind turbines simply exploit natural airflow to create mechanical energy that is converted to electricity. Offshore turbines are constructed of three-blade rotors driving encased generators perched on narrow cylindrical towers with internal maintenance access from an external landing platform above sea level. Structural size varies; recent OWFs have used 2.3 MW rated turbines, and there are already plans for 5 MW turbines. Rotor sweep (y, measured in metres) and hence tower height increase with power output (x, measured in MW) according to a power function ($y = 53.999x^{0.437}$, $r^2 = 0.998$; Danish Wind Energy Association 2003). Present typical 3.6 MW offshore wind turbines have a tower height of 77 m, a rotor sweep diameter of 100 m (clearance height of 27 m and total height of 127 m) and working speeds of 8–16 revolutions/min. It is generally assumed that the rotor sweep area represents the greatest risk of collision to flying birds and this clearly overlaps with the 0–50 m altitude range within which most seabirds commonly fly (Dierschke & Daniels 2003).

Despite a very broad range of opinions, there is a general consensus that the factors affecting birds resulting from the construction of OWFs can be distilled into three broad classes (shown in the uppermost row in Fig. 1). These comprise:

(1) a behavioural element, caused by birds avoiding the vicinity of the turbines as a behavioural response to a visual stimulus;

(2) a physical habitat element, where birds respond to destruction, modification or creation of habitat associated with turbine/ infrastructure construction; and

(3) a direct demographic element, resulting from mortality arising from physical collisions with the superstructures.

As we shall see below, there are problems associated with the direct measurement of the effects and, indirectly, with the assessment of the impacts of each one of these factors. Legislation requires that an assessment be made of the proximate effects of a new wind farm on birds. In this sense, the EIA must account for predicted changes in the local abundance and distribution of avian species; and in local biodiversity as a consequence of its construction and operation. Increasingly, however, there is a requirement for some assessment of the effects at greater spatial scales, including an assessment of the 'cumulative impacts' of several such developments. This of course necessitates an understanding of individual and additive impacts at the population level. For this reason, it is helpful to briefly review the legislative framework to identify specific ideal objectives to meet the requirements for EIAs with regard to OWFs.

Obligations under European Union legislation

In European Union (EU) states, all wind farm developments require some level of planning screening. Under Directive 2001/42/EC, national governments are required to undertake a strategic environmental assessment (SEA) of national wind energy plans and programmes that have the potential for an adverse impact on wildlife. Where there are potential transboundary effects regarding placements of OWFs, international co-ordination and collaboration should be sought. Specific projects also require a formal EIA (under Directive 85/337/EEC and amended by Directive 97/11/EC). This considers effects at local geographical scales (i.e. project level), assessed with regard to the individual avian populations involved, in contrast to the more strategic view of the SEA. However, the Directives also require some assessment of the cumulative effects and impacts arising from

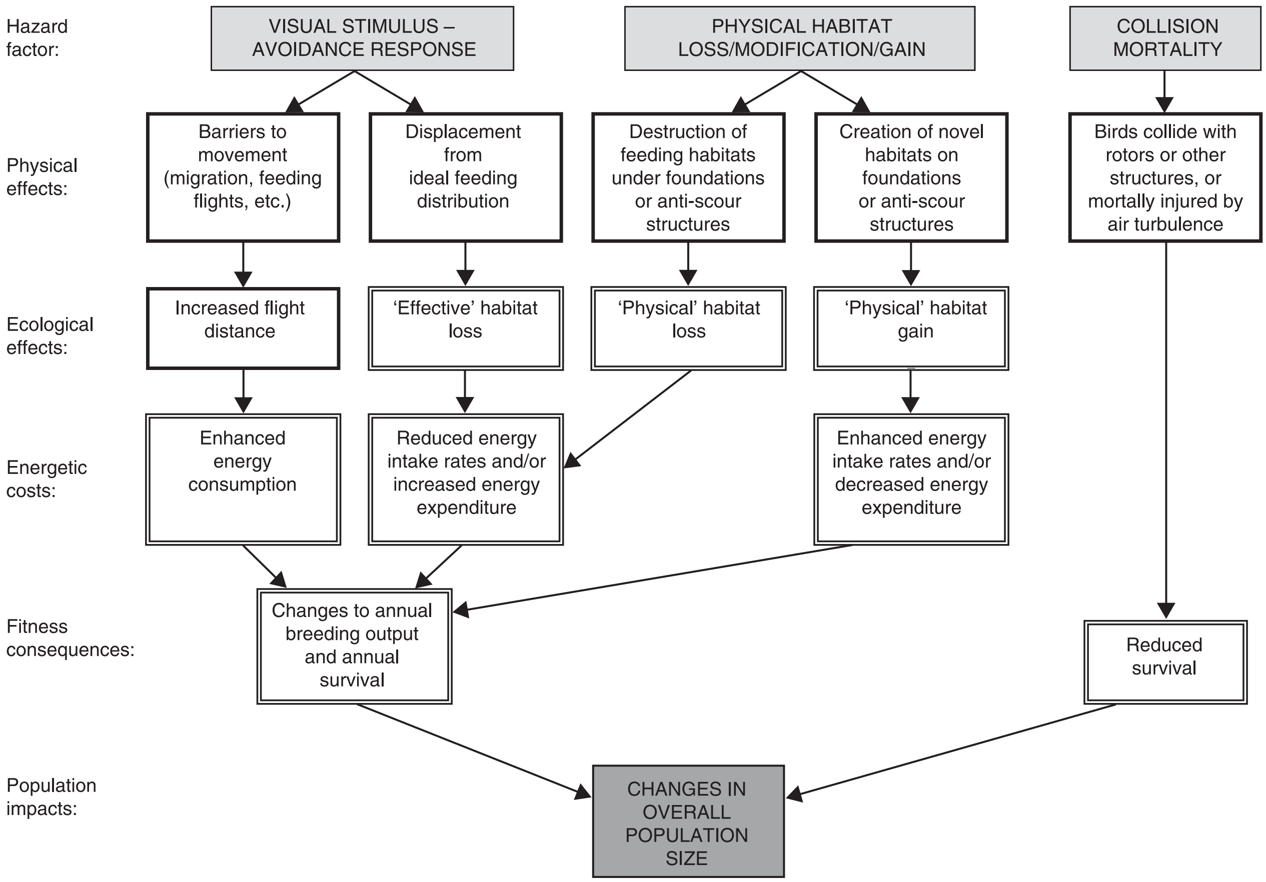

Figure 1. Flow chart describing the three major hazard factors (light shaded boxes) presented to birds by the construction of offshore wind farms, showing their physical and ecological effects on birds, the energetic costs and fitness consequences of these effects, and their ultimate impacts on the population level (dark shaded box). The boxes with a heavy solid frame indicate potentially measurable effects, the double framed boxes indicate processes that need to be modelled (see text for details).

each proposal (including associated on- and offshore infrastructure development, such as road improvements, power lines, transformer stations, under sea cables, etc.). Cumulative impacts also need to be considered in conjunction with other projects (which may include both other wind farms and other relevant human development projects), that impact upon the same flyway populations.

Measuring proximate local effects and ultimate population impacts

Unfortunately, the Directives and domestic legislation provide little guidance or case law to shape the precise requirements of SEAs or EIAs associated with OWFs. A major challenge is therefore to achieve some harmonization of approach, giving a general agreement on the overall aims and objectives of the process. Very few (effectively only two Danish and one Swedish) operational OWFs have provided long-term comprehensive case histories upon which to base an impact assessment. Hence, there is a need to define best practice in base-line studies: to inform upon sensitive siting of turbines to minimize deleterious effects on birds; and post-construction monitoring: to enhance predictive performance, based on feedback monitoring to improve our abilities to model effects. The information accumulated in these studies needs to address a range of issues, which will inevitably be species-, site- and season-specific when considering effects and impacts upon migratory birds. In terms of the behavioural and habitat elements, these studies need to specifically:

(1) assess the distribution and abundance of all locally feeding and migrating birds using a potential area;
(2) predict the extent of avoidance response; and
(3) report on the observed post-construction effects against predictions.

The assessment needs also to take into account the degree of habituation that may occur, whereby the strength of a particular response is moderated over time. Assessments of collision mortality should:
(1) assess the volume, direction, altitude and nature of all flying birds in the vicinity of a proposed wind farm area;
(2) predict the numbers of collisions under a variety of seasonal, environmental and weather conditions; and
(3) report on measured post-construction levels against predictions.

Such investigations enable an objective assessment of the potential effects on birds locally, but there remains a requirement to consider cumulative impacts. Hence, in both cases, these assessments need to take into consideration the local, regional and global sensitivity of each population involved and other factors affecting the population at a far greater spatial scale. Assessment of impacts at the population level therefore, poses a considerable challenge to the SEA and EIA processes. In all these cases, investment in post-construction monitoring, although initially expensive, will increasingly improve our ability to make predictions about, for example, habituation and collision rates.

Background to the Danish experience

Denmark lies centrally on the East Atlantic flyway and supports very high concentrations of migratory, staging and moulting waterbirds: 5–7 million birds of more than 30 waterbird species in winter. In several cases these constitute more than half of the wintering populations of some north-western Palearctic species (Laursen *et al.* 1997, Rose & Scott 1997, 2002). As a consequence, Denmark has special obligations under both the Ramsar and Bonn Conventions and the EU Birds Directive to protect and maintain these populations.

The Danish Government's energy action plan 'Energi 21' established a national target for a 50% reduction in carbon dioxide (CO_2) emissions by 2030 (as compared to 1988 levels). With limited opportunity for further erection of land-based wind farms in Denmark, a strategic 4000 MW capacity objective was established for OWFs and an overall assessment of marine waters (including environmental and economic interests) undertaken to identify potential locations. In 1997, an action plan for OWFs in Danish waters was published for consultation, concluding by proposing that five 'stage-one' demonstration projects should be undertaken to assess the technical, economic and environmental feasibility of large scale offshore wind electricity generating projects. In February 1998, the Danish Ministry of Environment and Energy gave permission for the construction of five offshore demonstration wind parks in Danish inshore waters. Of these, two have since been constructed, at Rødsand (Nysted) in south Denmark and at Horns Rev on the west coast of Jutland, completed in 2003 and 2002, respectively. Permissions were granted on condition that a programme of environmental studies would be undertaken to support the preparation of EIAs. The environmental studies were designed to cover the construction area (wind park and cable link areas), the impact area (the area during construction and operation in which there was expected to be an effect), and a reference area (a comparable area, free of wind turbine development). Particular emphasis was placed upon waterfowl and migrating bird species. The EIAs were to include proposals for a dynamic programme, monitoring positive and negative impacts on the environment, in both the construction and the operational phase, to continue 2–3 years post-construction.

One major objective of the monitoring programme was to enable a comparison between the predicted effects arising from the initial EIA, and the observed effects post-construction. An important element in the design of the programmes was to ensure that base-line monitoring was of sufficient duration to rule out 'natural variability' masking the effects that the programme was designed to detect during the operational phase.

DATA REQUIREMENTS AND COLLECTION METHODS

Supporting a Strategic Environmental Assessment

Despite the imperative presented to national governments to attain their Kyoto targets, development of offshore energy resources requires an international, national and regional SEA of the most suitable areas for such exploitation. Ideally, the first strategic level approach should determine the relative avian nature conservation interest of European marine waters, to establish a core overview of differential importance and therefore sensitivity. After this, the economic constraints on the suitability of different potential OWF sites to deliver power into the national grid can be considered in order to provide a 'wish list' of potential development sites, to compare against known avian distributions and assess the likely impacts on birds. From the industry side, this wish list would be compiled based upon the available wind resources in relation to the costs of offshore developments in the best areas. Constraints upon this would include, for example: water depth; substrate type; distance to shore; suitability of grid connections; and costs of transmission to distant centres of population etc. Such a ranking of feasible and cost-effective sites for development would then offer up a first level list of proposed sites for the consideration and assessment of potential consequences for, and interactions with, a range of other stakeholders and user-groups. Some of the issues necessitating wide consultation with appropriate stakeholders and statutory bodies (which lie outside the scope of this review) would include: conflicts with shipping lanes, military, fisheries, oil and gas industry, telecom linkages and many others. However, the first level of screening and consultation would include an assessment of the nature conservation values of the site, with regards to the statutory obligations directed by domestic and European legislation. From the avian conservation viewpoint, it is essential that the bird interest of a particular proposed wind farm site can be assessed in the international, national and regional context. This necessitates at least some idea of the distribution of resting and feeding birds in all sea areas during critical periods of the annual cycle (taken here to be wintering areas, spring staging areas, nesting and breeding feeding areas, moulting areas and autumn staging areas).

In Denmark, extensive data on the relative distribution of birds at sea were available from aerial census data supplemented with boat-based surveys available since the 1970s (e.g. Joensen 1973, 1974, Durinck *et al.* 1994, Laursen *et al.* 1997). These data formed the basis upon which to make a preliminary assessment of the favoured sites for development of wind energy in the sea. Such extensive knowledge enabled a first level assessment of the relative suitability of the five proposed wind farm sites in Denmark.

In most European states, such extensive knowledge of resting and feeding bird distributions at sea are generally lacking. Notable exceptions include those areas covered by the European Seabirds at Sea (ESAS) database (and associated analyses, e.g. Blake *et al.* 1984, Tasker *et al.* 1987, Carter *et al.* 1993, Mitchell *et al.* 2004) and/or subject to special monitoring (e.g. designated Special Protection Areas notified under the EU Birds Directive). However, ESAS coverage can be patchy, especially in shallower waters inshore. It is then neccessary for some phase 1 level survey of extensive areas of marine waters in order to make proper assessments of the relative importance of proposed sites. The ideal objectives of such a survey would be: to cover as large an area as possible in the time available; to sample as simultaneously as possible; use the greatest level of spatial precision possible; and to use observation platforms that create the least disturbance to abundance and distribution patterns. Suitable methods for achieving this, using transect grid coverage by aerial surveys, have been described by Camphuysen *et al.* (2004). Transect sampling of bird abundance based on counts from moving platforms, corrected for detectability using distance sampling approaches (Buckland *et al.* 2004) offers a very powerful tool for generating bird density surfaces. This is especially so when using spatial modelling techniques (such as generalized additive and mixed modelling) to incorporate environmental parameters as covariates to explain bird distributions and abundance (e.g. Hedley *et al.* 1999, Clarke *et al.* 2003). Such approaches offer the possibility to sample bird distributions using sparse transect coverage to interpolate modelled densities with confidence as a phase 1 survey (Camphuysen *et al.* 2004). These methods offer the opportunity for an objective ranking of 'hot spots' of high bird concentrations at particular times during the annual cycle or at least identify areas in need of more intensive survey.

Whilst such survey is ideal for defining the distribution of birds exploiting the sea for feeding or resting, instantaneous sampling is poor at defining avian migration intensity over large areas of open sea. Flight movements of birds between areas (especially during long distance migration and foraging flights between breeding sites, feeding areas and roosting sites) are by definition intense and of very short duration at various different altitudes, heavily dependent on season and weather. However, assessments of bird movements at local, small spatial scales (but set in a national or regional context) are required for the effective assessment of, for example, collision risk probabilities. Where terrestrial birds, as well as waterbirds, can be shown to migrate in very low densities, the local collision risk can be considered very much lower than in cases where large densities of birds migrate at turbine height through a proposed site. It is well known, for example, that migrants collect at the tips of peninsulas throughout the world prior to crossing the sea (e.g. Foy 1976, Alerstam 1990). Waterbirds are also concentrated by topography (e.g. Common Eiders *Somateria mollissima* at Nysted, Kahlert *et al.* 2004) or gather at sea prior to crossing the land

(Bergmann & Donner 1964, Bergmann 1974). Hence, it is likely that topography shapes migration routes out at sea, at least in near shore areas. Similarly, it is known that migrating birds crossing the sea may lose or gain height upon approaching land (e.g. Richardson 1978, Alerstam 1990). Any knowledge of the migration corridors and patterns of flight in three dimensions across the open sea (especially in near shore areas where wind farm development is most likely) is highly desirable to support effective siting of wind farms to avoid high collision risk areas.

Unfortunately, such data are not extensively or readily available in Europe. Only military, air traffic control or meteorological radars can currently provide sufficient coverage of mass migrations of birds over time at large spatial scales (i.e. 1–200 km), over a range of altitudes (Gauthreaux 1970, Desholm *et al.* 2005). Some species specific radar studies have been undertaken in Europe (e.g. Alerstam *et al.* 1974) using weather radar (e.g. in Finland & Koistinen 2000) or military radar (e.g. in Sweden, L. Nilsson *pers. comm.*, and Germany, O. Hüppop *pers. comm.*). However, the results have not been fully published and because the quality of data on bird migration altitude is variable, are generally not in a form suitable to support SEAs. There are a number of problems associated with using such radars, not least the conflict of interest, given that meteorological, air traffic control and military radars frequently filter out the signals reflected by birds. The operational lack of capability to distinguish bird migration at low (i.e. turbine sweep) altitudes is frequently another disadvantage of using such technology (Desholm *et al.* 2005). Nevertheless, the use of these existing sources of data and the development of specific bird radar equipment has the potential to deliver vital information in the future. Both could potentially be used to support the identification of migration corridors (e.g. those associated with promontories and peninsulas where birds tend to arrive and depart from) and the flight behaviour of birds (especially flight altitude) in the vicinity of proposed wind farm sites. This information is needed both to inform the SEA process and influence the local siting of turbines as pre-construction mitigation during the EIA process.

At present, there have been very few attempts in Europe to undertake a SEA associated with OWF development, despite the fact that the legislative framework requires this to be undertaken. Many of the specific environmental issues associated with a development will be addressed at site level by a project-specific EIA. A strategic assessment of where best to locate OWFs in national waters, to avoid specific conflict with resting and feeding waterbirds has only been undertaken in Denmark, Germany (the MINOS project, 'Marine warm-blooded animals in the North and Baltic Seas: foundation for assessment of offshore wind farms') and regionally in the UK. To the best of our knowledge no strategic national assessment of avian migration routes has been undertaken in this connection, with the exception of current studies in Germany (see Exo *et al.* 2003).

Developing a site-specific Environmental Impact Assessment

What species are involved? What is their distribution in time and space?

From the outset, it is essential to define the range of bird species occurring within the area of a proposed wind farm, whether these birds exploit the site during the breeding, moulting, staging or wintering periods, or simply pass through on migration. Useful historical data are likely to exist in a variety of forms. For example, shore-based sea-watching observations of passing birds have been compiled at migration watch points to give a picture of general bird migration in the vicinity of the Horns Rev OWF (Noer *et al.* 2000). Much seabird distribution data is held in archives (such as ESAS) or result from specific surveys of limited spatial scale. Although such sources of information are valuable, these data are often collected using different methods at a geographical or temporal resolution that does not provide a basis for impact assessment or a rigorous base-line for post-construction comparisons. A site-specific assessment of the species composition and abundance of birds in the area of a wind farm should also be undertaken. This should encompass a geographical area that includes construction, impact and reference areas; an assessment of the conservation status of the species or specific populations involved; and the conservation status of sites protected for their nature conservation interest in the immediate vicinity of a development.

Hazard factors and measurement of effects/impacts

The approach taken in the Danish model has been to attempt to quantify the physical effects of each of the three major factors on bird behaviour, abundance or distribution (Fig. 1). This helps to identify measurable parameters that can contribute to the measurement of local effects and feed directly into the local EIA process. However, although this tells us a great deal about how birds are likely to react locally, it is hard to translate the effects of changes in distribution or displacement, to the specific consequences for an individual bird and its lifetime fitness, or for the population as a whole. This is important if we are to determine the cumulative impacts of many such wind farms in a given area or along a species flyway corridor. It is even more important if we are going to assess the relative impacts of OWFs in comparison to other anthropogenic factors affecting that population. Such comparisons and assessments of impacts from a combination of developments necessitate the measurement of impacts using a common currency. The ultimate measure to understand changes in population is that of fitness, namely changes in vital processes of birth and death rate (see Fig. 1), which ultimately affect annual changes in overall population size. However, with the exception of collision deaths, it is difficult to directly relate displacement of an individual bird from its ideal feeding position, to its reproductive success or to its survival probability. For this reason, it becomes necessary to use the measurable local effects to model ultimate population impacts.

Given the physical effects that arise from each of the factors shown in Fig. 1, the rationale has then been to attempt to determine the ecological effects on the birds, and in some cases translate these effects directly into additional energetic costs incurred as a result of post-construction conditions. In some circumstances, changes in these energetic costs can be incorporated in individual behaviour-based models to determine the potential fitness consequences at the individual level, which can then provide a basis for impacts at the population level (as is being done for Common Scoter *Melanitta nigra* see Kaiser *et al.* 2006). At the population level, it becomes possible to incorporate and/or model other cumulative impacts to start to address the issue within the EIA process.

Avoidance response – barriers to movement

Initial observations suggest that some birds chose to fly outside an offshore wind turbine cluster rather than fly between the turbines (Desholm & Kahlert 2005). Such behaviour reduces collision risk, but means that OWFs might represent a barrier to movement, either to local feeding and roosting flights, or to longer migratory flights (Dirksen *et al.* 1998, Tulp *et al.* 1999, Pettersson & Stalin 2003, Kahlert *et al.* 2004, Desholm & Kahlert 2005). The extent to which such avoidance constitutes a problem depends on the species, the size of the OWF, the spacing of the turbines, the extent of extra energetic cost incurred by the displacement of flying birds (relative to the normal flight costs pre-construction) and their ability to compensate for this degree of added energetic expenditure. Very large-scale developments could ultimately have a disruptive effect on linkages between feeding, nesting and roosting areas and perhaps finally create a barrier that birds will not cross at all, completely re-routing the flight trajectory – although no such effect has been reported to date.

The ideal objective therefore, is to construct a frequency distribution of individual bird and flock trajectories (identified to species during day and night) in three-dimensional space through a defined corridor of air space in and around the proposed OWF prior to its construction. This necessitates consideration of the spatial scale of the migration area to be monitored, dependent upon the distance over which the OWF is visible to birds and the range of the remote sensing technology equipment to be used (see Desholm *et al.* 2006). Gathering such data provides a basis for comparisons of the frequency distributions through the same area post-OWF construction in a manner that accounts for differences in weather conditions. These requirements are rigorous and difficult to attain, but continuing improvements in the field of remote sensing offer increasing opportunities to use radar and thermal imaging equipment to construct such frequency distributions (see Kahlert *et al.* 2004 and Desholm *et al.* 2005 for review of methods and techniques).

Given radar studies of pre- and post-construction flight volume, direction and tracks, it is possible to quantify the level of avoidance shown amongst bird trajectories that result following wind farm construction (Desholm & Kahlert 2005). Mechanical models (e.g. Pennycuick 1989) can then be used to assess the relative additional costs of these flights. Such local avoidance by migrating birds is likely to be relatively trivial in energetic terms, since avoidance of present scale OWFs consisting of 80–100 turbines is likely to incur additional flight costs of less than 20 km to completely avoid the structures. At the local scale, such a limited extension to a migration flight of several hundred kilometres, is likely to contribute very little to extra energy expenditure compared to, encountering strong and unfavourable winds, for example. Such extra energy costs are likely to be compensated for by slightly enhanced feeding rates. Under these circumstances, at the local single OWF level, the additional energetic costs are unlikely

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to be significant. However, this may not be the case for birds commuting daily between feeding and other areas used in the daily cycle. These would include, for example, Common Scoter and Long-tailed Ducks *Clangula hyemalis*, moving daily between feeding and roosting areas on their wintering grounds. Breeding gulls (Laridae) or terns (*Sterna* spp.) also move between marine foraging and terrestrial nesting areas, where additional flight costs may increase normal energy expenditure and/or survival of nestlings may be affected if provisioning rates decrease. At a greater spatial scale, construction of OWFs along the migration corridor of a long-distance migratory waterbird may begin to have a greater cumulative energetic cost. In this context, it is important that such additional costs that arise from this source of barrier effect be incorporated into modelling of overall annual energy budgets to assess the effects on fitness and ultimately the potential for impacts at the population level. This approach also means that some comparative assessment of population impacts can be made when considering the effects of OWFs vs. other forms of human activities.

Displacement from ideal feeding distribution

Following construction of a wind farm, waterbirds may show a spatial response to the new constructions in the sea. Waterbirds may avoid the vicinity of novel, man-made structures; may be disturbed by the visual stimulus of rotating turbines; or be displaced by the boat/ helicopter traffic associated with maintenance. Whatever the cause, the result is that birds are displaced from a preferred feeding distribution, which results in effective habitat loss in the vicinity of the turbines. Apart from the relatively small area of seabed habitat lost under the foundations (and any surrounding associated antiscour constructions), the habitat and associated food resources are likely to remain physically intact. However, if birds of a given species are hesitant to approach to within half of the distance between adjacent turbines of a single project, the entire wind farm area, and an avoidance strip around the outer turbines, will become effectively lost as a feeding area.

The objective here, therefore, is to assess the degree of habitat loss that results for a given population of birds by the creation of the OWF. This should be based on as large a sample gathered during as many base-line years (at least 3) as possible to account for year to year variation in bird abundance and distribution (Camphuysen *et al.* 2004). Such direct assessments of habitat extent and quality are costly and time consuming, so effective and actual habitat loss can be measured using bird densities as a proxy measure of bird habitat. To this effect, aerial survey has proved a valuable tool for sampling bird distributions using distance sampling techniques to correct bird densities for the declining detectability of individuals with increasing distances from the observer (Buckland *et al.* 2004, Camphuysen *et al.* 2004). Spatial modelling techniques can then be used to generate bird density surfaces with confidence intervals over large areas of open sea based on transect samples to compare pre- and post-construction distributions and abundance (see above). The aim is to assess the density of birds throughout the proposed OWF area and a control area around this, prior to construction to predict the degree of habitat loss liable to occur post-construction, assuming different avoidance scenarios. In addition to informing the EIA process, this approach also offers the opportunity to undertake statistically robust comparisons of pre-construction base-line densities with post-construction observations (Fig. 2). This enables an assessment of the extent of total habitat loss and the extent of any graded avoidance response (Fig. 2). Furthermore, with sequential post-construction monitoring over a series of years, it will be possible to introduce a temporal element into the modelling to take account of year to year variation in displacement and the extent to which habituation may occur.

It is important to stress the need for adequate base-line and post-construction sampling. A base-line period must be long enough to discern some degree of natural variation pre-construction, matched by a similar period post-construction. Since the construction of the Øresund Fixed Link and Nysted OWF, three year base-lines have defined current practise in Danish bird studies (Noer *et al.* 1996, Kahlert *et al.* 2004). In relation to the erection of German offshore wind farms, a minumum of 2 years were proposed for base-line studies, with 3–5 year post-construction monitoring (Hüppop *et al.* 2002). Although these are long (and expensive) time frames for data collection, this is important to account for the natural variability in bird abundance. For instance, in the case of the Long-tailed Duck distribution at Nysted in south Denmark, using data from only 2 (and consistent) base-line years in 2001 and 2002 would suggest a dramatic displacement of birds from the OWF in 2003 out to almost 15 km. However, the baseline data from 2000 showed that the bird distribution during 2003 fell within the variability of the baseline sampling (Fig. 3).

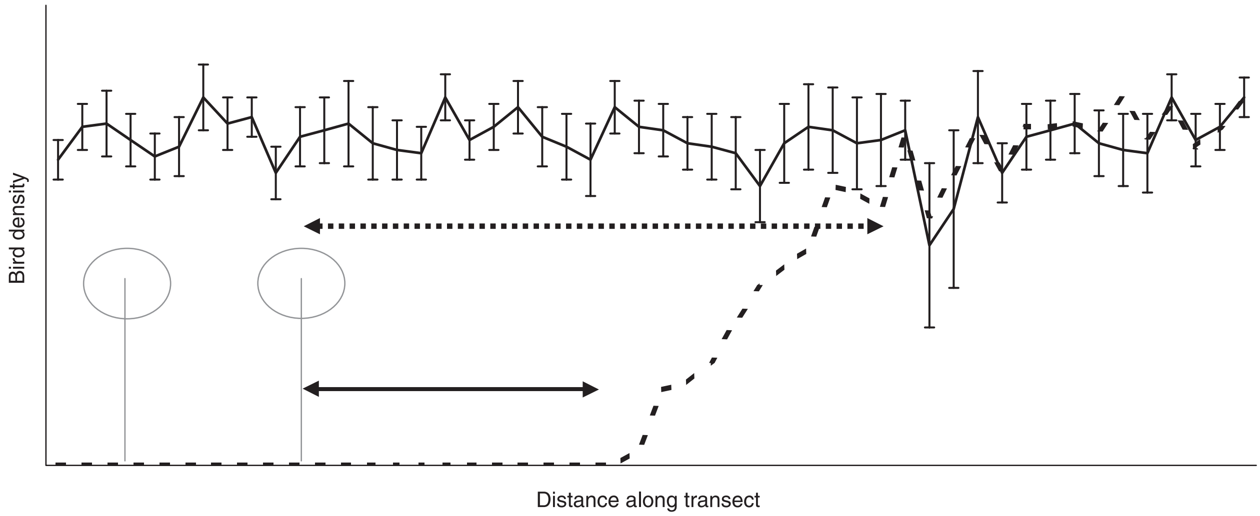

Figure 2. Theoretical two-dimensional representation of the modelled bird densities generated by spatial modelling as described in the text. The solid plotted line identifies the bird densities in grid cells modelled from aerial survey counts prior to the construction of the offshore wind farm (represented by two wind turbine symbols), the vertical bars indicate confidence intervals around these estimates. The dotted plotted line indicates the observed modelled bird densities post-construction (without confidence intervals for clarity), demonstrating complete avoidance of the area within the offshore wind farm. Note also an avoidance zone outside the turbines (solid arrow), and a surrounding area which experiences reduced bird densities as a result of avoidance and a graded avoidance response (dotted arrow). The integrated area between the two curves represents the difference in bird density resulting from the construction of the wind farm.

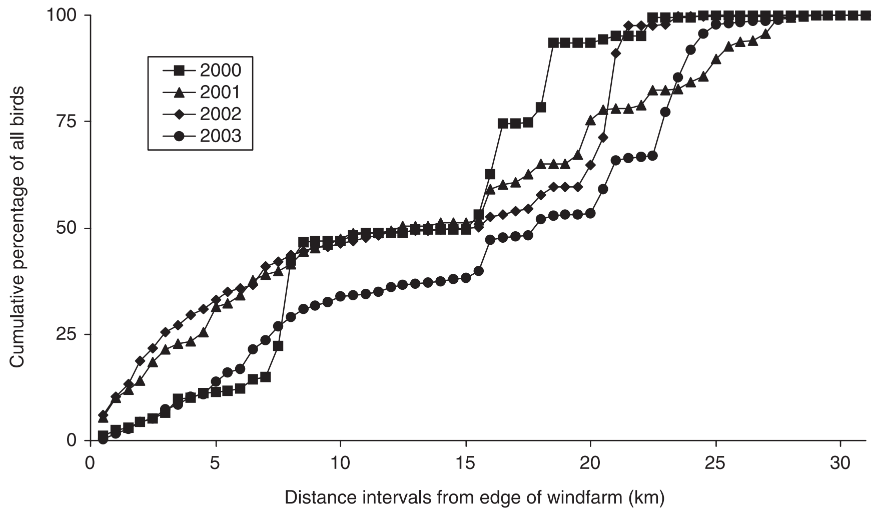

Figure 3. Cumulative percentage distribution of Long-tailed Ducks *Clangula hyamelis* at 500 m intervals from the periphery of the Nysted offshore wind farm, based on all aerial survey data in 2000, 2001 and 2002 (pre-construction), and post-construction in 2003. See Kahlert *et al.* (2004) for full explanation and methods.

Where food supply is limiting, displacement from ideal foraging opportunities will have an effect on the displaced individuals. Birds may be forced to move elsewhere, with an associated energetic cost with that movement. Following the construction of the Øresund Bridge, Common Eiders displaced by associated habitat destruction showed a graded response. Post-construction, bird numbers increased at other sites more than 7 km from the original foraging area, presumably because there were no alternative feeding sites in the vicinity of the construction site (Noer & Christensen 1997). Hence, the size of any monitored reference area must take account of the potential scale of spatial rearrangement post-construction. For some particularly critical periods in the avian life cycle (e.g. moulting sites used by waterbirds), there may be such specific requirements on habitat characteristics that no alternative sites physically exist, exposing the birds forced to use other unsuitable sites to elevated fitness costs (e.g. enhanced predation risk whilst flightless).

Displaced birds may be forced to move elsewhere to feed in potentially less suitable (i.e. energetically profitable) conditions (e.g. diving in deeper water, or foraging in areas with reduced prey densities). They may also experience increased competition from higher densities of birds in areas to which they are displaced. To determine the effects of such processes requires a fundamental knowledge about feeding opportunities throughout the migratory range of the population concerned, a detailed knowledge of the feeding ecology of the species and some assessment of the behavioural implications for feeding at different prey and predator densities (West & Caldow 2006, Pettifor *et al*. 2000). For a restricted range of critical species, it may be possible to gather such data to construct individuals-based spatially explicit population models to test for the effects of such 'effective habitat loss' on energy intake and ultimately on fitness consequences (i.e. breeding success and annual survival). This approach is already being developed for the assessment of the effects of disturbance and habitat loss from wind farms on Common Scoter (Kaiser *et al*. 2006). This species is of critical importance throughout the western Palearctic because of its selection of sandy substrates in shallow coastal waters which were initially the preferred situations for the development of OWFs because of nearness to shore and the ease of ramming foundations into the soft substrates (Fox 2003).

Destruction and/or modification of feeding habitat

The extent of physical loss to turbine foundations and to antiscour protection provision has never amounted to more than 2% of the total area of a wind farm in the Danish experience. For this reason, physical habitat loss has been considered under disturbance loss, since these two effects cannot be distinguished, not withstanding that the area of habitat affected is small. In relation to the creation of new habitats and food resources associated with the novel substrates provided by the turbine towers and antiscour protection, these have tended to be considered as trivial in terms of the overall EIA, on the basis of the restricted area involved. Nevertheless, where boulder protection is introduced to reduce scour to purely sandy substrates, such artificial reef structures may attract fish species (e.g. Jensen *et al*. 1994) that were previously absent (and hence piscivorous birds). Certainly gulls (especially Herring Gull *Larus argentatus*) and terns showed increased abundance at the Horns Rev wind farm post-construction compared to the base-line pre-construction. However, it was not clear if this resulted from birds being attracted to the turbines as loafing structures or to the associated boat traffic as potential food sources (Christensen *et al*. 2003, Petersen *et al*. 2004). Cormorants (*Phalacrocorax carbo*) are attracted to turbine maintenance platforms simply to use them as loafing structures (Kahlert *et al*. 2004), and potentially also because of enhanced feeding opportunities associated with the wind farm. Hence, wind farm construction may both remove and add structures and habitats that affect the abundance, distribution and diversity of the local avifauna. To date, because these modifications affect habitat areas that constitute less than 5% of the total wind farm area, and because the bird species associated tend to be abundant, widespread and those of little conservation concern, these effects have not been considered of great importance. Nevertheless, such changes in habitat can be measured using bird density measurements as outlined above and this may be an issue that will merit greater attention in the future.

Collision rates

Birds can be injured or killed by interactions with wind turbine structures in three ways: by hitting the stationary superstructure, the stationary or rotating rotors, or by being caught and injured in the pressure vortices created in the wake of the rotor blades. Birds, especially night-migrating passerines, are well known to collide with stationary objects, both on land and at sea, such as towers (e.g. Evans 2000, Kerlinger 2000), especially those with certain types of illumination (e.g. Gauthreaux & Belser 2000, Manville 2000). OWFs require navigation lights under legislation relating to maritime and airborne traffic. In conditions of poor visibility, birds tend to be drawn towards continuous lights, which may substantially lower avoidance rates. Equally illumination may enhance avoidance and light safe potential resting places at sea during adverse conditions. Disorientated and unconscious birds are also more likely to die (as a result of drowning) offshore compared to those on land (Tingley 2003).

Collision mortality is often considered to be the most important hazard presented to birds by wind turbines constructed in the sea because the impact of such additional mortality can be seen as having an immediate consequence at the population level. It is axiomatic to state that deaths occurring through collision with the turbines (or by the turbulent airflow associated with the blades around the sweep area) will reduce population size. However, the population dynamics of some avian species give them a greater resilience to extra mortality over several generations than other species. For this reason it is very important to estimate collision rates to determine the extent of this source of mortality and interpret this in the context of the population concerned.

Our aim would be to measure the rate of flight movements through the area of a proposed OWF and from this explain the collision risk frequency expected post-construction. In other words, we need to model the deterministic probability of birds hitting the turbines corrected for the ability to avoid them. But how do we estimate collision risk and especially bird avoidance rates pre-construction as a contribution to an EIA? Radar can be used to track the altitude and trajectories of birds in the vicinity of a proposed OWF prior to construction. This is important to measure the volume of bird movement that occurs through the area at different altitudes under a range of annual, seasonal and meteorological conditions (e.g. Christensen *et al.* 2003, Kahlert *et al.* 2004, but see Desholm *et al.* 2006 for limitations on data collection). Furthermore, there exist statistically sound models to predict collision risk of birds within the sweep area of the turbine rotors (e.g. Tucker 1996, Band *et al.* 2005) based on these frequency distributions (Chamberlain *et al.* 2005, 2006). Sensitivity analyses show that the probabilities of collision provided by such approaches show little change in response to bird size, but are reliant upon accurate flight altitude measurements to determine collision risk. The final calculation of avian mortality incorporates the parameter $(1-\alpha)$, where α represents the probability of avoidance, multiplied by collision probability and the bird numbers at risk entering the turbine sweep area. The very few measures of avoidance rates that do exist in the literature are high (> 0.90, see Chamberlain *et al.* 2005, 2006) creating large-scale adjustments in mortality rates. Hence, small errors in avoidance rates have very large effects on percentage changes in predicted mortality rates, dwarfing the effects of changes in other fitted parameters in the model. Yet avoidance rates of individual birds and the factors affecting these remain poorly known.

Estimates of avoidance rates on land are derived from the ratio of mortality (estimated from corpse searches and collection) to the estimated number of birds flying in the risk area. However, both of these estimates are subject to considerable error, which will have a large effect on the precision of mortality estimates (Chamberlain *et al.* 2005, 2006). Given the species-, site- and weather-specific variations in avoidance rates, it is deemed unacceptable to use avoidance rates from other studies without clear and rigorous justification. For this reason, there is a very clear and urgent need to gather extensive and better quality data on state specific avoidance rates of different bird species to turbines to enable effective parameterization of bird avoidance rates to incorporate into collision risk modelling. At Nysted OWF in southern Denmark, radar studies showed that Common Eiders modified their flight trajectories (in response to the visual observation of the turbines) at an average distance of 3 km during daylight (less by night) compared to pre-construction flight patterns (Kahlert *et al.* 2004, Desholm & Kahlert 2005). Similar adjustments to flight orientation of other species have been recorded at the Horns Rev OWF (Christensen *et al.* 2003). Furthermore, from one single TADS sequence, it is known that passerines exhibit the ability to apparently stop still in space in very close proximity to the turbine rotor sweep and avoid collision by flying away from the danger area (Desholm 2003, 2005). It must be stressed however, that case studies of this type are extremely few in number. Such a range of responses at very different spatial scales requires much development of radar and thermal imaging hardware (e.g. Thermal Animal Detection System, [TADS]) and gathering of more extensive data on relatively rare events (Desholm *et al.* 2005). It must be remembered that the extent of data available on such encounters between offshore wind turbines and birds remains very limited, and one must remain extremely prudent in drawing general conclusions from such observations made under specific circumstances associated with relatively few wind farms.

This area of research and monitoring is a very urgent priority for the future, both to identify the limits of collision risk models during the EIA stage and to gather data on actual collision rates post-construction, to test the validity of the predictive methods. It is known that birds collide with a variety of man-made objects (e.g. lighthouses, bridges, tower blocks, communication towers; Avery *et al.* 1976, 1980, Kerlinger 2000, Manville 2000, Jones & Francis 2003) under conditions of poor visibility. It is likely that the same will occur at OWF occasionally although the rarity of such events makes it difficult to determine their frequency with accuracy and precision. However, were it possible to correlate high collision rates with particular meteorological conditions at critical times of the year, this would offer a basis for mitigation measures. For example, it may be possible to shut down turbines during those rare events when poor weather and heavy migration conspire to create unusually high collision risk, if stopping turbines proves to be an effective mitigation measure to reduce collision rate.

So far, such measurement of actual collision rates post-construction at OWFs has proven difficult, with the only effective method using infra red thermal imagery technology to gather data from sampled sections of the turbine sweep area, triggered by warm-bodied objects entering the field of view (Desholm 2003). Such equipment is expensive and costly to operate, so there remains a need for a cheap equipment solution that provides time specific records of avian collision on an extensive scale to better understand the conditions under which collision risk is elevated (Desholm *et al*. 2006).

Whilst it may be possible to estimate collision rates at turbines using this type of approach it is also necessary to model the effects of such mortality over longer time periods to assess the impacts of such mortality on different populations exhibiting different sensitivities. Short-lived species (such as passerines) tend to be highly fecund, and in situations with strong density dependent effects, it may be that the high reproductive potential of a population can replace lost individuals relatively quickly to maintain population size. In contrast, this is not the case for relatively long-lived species (such as divers *Gavia* spp., and many raptors) which raise very few young throughout their lifetime. These species are less able to replace lost numbers over short time intervals (dependent also upon the extent of available breeding habitat and the pool of non-breeding sexually mature individuals), such that additional mortality is more likely to cause sustained declines in numbers over time. It is therefore essential to establish the level of collision rates associated with turbines at sea, the species and populations involved and to undertake population modelling (incorporating different strengths of density dependence) to assess the sensitivity to the levels of observed collision mortality. This is especially important to enable the assessment of the potential cumulative impacts of more than one wind farm development along the flyway corridor of a given population.

DISCUSSION

What is clear is that we still have a long way to go before we can consider our toolbox complete for obtaining the necessary data for the development of effective EIAs for OWFs. This review emphasizes the need for the collation and analysis of data at different spatial and temporal scales, in order to address the strategic impact of a wind farm (in terms of the siting on an international, national and regional level) as well as the local effects of the construction of a specific wind farm and ultimately its impact on populations. The challenges are many and varied, but this gap analysis shows that we require more studies which involve before/after and control/impact comparative studies to validate the data from our existing OWF EIAs, to enable improved predictions to support future EIAs.

One of the most important guiding principles is the need for the adoption of common (preferably international) agreed best practice standards to enable standard collation of data and to ensure the most effective cross comparison of experiences.

At present, there exist good before, during and after construction monitoring data for resting, feeding and migrating birds relating to the two Danish OWFs described above. However, these are ultimately species-, season- and site-specific experiences from just two sites with only 2 (potentially atypical) post-construction years of observations. In the UK, the COWRIE (Collaborative Offshore Wind Research into the Environment) Steering Group has funded strategic research initiatives. It has also taken the lead on the development of recommended survey and monitoring methods as industry standards for UK OWF developments (e.g. marine bird survey methods and remote sensing technologies; Camphuysen *et al*. 2004, Desholm *et al*. 2006). It is increasingly important that adequate monitoring be put in place to see how predictions made in EIAs for OWFs perform against reality post-construction; without such feedback monitoring, we shall not be in a position to improve our ability to make effective EIAs in the future. We also increasingly need a centralized data handling facility to collate and curate data and ensure common experiences are made available to all the stakeholders and professionals involved with the development of OWFs. Again, this forms the basis of a new COWRIE initiative, which has been awarded after tender. Plans are also in hand to develop mechanisms to share experiences at the

European Union level, currently under development by the European Commission (M. O'Briain, pers. comm.).

It would seem that many national European programmes to develop offshore wind resources are progressing without undertaking full SEAs. This process requires the extensive mapping of resting and feeding waterbird densities throughout national waters at all critical periods of the annual cycle to define areas of differing levels of importance and sensitivity. Such a strategic assessment would aid in zoning extensive sea areas in terms of their suitability for development. It would also avoid the unfortunate discovery of further hitherto unknown concentrations of resting and feeding waterbirds during the EIA process (*cf*. concentrations of Common Scoter in Liverpool Bay and of Red-throated Divers *Gavia stellata* in the Thames). The methods for undertaking such extensive phase 1 survey using aerial survey techniques are now well established at the finer scale for supporting EIAs of individual OWFs. Although the mapping of important migratory routes at sea (incorporating all important altitude data) has not been undertaken to date, new use of extensive large scale weather, military, and air traffic control surveillance radar is recommended in the immediate future. Such techniques could prove useful to define areas, routes and behaviour of migrating birds to effectively describe the most intensively used migration corridors in three-dimensional space to provide large-scale spatial data for migrants. Such layers in an environmental GIS database would provide an invaluable tool for preplanning assessment of the potential nature conservation issues associated with development of offshore wind resources in particular areas.

Given the logistical difficulties of working at sea in a harsh marine environment, we still face many challenges in our ability to determine even the effects of the construction of wind farms at sea on birds. This is especially the case as the proposed sites for turbines move further from shore, where our ability to observe birds from land is considerably lessened. The use of aerial survey to map avian densities, remote techniques such as radar (to track increases in flight distances and avoidance responses) and infra-red thermal imagery (to measure collision rates) has greatly enhanced our ability to measure the local effects by pre- and post-construction data comparisons. We would strongly urge that due consideration is given to the establishment of observational platforms at the sites of offshore wind farms in the future. It is essential, despite cost implications, to gather adequate pre-construction remote sensing data (such as radar and TADS imagery) to support well-founded EIA development.

In addition, we need to invest greater efforts in modelling tools because our greatest challenge remains the conversion of these measurements of local effects into impacts at the population level. This can be achieved by using modelling tools and the skills available to hand at present. However, this process needs to be undertaken quickly and effectively for those species and populations whose flyway corridors and geographical ranges overlap most with the areas scheduled for development. Such modelling is vital to establish the likely fitness consequences for the populations concerned of all the effects of constructing OWFs so we can establish a common currency in terms of population impacts. This is especially important given that environmental impact assessment procedures Directive 85/337/EEC as amended by Directive 97/11/EC require that some assessment is made of the cumulative impacts of multiple wind farms and other developments scattered throughout the flyway of migratory populations. Such approaches are essential in order to offer mechanisms for assessing the cumulative impact of many wind farms and the combined effects of other anthropogenic factors that affect population processes in migratory birds.

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REFERENCES

Alerstam, T. 1990. *Bird Migration*. Cambridge: University Press.

Alerstam, T., Bauer, C.-A. & Roos, G. 1974. Spring migration of Eiders *Somateria mollissima* in southern Scandinavia. *Ibis* **116**: 194–210.

Anonymous. 2002. *Vindkraft Till Havs – En Litteraturstudie Av Påverkan På Djur Och Växter*. Swedish Nature Protection Agency Report no. 5139. Stockholm: Naturvårdsverket Förlag.

Avery, M.L., Springer, P.F. & Cassel, J.F. 1976. The effects of a tall tower on nocturnal bird migration – a portable ceilometer study. *Auk* **93**: 281–291.

Avery, M.L., Springer, P.F. & Dailey, N.S. 1980. *Avian Mortality at Man-Made Structures: an Annotated Bibliography (Revised)*. Washington, DC: United States Fish and Wildlife Service Report. FWS/OBS-80/54.

Band, W., Madders, M. & Whitfield, D.P. 2005. Developing field and analytical methods to assess avian collision risk at wind farms. In De Lucas, M. Janss, G. & Ferrer, M., eds. *Birds and Wind Power*: Barcelona: Lynx Edicions.

Barrios, L. & Rodríguez, A. 2004. Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. *J. Appl. Ecol.* **41**: 72–81.

Bergmann, G. 1974. The spring migration of the Long-tailed Duck and the Common Scoter in western Finland. *Ornis Fennica* **51**: 129–145.

Bergmann, G. & Donner, K.O. 1964. An analysis of the spring migration of the Common Scoter and the Long-tailed Duck in southern Finland. *Acta Zool. Fennica* **105**: 1–59.

Blake, B.F., Tasker, M.L., Jones, P.H., Dixon, T.J., Mitchell, R. & Langslow, D.R. 1984. *Seabird Distribution in the North Sea.* Huntingdon, UK: Nature Conservancy Council.

BMU. 2001. Windenergienutzung auf See: Positionspapier des Bundesministeriums für Umwelt, Naturschutz. und Reaktorsicherheit zur Windenergienutzung im Offshore-Bereich vom 07.06.2001. Berlin: BMU.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.K., Borschers, D.L. & Thomas, L. 2004. *Advanced Distance Sampling*. Oxford: Oxford University Press.

Camphuysen, C.J., Fox, A.D., Leopold, M.F. & Petersen, I.K. 2004. *Towards standardised seabirds at sea census techniques in connection with environmental impact assessments for offshore wind farms in the UK. A Comparison of Ship and Aerial Sampling Methods for Marine Birds and Their Applicability to Offshore Wind Farm Assessments*. Report by Royal Netherlands Institute for Sea Research and the Danish National Environmental Research Institute to COWRIE BAM 02–2002. London: Crown Estate Commissioners. Available at: http://www.thecrownestate.co.uk/1352_bird_survey_ phase1_final_04_05_06.pdf.

Carter, I.C., Williams, J.M., Webb, A. & Tasker, M.L. 1993. *Seabird Concentrations in the North Sea: an Atlas of Vulnerability to Surface Pollutants*. Aberdeen, UK: Joint Nature Conservation Committee.

Chamberlain, D., Freeman, S., Rehfisch, M.M., Fox, A.D. & Desholm, M. 2005. *Appraisal of Scottish Natural Heritage's Wind Farm Collision Model and It's Application*. BTO Research Report 401 to English Nature. Thetford, UK: British Trust for Ornithology.

Chamberlain, D.E., Rehfisch, M.R., Fox, A.D., Desholm, M. & Anthony, S. 2006. The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. In *Wind, Fire and Water: Renewable Energy and Birds. Ibis* **148** (Suppl. 1): 198–202.

Christensen, T.K., Clausager, I. & Petersen, I.K. 2003. *Base-line investigations of birds in relation to an offshore wind farm at Horns Rev., and results from the year of construction*. NERI Report. Rønde: National Environmental Research Institute. Available at: http://www.hornsrev.dk/Miljoeforhold/miljoerapporter/Base-line-Rap%20mar%2003a.pdf.

Clarke, E.D., Spear, L.B., McCracken, M.L., Marques, F.F.C., Borchers, D.L., Buckland, S.T. & Ainley, D.G. 2003. Validating the use of generalized additive models and at-sea surveys to estimate size and temporal trends of seabird populations. *J. Appl. Ecol.* **40**: 278–292.

Danish Wind Energy Association. 2003. Size of wind turbines. Available at: http://windpower.org/en/tour/wtrb/size.htm.

Desholm, M. 2003. *Thermal Animal Detection System (TADS). Development of a method for estimating collision frequency of migrating birds at offshore wind turbines*. NERI report. Rønde: National Environmental Research Institute. Available at: http://www.dmu.dk/1_viden/2_publikationer/3_fagrapporter/rapporter/FR440.pdf.

Desholm, M. 2005. *Preliminary Investigations of Bird-Turbine Collisions at Nysted Offshore Wind farm and Final Quality Control. of Thermal Animal Detection System (TADS); Autumn 2003 and Spring 2004*. NERI Report. Rønde: National Environmental Research Institute.

Desholm, M., Fox, A.D. & Beasley, P. 2005. *Best practice Guidance for the Use of Remote Technologies for Observing Bird Behaviour in Relation to Offshore Wind farms*. Report by the Danish National Environmental Research Institute and QinetiQ to COWRIE REMOTE-05–2004. Crown Estate Commissioners: London. Available at: http://www.thecrownestate.co.uk/1355_remote_techniques_int_rpt_05_03_21.pdf.

Desholm, M., Fox, A.D., Beasley, P. & Kahlert, J. 2006. Remote techniques for counting and estimating the number of bird-wind turbine collisions at sea: a review In *Wind, Fire and Water: Renewable Energy and Birds. Ibis* **148** (Suppl.1): 76–89.

Desholm, M. & Kahlert, J. 2005. Avian collision risk at an offshore wind farm. *Biology Letters* **1**: 296–298.

Dierschke, V. & Daniels, J.-P. 2003. Zur Flughöhe ziehender See-, Küsten-und Greifvögel im Seegebiet um Helgoland. *Corax* **19**: 35–41. (In German with English summary.)

Dirksen, S., Spaans, A.L. & van den Winden, J. 1998. Nocturnal collision risks with wind turbines in tidal and semi-offshore areas. In Ratto, C.F. & Solari, G., eds. *Wind Energy and Landscape. Proceedings of 2nd European and African Conference on Wind Engineering*: pp. 99–108. Rotterdam: Balkema.

Durinck, J., Skov, H., Jensen, F.P. & Pihl, S. 1994. *Important Marine Areas for Wintering Birds in the Baltic Sea*. Copenhagen: Ornis Consult.

Evans, W.R. 2000. Avian mortality at communication towers: background and overview. In *Avian Mortality at Communication Towers* (eds Evans, W.R. & Manville, A.M.). *Proceedings of the Workshop on Avian Mortality at Communication Towers, August 11, 1999*. Ithaca, NY: Cornell University. Available at: http://migratorybirds.fws.gov/issues/towers/agenda.html.

Exo, K.-M., Hüppop, O. & Garthe, S. 2003. Birds and offshore wind farms: a hot topic in marine ecology. *Wader Study Group Bull.* **100**: 50–53.

Fox, A.D. 2003. Diet and habitat use of scoters *Melanitta* in the Western Palearctic – a brief overview. *Wildfowl* **54**: 163–182.

Foy, R.W. 1976. Recoveries and foreign retraps of birds banded at Island Beach NJ. *J. Field Ornithol* **47**: 214–230.

Garthe, S. & Hüppop, O. 2004. Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. *J. Appl. Ecol.* **41**: 724–734.

Gauthreaux, S.A. 1970. Weather radar quantification of bird migration. *Bioscience* **20**: 17–20.

Gauthreaux, S.A. & Belser, C.G. 2000. The behavioral responses of migrating birds to different lighting systems on tall towers. In: *Avian Mortality at Communication Towers* (eds Evans, W.R. & Manville, A.M.). *Proceedings of the Workshop on Avian Mortality at Communication Towers, August 11, 1999*. Ithaca, NY: Cornell University.

Hedley, S.L., Buckland, S.T. & Borchers, D.L. 1999. Spatial modelling from line transect data. *J. Cetacean Res. Manage* **1**: 255–264.

Hötker, H., Thomsen, K. & Köster, H. 2004. *Auswirkungen Regenerativer Energiegewinnung Auf die Biologische Veilfalt an Beispiel der Vögel und der Fledermäuser – Fakten, Wissenslücken, Anforderungen an die Forschung, Ornithologische Kriterien Zum Ausbau Von Regenerativen Energiegewinnungsformen*. Report from NABU to Bundesamt für Naturschutz. Available at: http://www.wind-energie.de/informationen/voegel-und-wea/studie-nabu-VoegelRegEnergien.pdf.

Hüppop, O., Exo, K.-M. & Garthe, S. 2002. Empfehlungen für projektbezogene Untersuchungen möglicher bau- und betriebsbedingter Auswirkungen von Offshore-Windenergieanlagen auf Vögel. *Ber. Vogelschutz* **39**: 77–94.

ICES. 2003. Report of the Working Group on Seabird Ecology. Document no. CM. 2003/C: 03. ICES, Copenhagen: Denmark.

Jensen, A.C., Collins, K.J., Lockwood, A.P.M., Mallinson, J.J. & Turnpenny, W.H. 1994. Colonisation and fishery potential of a coal-ash artificial reef, Poole Bay, United Kingdom. *Bull. Mar. Sci.* **55**: 1263–1276.

Joensen, A.H. 1973. Moult migration and wing-feather moult of seaducks in Denmark. *Danish Rev. Game Biol.* **8** (4): 1–42.

Joensen, A.H. 1974. Waterfowl populations in Denmark 1965–73. A survey of non-breeding populations of ducks, swans and coot and their shooting utilisation. *Danish Rev. Game Biol.* **9** (1): 1–206.

Jones, J. & Francis, C.M. 2003. The effects of light characteristics on avian mortality at lighthouses. *J. Avian Biol.* **34**: 328–333.

Kahlert, J., Petersen, I.K., Fox, A.D., Desholm, M. & Clausager, I. 2004. *Investigations of Birds During Construction and Operation of Nysted Offshore Wind Farm at Rødsand. Annual Status Report 2003*. National Environmental Research Institute Report Commissioned by Energi E2 A/S. Rønde: NERI. Available at: http://uk.nystedhavmoellepark.dk/upload/pdf/Birds2003.pdf.

Kaiser, M.J., Galanidi, M., Elliott, A.J., Showler, D.A., Caldow, R.W.G. & Sutherland, W.J. 2006. Disturbance displacement of Common Scoters in relation to wind farms. In *Wind, Fire and Water: Renewable Energy and Birds. Ibis* **148** (Suppl. 1): 110–128.

Kerlinger, P. 2000. *Avian Mortality at Communication Towers: a Review of Recent Literature, Research and Methodology*. Cape. May, NJ: Curry & Kerlinger, L.L.C. Available at: http://migratorybirds.fws.gov/issues/towers/review.pdf.

Koistinen, J. 2000. Bird migration patterns on weather radars. *Phys. Chem. Earth (B)* **25**: 1185–1194.

Langston, R.H.W. & Pullan, J.D. 2003. Wind farms and Birds: An analysis of the effects of wind farms on birds, and. *Guidance on Environmental Assessment Criteria and Site Selection Issues*. Report to the Standing Committee on the Convention on the Conservation of Wildlife and Natural Habitats. Strasbourg: Council of Europe.

Larsson, A.K. 1994. The environmental impact from an offshore plant. *Wind Engineering* **18**: 213–218.

Laursen, K., Pihl, S., Durinck, J., Hansen, M., Skov, H., Frikke, J. & Danielsen, F. 1997. Numbers and Distribution of Waterbirds in Denmark 1987–89. *Danish Rev. Game Biol.* **15** (1): 1–181.

Manville, A.M. 2001. *The ABCs of avoiding bird collisions at communications towers: the next steps. Proceedings of the Avian Interactions Workshop, December 2, 1999, Charleston SC Electric*. Concord, California: EPRI Technical Report.

Mitchell, P.I., Newton, S.F., Ratcliffe, N. & Dunn, T.E. 2004. *Seabird Populations of Britain and Ireland*. London: Poyser.

Noer, H. & Christensen, T.K. 1997. *Monitoring Breeding Eiders at Saltholm, 1996*. NERI report commissioned by Øresundskonsortiet. Rønde: National Environmental Research Institute, Ministry of Environment and Energy.

Noer, H., Christensen, T.K., Clausager, I. & Petersen, I.K. 2000. *Effects on Birds of an Offshore Wind Park at Horns Rev.: Environmental Impact Assessment*. Commissioned by Elsamprojekt A/S 2000. Rønde: National Environmental Research Institute. Available at: http://www.hornsrev.dk/miljoeforhold/miljoerapporter/Baggrundsrapport_18.pdf.

Noer, H., Fox, A.D., Clausen, P., Petersen, B.M., Kahlert, J. & Christensen, T.K. 1996. *Effects of the construction of a fixed link across Øresund on waterfowl populations: Environmental impact assessment*. NERI report. Rønde: National Environmental Research Institute.

Orloff, S. & Flannery, A. 1992. *Wind Turbine Effects on Avian Activity, Habitat Use, and Mortality in Altamont Pass and Solano County Wind Resource Areas (1989–91). Final Report*. Planning Departments of Alameda, Contra Costa and Solano Counties and the California Energy Commission. Tiburón, CA: BioSystems Analysis Inc.

Orloff, S. & Flannery, A. 1996. *A Continued Examination of Avian Mortality in the Altamont Pass Wind Resource Area*. Final Report to the California Energy Commission. Tiburon, CA: BioSystems Analysis.

Pennycuick, C.J. 1989. *Bird Flight Performance. A Practical Calculation Manual*. Oxford: Oxford University Press.

Percival, S. 2005. Birds and wind farms: what are the real issues? *Br. Birds* **98**: 194–204.

Petersen, I.K., Clausager, I. & Christensen, T.K. 2004. *Bird Numbers and Distribution in the Horns Rev Offshore Wind Farm Area*. NERI report. Rønde: National Environmental Research Institute. Available at: http://www.hornsrev.dk/Miljoeforhold/miljoerapporter/Bird_numbers_2003%20status_report.pdf.

Pettersson, J. & Stalin, T. 2003. *Influence of Offshore Windmills on Migration Birds in Southeast Coast of Sweden*. Report to GE Wind Energy.

Pettifor, R.A., Caldow, R.W.G., Rowcliffe, J.M., Goss-Custard, J.D., Black, J.M., Hodder, K.H., Houston, A.I., Lang, A. & Webb, J. 2000. Spatially Explicit, Individual-based, Behavioural Models of the Annual Cycle of Two Migratory Goose Populations. *J. Appl. Ecol.* **37** (S1): 103–135.

Richardson, W.J. 1978. Reorientation of nocturnal landbird migrants over the Atlantic Ocean near Nova Scotia in autumn. *Auk* **95**: 717–732.

Rose, P.M. & Scott, D.A. 1997. *Waterfowl Population Estimates*, 2nd edn. Wetlands International Publication. 44. Wageningen, The Netherlands.

Rose, P.M. & Scott, D.A. 2002. *Waterbird Population Estimates*, 3rd edn. Wetlands International Global Series no. 12. Wageningen, The Netherlands.

Tasker, M.L., Webb, A., Hall, A.J., Pienkowski, M.W. & Langslow, D.R. 1987. *Seabirds in the North Sea*. Peterborough: Nature Conservancy Council.

Thelander, C.G. & Rugge, L. 2001. *Examining bird risk behaviors and fatalities at the Altamont Wind Resource Area: a second year's progress report*, pp. 5–14. In: Proceedings of the National Avian-Wind Power Planning Meeting, I.V. Carmel. Calif., May 16–17, 2000. Prepared for the Avian Subcommittee of the National Wind Coordinating Committee, by RESOLVE, Inc. Washington, D.C.

Tingley, M.W. 2003. *Effects of Offshore Wind farms on Birds*. Published B.A. Thesis. Cambridge, MA: Harvard University. Available at: http://safewind.info/pdf/TingleyThesis2003.pdf.

Tucker, V.A. 1996. A mathematical model of bird collisions with wind turbine rotors. *J. Solar Energy Engineering* **118**: 253–262.

Tulp, I., Schekkerman, H., Larsen, J.K., van der Winden, J., van de Haterd, R.J.W., van Horssen, P., Dirksen, S. & Spaans, A.J. 1999. *Nocturnal Flight Activity of Sea Ducks Near the Wind farm Tunø Knob in the Kattegat*. Report no. 99.30. Wageningen, The Netherlands: IBN-DLO.

West, A.D. & Caldow, R.W.G. 2006. The development and use of individuals-based models to predict the effects of habitat loss and disturbance on waders and waterfowl. In *Wind, Fire and Water: Renewable Energy and Birds*. *Ibis* **148** (Suppl.1): 158–168.