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# Mitigation Measures for Wildlife in Wind Energy Development, Consolidating the State of Knowledge — Part 1: Planning and Siting, Construction

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During this rapid development of wind energy aiming to combat climate change worldwide, there is greater need to avoid, reduce, and compensate for impacts on wildlife: Through the effective use of mitigation, wind energy can continue to expand while reducing impacts. This is a first broad step into discussing and understanding mitigation strategies collectively, identifying the current state of knowledge and be a beneficial resource for practitioners and conservationists. We review the current state of published knowledge, both land-based and offshore, with a focus on wind energy–wildlife mitigation measures. We state measures and highlight their objective and discuss at which project stage it is most effective (e.g. planning, construction, and operation). Thereafter, we discuss key findings within current wind energy mitigation research, needing improved understanding into the efficacy of wildlife mitigation as well as research into the cost aspects of mitigation implementation. This paper is divided into two articles; Part 1 focuses on mitigation measures during planning, siting, and construction, while Part 2 focuses on measures during operation and decommissioning.

*Keywords*: Wind energy; wildlife; efficacy; impact mitigation; onshore; offshore.

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# Introduction

The concern of global climate change has benefitted wind energy as a source of electricity generation which produces minimal carbon emissions or air pollution, does not require water withdrawal and consumption, and does not cause devastating effects on wildlife and their habitats (AWWI, 2015). However, this 'green energy' is not completely green as there are some adverse effects on wildlife like displacement, habitat fragmentation, collision, and direct mortality (Gartman *et al.*, 2014). There are basic principles behind mitigation (Köppel *et al.*, 2014) that avoid, reduce, and compensate for impacts from wind energy development. These principles lay the groundwork for measures to be addressed in the making of environmental impact assessments and biological assessments; they can be applied at national or regional scales (e.g. macro-siting requirements) while others can be applied at the local scale where measures are species- or situation-specific (e.g. deterrence measures) (Mascarenhas *et al.*, 2015). While research has focused more on flight behaviour, disturbance, and impacts than on methods to reduce displacement and collision mortality, there has been a recent shift in evaluating mitigation techniques and their effectiveness to reducing these impacts. This paper provides an opportunity to comprehensively understand where current practice and research lie for mitigation measures in wind energy development, aiming to see where further research is needed, and to help answer the question, 'What's next?' in this field. This paper is to help not only developers, planners, and biologists grasp a better understanding of the use of mitigation in wind energy but also to help researchers pinpoint where research is further needed.

It is important to collectively show what consolidated and agreed upon knowledge exists (cf. Schuster *et al.*, 2015) and where further research is needed in understanding the efficacy of mitigation measures. This is our aim for both land-based and offshore wind facilities and for the most relevant species groups, including local and migratory bats, migratory and land-based birds, raptors, seabirds, as well as non-volant (e.g. non-flying) species such as marine mammals, terrestrial mammals, reptiles, and amphibians. While enormous efforts have been made offshore for mitigation (e.g. sound reduction during pile-driving), offshore collisions are poorly understood, thus challenging which mitigation measures are most feasible and effective (Hill, 2015).

Recent publications have given beneficial comprehensive lists of either impacts on wildlife or mitigation for particular species groups (cf. Schuster *et al.*, 2015; May *et al.*, 2015; Mascarenhas *et al.*, 2015; Vaissière *et al.*, 2014; Marques *et al.*, 2014; Lovich and Ennen, 2013). However, this paper solely concentrates on a mitigation measure's effectiveness based on empirical evidence (or lack thereof), and the remaining gaps for all species land-based and offshore. We provide a synoptical table showing mitigation categories (Fig. 1) and classify their associated research on relevant species groups. Research was conducted by the Environmental Assessment and Planning Research Group at the Berlin Institute of Technology (TU Berlin) and funded by the German Federal Ministry (BMWi) as part of the 'Impacts of Wind Energy Development on Wildlife — An International Synopsis' project.

It is also essential to know that mitigation measures are case-by-case sensitive as they are species- and site-specific, thus monitoring before–after control-impact (BACI) of measures and basing decisions on research using the BACI monitoring design (Stewart-Oaten *et al.*, 1986) is highly recommended to ensure the best efficacy to reduce impacts to wildlife. There have been beneficial meeting proceedings, technical reports, and guidance from e.g. the US National Wind Coordinating Committee 'Toolbox' (NWCC Mitigation Subgroup and Rechtenwald, 2007), European Commission (Sundseth, 2011), United Kingdom's COWRIE Ltd.'s Offshore Reports, and Germany's Fachagentur Windenergie an Land (TU Berlin *et al.*, 2015) all aiming to implement mitigation measures more efficiently.

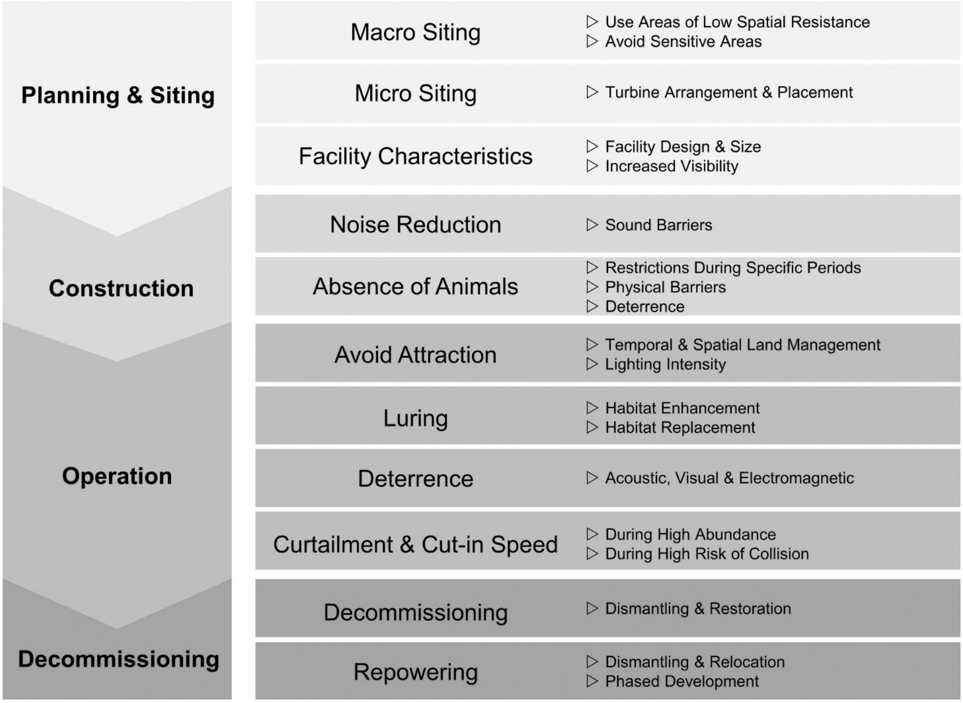
## Methodology

Through a qualitative review process, we analysed international research involving mitigation measures for wildlife in the wind energy field. The overview of all mitigation measures is based on over 250 documents ranging from scientific (106 peer-reviewed journal articles and books) to grey literature (reports, articles, websites, and guidances) and to review contributions of recent international conferences such as: Conference on Wind Energy and Wildlife Impacts (CWW2011, Trondheim, Norway); Conference on Wind Power and Environmental Impacts (CWE2013, Stockholm, Sweden); WinMon.BE Conference: Environmental Impact of Offshore Wind Farms (2013, Brussels, Belgium); StUKplus Conference: Five Years of Ecological Research at *Alpha Ventus* (2013, Berlin, Germany); and Conference on Wind Energy and Wildlife Impacts (CWW2015, Berlin, Germany). In addition, as Germany is a major wind developer on a global scale, we include German references in the paper to help developers, wildlife experts, and researchers further understand current German research practices that would otherwise be difficult to access.

This paper covers publications up to late-2015. We used Google Scholar, Web of Science, Science Direct, and TETHYS (an online knowledge management platform for relevant publications, http://tethys.pnnl.gov) and in a broad-termed approach due to scarce empirical research pertaining to the efficacy of mitigation measures for all wildlife in wind energy, both land-based and offshore. As seen in

Appendix A, our research originally focused only on peer-reviewed articles and published books. However, we extended our search to include reports and grey literature as significant gaps were seen in peer-reviewed literature but were therefore substantiated through grey literature (e.g. land management and visibility). As this synoptical paper provides the current state of the overall knowledge on mitigation measures, this inclusion of grey literature is necessary.

Based on the reviewed literature, we categorised eleven mitigation types with their particular measures that can be seen in Fig. 1. Our focus lies mainly within avoidance and minimisation measures used in wind energy development. This paper (Part 1) focuses on planning, siting, and construction mitigation measures, and its sister article (Part 2) focuses operational and decommissioning mitigation measures. We exclude the discussion of in-lieu fees or any monetary reparations as well as excluding the discussion of policies allowing the risk of species collision acceptable under certain conditions (e.g. US Incidental Take Permits) and compensatory mitigation. Lastly, while it is essential to note the importance of monitoring as mitigation is based heavily on the research collected during monitoring periods, it will not be covered in this paper.



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|---|---|---|
| **Planning & Siting** | Macro Siting | ▷ Use Areas of Low Spatial Resistance<br>▷ Avoid Sensitive Areas |
| | Micro Siting | ▷ Turbine Arrangement & Placement |
| | Facility Characteristics | ▷ Facility Design & Size<br>▷ Increased Visibility |
| **Construction** | Noise Reduction | ▷ Sound Barriers |
| | Absence of Animals | ▷ Restrictions During Specific Periods<br>▷ Physical Barriers<br>▷ Deterrence |
| **Operation** | Avoid Attraction | ▷ Temporal & Spatial Land Management<br>▷ Lighting Intensity |
| | Luring | ▷ Habitat Enhancement<br>▷ Habitat Replacement |
| | Deterrence | ▷ Acoustic, Visual & Electromagnetic |
| | Curtailment & Cut-in Speed | ▷ During High Abundance<br>▷ During High Risk of Collision |
| **Decommissioning** | Decommissioning | ▷ Dismantling & Restoration |
| | Repowering | ▷ Dismantling & Relocation<br>▷ Phased Development |

Fig. 1. Mitigation measure classification.

As stated previously, Appendix A shows the peer-reviewed state of research based on the source, species group, and discussion type. Once a source has been categorised under the appropriate mitigation measure and species type, it then falls within a ‘recommendation’, ‘observation’, or ‘investigation’ category. For instance, if a source investigates impacts from wind energy on a particular species or species group and suggests a mitigation measure in order to avoid or reduce the impact researched, the source would fall under ‘recommendation.’ The source’s research does not observe the mitigation measure nor provide empirical evidence as to the efficacy of the measure. A source is more significant as an ‘observation’ when the research monitors or literally observes wildlife effects based on the implemented mitigation measure. Lastly, a source categorised as ‘investigation’ is most significant in this paper as research directly focuses on a mitigation measure, providing empirical and/or even statistical evidence as to the efficacy of the measure and possibilities for improvement. While we provide information about the significance of the sources, we cannot take a step further explicitly listing which measures are and are not effective as the number of significant sources is insufficient and effectiveness is always case-specific.

Sections 3–11 provide further detailed discussion of each measure as shown in Fig. 1; first, we provide what is the objective of the measure and its submeasures, then we provide current research based on the species groups.

## Macro-Siting

Mitigation should first begin in the planning phase when selecting a location for a wind facility, otherwise known as macro-siting. For developers having to undergo an Environmental Assessment (EA), Environmental Impact Assessment (EIA), or Strategic Environmental Assessment (SEA), this stage primarily occurs in the scoping phase at the beginning of a project timeline, providing a framework for the entirety of the project (Turvey, 2015; Geißler, 2013). During this stage, pre-construction mitigation options are available in order to avoid high-risk areas (Arnett, 2015). Wind facilities should to be placed in locations of low spatial resistance, planned away from conservation areas, and strategically positioned based on the topography of the area or specific landscape elements that constitute high habitat quality for wildlife in order to decrease negative impacts (Ledec *et al.*, 2011; TU Berlin *et al.*, 2015; Drewitt and Langston, 2008). Macro-siting is effective, for instance, for migratory birds who move from breeding to non-breeding grounds and are dependent on weather patterns with topographical features (e.g. coastlines, straits, mountain ranges, and passes) being their ‘roadmaps’; thus, it is important to avoid high-concentration areas where spatial and temporal distribution of these species is known (Liechti *et al.*, 2013).

## Use areas of low spatial resistance

Areas of low spatial resistance are environments which allow structures, e.g. wind turbines, to be built as they would not present restrictions of movement or day-to-day activities to sensitive species. When surveying for these areas, broad geographical planning for a wind energy project can be most effective in avoiding impacts on nature, e.g. displacement, and to reduce future risk of problems during later stages of the project (Marques *et al.*, 2014). For *birds and bats*, Johnson *et al.* (2007) recommends selecting sites away from major bird feeding, roosting, and resting areas, as well as wetlands, rookeries, and low-level flight paths. Focus should also be on micro-habitats for birds such as swales, ridge-tops, canyons, and rims (Johnson *et al.*, 2007). Obermeyer *et al.* (2011) recommends siting wind turbines in agricultural areas as they represent low-quality habitats which can be difficult supporting at-risk species and other wildlife or natural plants. This is broadly recommended by the American Wind Energy Association to use lower-quality habitats such as active agriculture and row crop lands, managed pastures, brownfield or industrial sites, fragmented landscapes, and disturbed rangelands (Giovanello and Kaplan, 2008). For *bats*, Rodrigues *et al.* (2014) further state forests, wetland, and hedgerow networks, habitat features such as individual trees, waterbodies, and water courses need to be taken into account, as well as large river valleys for migratory bats as populations are larger in these areas. Another recommendation by Northrup and Wittemyer (2013) for *non-migratory bats* is to avoid siting near known bat colonies and their surrounding habitats that are used for foraging and nesting. This is also applicable to *breeding and resting birds* as foraging, nesting, and soaring areas (i.e. their spatial concurrence as observed by Bright *et al.* (2008)) need to be taken into account.

It is recommended by EUROBATS to not install turbines in forested areas or within 200 m of these areas (Rodrigues *et al.*, 2014), but as the erection of turbines in forested areas in European countries like Germany continues, research is needed. Empirical research in this topic is minimal, but recommendations from these studies have proven beneficial and are used in national guidelines such as US Fish and Wildlife Service (USFWS) (2012) 'Land-Based Wind Energy Guidelines', Scotland's 'Scottish National Heritage Spatial Planning for Onshore Wind Turbines — Natural Heritage Considerations' Turvey (2015), or in regional guidelines such as in Germany, 'Guidelines for species and habitat protection in the planning and approval of wind turbines in North Rhine-Westphalia' (translated) (MKULNV and LANUV, 2013).

Research investigating methods on how to properly site locations based on wildlife is minimal and there is even less on the success of macro-siting measures to avoid wildlife displacement. Understanding how species are adapting to facility buffers is needed, as only one investigation by Madsen and Boertmann (2008) concluded that pink-footed geese (*Anser brachyrhynchus*) habituate to small-scale wind farms, as displacement distances diminished and began foraging within the wind farm. Tellería (2009) studied migratory wood pigeons (*Columba palumbus*) migrating through Spain to depict their movements and see if their flow of movement crossed various concentrations of wind facilities in the country. He recorded that a majority of pigeons (50%) was concentrated in a 50 km wide central belt with few wind facilities but the adjacent belt with considerable number of wind facilities recorded 30% of the ringed pigeons (Tellería, 2009). Conclusively, these two 100 km bands contained 80% of these migratory birds, giving better claim that all potential construction sites for wind energy need to be more effectively considered, not only at local levels but at national, and even international levels in order to prevent cumulative effects of wind farms on migratory birds (Tellería, 2009).

For *offshore wind farm* (*OWF*) *development*, locating areas of importance offshore can be difficult as the distribution of concentrations, variability in numbers, and times of occurrence vary for multiple species. In addition, marine species are highly mobile and have wide distributions, such as the harbour porpoise (*Phocoena phocoena*) in the North Sea. Thus, pre-construction habitat use in European seas has been researched for seabirds (Drewitt and Langston, 2006; Bellebaum *et al.*, 2010; Loring *et al.*, 2014), migrating birds (Loring *et al.*, 2014; Bellebaum *et al.*, 2010), harbour porpoises (Scheidat *et al.*, 2012), and harbour seals (*Phoca vitulina*) (Brasseur *et al.*, 2012) in order to provide distribution information for siting OWF. Europe already has some legislative constraints in terms of siting including: Minimum distances from areas of environmental interest; residential and productive activities (i.e. tourism and farming); infrastructure networks (i.e. voltage lines); ports; and already established nature reserve sites (i.e. NATURA 2000 areas) (Spiropoulou *et al.*, 2015; Commission of the European Communities, 2008). Yet OWFs are not generally excluded from protected areas and marine activities such as fisheries, shipping, and military uses, which can cumulatively cause large-scale disturbance and habitat loss for sensitive species, such as the common loon (Kubetzki *et al.*, 2011; Aumüller *et al.*, 2013). Marine spatial planning varies depending on the geographical location and country as well as the need for other human activities (e.g. fishing and tidal energy). Conclusively, investigative research into offshore wind development mitigation is difficult because there is a lack of proper technology and planning to monitor effects of mitigation. While it is recommended by Hill (2015) and Aumüller *et al.* (2013) to establish large migration corridors between the wind facilities for migrating waterfowl and passerines, or just a minimum distance between OWFs for all migrating birds, we lack research results into migration corridor size. Kubetzki *et al.* (2011) recommend avoiding coastal areas and straits, as flight intensity of migrating birds is very high. Identifying sensible areas for marine spatial planning underwater is recently being done through benthic monitoring (Dannheim *et al.*, 2015), helping developers, stakeholders, and authorities better establish locations for future OWF.

Macro-siting research for *non-volant onshore species* is nominal. Through an observation by Lovich *et al.* (2011) and Lovich and Ennen (2011), they explain how site selection for renewable energy is a critical factor in minimising negative effects on the US Mojave desert tortoise (*Gopherus agassizii*). Skarin *et al.* (2013) heed caution to wind facility planning for reindeer (*Rangifer tarandus*) as their habitat is already very fragmented and wind facilities could influence habitat use and range use, movement corridors, and their surrounding areas. However, it has been noted of this species to acclimatise to wind turbines (Colman *et al.*, 2012; May *et al.*, 2012).

## Avoid sensitive areas

Macro-siting also entails avoiding conservation areas, nature reserves, national parks, and in general, federally protected areas (Manville II, 2005; Drewitt and Langston, 2006). These are areas of high species or animal abundance, or where threatened species or those likely prone to collision are present (Marques *et al.*, 2014). Drewitt and Langston (2006) further this by ensuring key areas of conservation importance and sensitivity are avoided. Buffer zones are recommended (Arnett and Baerwald, 2013) to ensure sufficient distance between these conservation areas and the wind facility. Norway's Smøla wind facility has provided beneficial impact studies for research demonstrating negative impacts on the breeding success of bird species (namely white-tailed eagles (*Haliaeetus albicilla*)) and relay the importance to identify important breeding areas during pre-construction (Dahl *et al.*, 2015). Avoidance of these areas in macro-siting has been considered 'common knowledge' for land and wind energy developers and while no investigative research has been specifically done regarding this topic, it is necessary in the planning stages.

Strategic planning at local or regional levels should be based on animal populations, their preferred habitats and flight paths, and sensitive topographic locations (Marques *et al.*, 2014). Based on International and EU legislation, *offshore* spatial marine planning can be established in all EU coastal nations and can be used to pinpoint specific locations of areas of low spatial resistance for OWF development. This can be seen in Scotland, where they have developed a Sectoral Marine Plan in which six offshore wind energy sites could be leased upon government agreement (Davies and Pratt, 2014).

For bird species that use landscape elements for migration and hunting or foraging grounds, it is often recommended to avoid siting wind farms in sensitive areas. One approach of identifying those areas can be studies on their home range via visual observations or telemetric studies. According to Mammen *et al.* (2014), the larger the distance between nesting sites and wind farms and consequently the overlap of home range and wind farm, the smaller the collision risk. For the red kite (*Milvus milvus*), they specify and recommend a buffer zone of 1250 m around refuges for example. Other authors (Pfeiffer and Meyburg, 2015) point out the correlation between home range size and food availability (being an indicator for habitat quality), making it difficult to generalise such recommendations. Grajetzky and Nehls (2014) investigated displacement of Montagu's harrier (*Circus pygargus*), recommending that as these species do not avoid wind farms, it is important to take into account their breeding sites as they fly within the 'hazard zone' of the rotor swept area near their nesting sites and to establish distances along their flight corridors to food areas. They also state a 300 m distance around turbines be kept free of field crops attractive as breeding habitats, especially in intensively agriculture landscapes with few structures (Grajetzky and Nehls, 2014). For the Australia crane (*Grus rubicunda*), Hill *et al.* (2011) generally recommend adopting turbine-free buffers around essential breeding and flocking habitats. Facilities, or more specifically wind turbines, should be in areas unattractive for raptors, siting away from cliff and rim edges, dips and along ridges, and small mammal colonies (Manville II, 2005). Risk is reduced when placing turbines away from ridge edges (as investigated for the bearded vulture [as investigated for the regionally Endangered bearded vulture *Grypaetus barbatus meridionalis*] and the globally vulnerable southern African endemic cape vulture (*Gyps coprotheres*) in South Africa and Lesotho) not only for raptors (Johnson *et al.*, 2007), but for bats as well (Rodrigues *et al.*, 2006) as these ridges create an updraft many species use when flying. Similar observation in Spain was done by de Lucas *et al.* (2008) for raptors and the griffon vulture (*Gyps fulvus*) as bird collisions can be dependent on elevation above sea level and to avoid placing turbines on tops of hills with gentle slopes.

For *bats*, they also move along linear structures such as rivers and river valleys (Furmankiewicz and Kucharska, 2009) as well as forest edges and hedges (as observed by Kelm *et al.* (2014)). Other places include older trees with cavities currently being preserved (Peste *et al.*, 2015), or nurseries, winter quarters, and sleeping places (Arnett and Baerwald, 2013; Minderman *et al.*, 2012). Rodrigues *et al.* (2006, 2014) further complements recommendations to avoid narrow migration routes as well as concentrated feeding, breeding, and roosting areas. Johnson *et al.* (2004) investigated that distances to trees and forests may have effects on fatalities as bat activity decreases with distance from forests.

As stated previously, while little investigative or observational research in the topic has been published thus far, the number of recommendations has been influential in wind energy guidance and even legal spatial planning documents. The USFWS (2012) recommends that new wind energy development be sited outside of an 8 km buffer zone around active greater prairie chicken (*Tympanuchus cupido*) leks (i.e. community sites). Recent investigation by Winder *et al.* (2015) confirm that both male and female greater prairie chickens have negative behavioural responses to wind energy development within 8 km of turbines. Similar impacts are said for the lesser prairie chicken (*Tympanuchus pallidicinctus*), but lack clear recommendation in avoiding their already significantly-reduced habitat; Pruett *et al.* (2009) recommend the need to conserve and connect their habitat ranges and to provide legal guidance in wind turbine placement. Similar is recommended for sage grouse (*Centrocercus urophasianus*) by (LeBeau *et al.*, 2014) to place turbines at least 5 km from nesting and brood-rearing habitats in order to minimise wind development impacts. In UK, through Natural England's interim guidance, it is advised that blade tips of turbines are to be at least 50 m from the highest part of hedges, tree-lines, or woodlands in the vicinity or any habitat features or structures suitable for roosting (Mitchell-Jones and Carlin, 2014). These measures recommended from official guidances can be beneficial for developers to establish measureable distances so as to minimise additional permits or licenses, or be required to carry out additional working practices or necessary precautions as to avoid breaking any laws or regulations (Mitchell-Jones, 2004).

The use of sensitivity maps has proven a beneficial tool in informing decision-makers in the planning stages about the potential conflicts with migratory species (Liechti *et al.*, 2013). Switzerland (Aschwanden *et al.*, 2005, 2013) and Scotland (Bright *et al.*, 2008) have invested in this concept onshore for identifying areas in their countries where wind facilities may pose a medium to high risk to important bird populations. Local authorities and wind planners can use up-to-date information on endangered or threatened species and be able to pinpoint exact locations where developing a wind facility is most feasible (The RSPB, 2006). *Offshore*, coastal and marine habitats are highly dynamic but sensitive areas can be identified as well. Garthe and Hüppop (2004) established a wind farm sensitivity index which calculates different species' attributes such as flight activity, population size, and flexibility in habitat use. This index shows for the Southeastern North Sea that coastal waters are of greater vulnerability than waters further offshore throughout the whole year. Bradbury *et al.* (2014) established a Seabird Mapping and Sensitivity Tool (SeaMaST) in English territorial waters, and a similar map of avian hotspots was developed by Zipkin *et al.* (2015) for the US Atlantic Ocean combining statistical data on species and seasonal distribution.

Another integrative approach is the use of local zoning maps for particular species' local population, where an area is categorised into zones of high, medium, low, or no risk and can guide developers in proper macro-siting (TU Berlin *et al.*, 2015). The use of local land-use plans is growing in Germany and has provided beneficial insight into more efficient planning (Geißler, 2013). Furthermore, an action plan for a small capercaillie (*Tetrao urogallus*) population in the Black Forest in Germany was created aiming to sustain the population and guaranteeing genetic exchange by establishing wind energy zoning areas based on the population's size, breeding, and nursing areas. This tool minimises unnecessary research and time for wind energy developers and can be adaptable for any species or region (FVABW, 2013).

## Micro-Siting

Additional to the geographical and topographical facility location, choosing the turbine layout and design of the facility is just as crucial. To avoid turbine collisions, the best recommendations are to avoid flight corridors (Hüppop *et al.*, 2006), place turbines parallel (not perpendicular) to flight direction (Drewitt and Langston, 2006), and arrange turbines in clusters or rows (Smallwood and Thelander, 2005; Larsen and Madsen, 2000). The spatial arrangement of turbines within the facility is otherwise known as micro-siting. Similar to macro-siting, micro-siting research recommendations have been based on observations but few based on investigative research.

For *birds*, it is important to understand flight corridors and establish spatial buffers away from these areas, or provide corridors between the clusters of turbines aligned with main flight trajectories for species to fly through (Drewitt and Langston, 2006). Drewitt and Langston (2006), Hüppop *et al.* (2006), and Smallwood and Thelander (2004) further recommend grouping turbines to avoid alignment perpendicular to main flight paths or known bird movements, and Johnson *et al.* (2007) recommend 'stringing' turbines with known avian flight paths without inputting any breaks or gaps which could tempt birds to fly through the facility instead of over the string of turbines.

For *bats*, an investigation was done in Alberta, Canada by Baerwald and Barclay (2011) in better understanding weather variables and turbine location on the activity of hoary (*Lasiurus cinereus*) and silver-haired bats (*Lasionycteris* *noctivagans*). In terms of spatial arrangement, bat fatalities did not vary with the turbine position in the row but did vary within turbine position within the wind facility. They noted higher mortality in the northern part of the facility than the southern part while fatalities on the east and west were the same (Baerwald and Barclay, 2011), thus concluding the need for land developers to gain a full understanding of flight directions of species to better place turbines within the facility.

Drewitt and Langston (2006, 2008) advise to site turbines in either clusters or rows to reduce the development footprint on wildlife and the landscape. Dai *et al.* (2015) state for birds and bats that it is easier to create a balanced, simple, and consistent wind facility using the fewest number of turbines and establishing a simple layout such as a double link, triangle, or grid for regular landscapes (i.e. open or level space). This 'regular layout' recommendation by Dai *et al.* (2015) of a facility is beneficial in increasing the busy appearance of the wind facility and may discourage birds from flying into this airspace. Particularly for *raptors*, as observed by Smallwood and Thelander (2004, 2005), they avoid operating turbines as well as densely packed turbine fields. Krone *et al.* (2014) recommends a compact arrangement of the turbines instead of widely scattered turbines to reduce fatality numbers. Yet as May *et al.* (2015) states, clustering remains unclear as even though the turbines will be tightly together taking up less topographical area, the area itself becomes completely unaccessible as the reduced openness would limit any sort of movement.

*Offshore*, research into effective placement of turbines within a facility (e.g. rows, clusters, etc.) lacks. BioConsult and ARSU 2010 researched bird migration on the Island of Fehmarn, Germany, finding individual birds and small flocks of birds fly through permeable wind facilities, i.e. when distances between turbines is large enough. As offshore migrating paths are often used by large flocks, which tend to completely avoid wind facilities, the alignment of turbines should take these flight paths into account. Offshore modelling by Masden *et al.* (2012) for the common eider (*Somateria mollissima*) recommends arranging turbines in clusters as these birds were more likely to avoid a group of turbines than a single row of turbines. It is recommended by Hill (2015) to restrict the number of offshore buildings so as to minimise impacts, but no investigations or recommendations currently provide effective micro-siting measures.

## Facility Characteristics

When designing the wind facility, there are a number of technical factors to take into account such as the design (i.e. tower type), size (i.e. vertical extent and height of the rotor swept area), and visibility (i.e. lighting and tower colour). These factors are dependent upon where the facility is to be developed as weather patterns, wildlife movement, and facility size determine which turbine model and design are most appropriate as well as based on country and industry targets.

## Facility design and size

Self-supporting tubular towers (Manville II, 2005; Johnson *et al.*, 2007) have become standard in wind energy development as the use of lattice towers can allow *birds* to perch and nest, increasing blade collision risk. It is recommended to adjust the turbine tower height 'where feasible' (Manville II, 2005) as the rotor swept area is the greatest risk to birds and bats. Through investigation by Grajetzky and Nehls (2014), turbine height influences collisions risk. For some birds, taller towers in combination with certain turbine types are recommended as their flight trajectories can be below the rotor swept zone. An investigation done by Krijgsveld *et al.* (2009) studied the collision rate of birds with 78 m height turbines to old-generation turbines (67 m) in the Netherlands, concluding the number of individuals were similar but the overall risk was three-fold lower in terms of comparing the large rotor surface and higher altitude range. Birds are more able to fly below the rotor swept zone and, with turbines being more spread out due to their size, are also able to pass safer between the turbines (Krijgsveld *et al.*, 2009). Lower collision risk with more modern turbines can also be due to the slower speed of rotor revolutions (Krijgsveld *et al.*, 2009; AWWI, 2015), but further empirical and comparative research is needed.

In terms of facility design, Schaub (2012) investigated the relationship between collision risk of the red kite and the distance between wind turbines and kite's nest location, providing through simulations that 'the larger the number of wind turbines and the more they were spread out in the landscape, the more depressed the population growth rate became.' It is recommended to conduct small-scaled impact studies when planning new wind facilities but at larger spatial scales so as to minimise impacts (Schaub, 2012).

However, investigations by Arnett *et al.* (2008), Barclay *et al.* (2007), and recommendation by Northrup and Wittemyer (2013) state shorter towers be installed to reduce impacts on *bats*. This is a concern for repowering as turbines are, while fewer, becoming larger with rotor blades within the movement heights of migratory bats. Additionally, it is important to note that tower type and height varied [50–80 m (Barclay *et al.*, 2007) and 50, 65, or 78 m (Arnett *et al.*, 2008)] during their research and current modern turbines range in height from 60 m to 80 m (200–260 ft) with blade tips reaching over 140 m (460 ft) (AWWI, 2015) in the US. However in Europe, 160–170 m is average with single turbines reaching up to 200 m (Deutsche WindGuard GmbH, 2015), implicating some research cannot directly apply to new facility developments. Mitigation measures should be centred on turbine height and blade size when considering facility characteristics, and centred on which at-risk species may fly through the facility.

*Offshore*, the use of floating turbines (Bailey *et al.*, 2014) or gravity foundation turbines (Skeate *et al.*, 2012) can be an option in selecting turbine models, but currently most involve direct foundation into the sea floors. Nevertheless, height and design of the turbine are crucial depending on a number of factors, including bird and bat flight heights and species' distribution. It is also important to take into account the fluxes of particular species as weather (visibility and temperature), time of day (or night), and flight pattern (migrant or seabird) should be factors incorporated into the design and height of offshore turbines (Fijn *et al.*, 2015). This can be important during bad weather conditions, as all birds tend to fly lower or try to land at illuminated areas (Bellebaum *et al.*, 2010). Johnston *et al.* (2014) investigated flight heights of marine birds in correlation to turbine hub heights. It is recommended to use larger (and fewer) turbines with increased turbine heights to lower the proportion of birds at risk of collision (Johnston *et al.*, 2014). Similar can be said for migratory birds, as their flight is above turbine heights, 400 m above sea level with head winds and up to 1000 m high with tail winds (Bellebaum *et al.*, 2010).

## Increased visibility

There still lacks proper scientific evidence on which patterns or colours are most efficient in triggering an avoidance behaviour for species passing by or through the wind facility. Yet, some research has been conducted on measures to reduce motion smear and thus increase visibility for *birds*. Hodos (2003) and Hodos *et al.* (2001) experimented with a variety of patterns for the American kestrel (*Falco sparverius*) such as a staggered-strip pattern, single-coloured blades, and various colour contrasts. It was recommended a single solid black blade is the most visible stimulus, but this was not tested in a field setting and not tested on other species or with moving backgrounds. Other recommendations include use of high-contrast patterns for turbine blades (Dai *et al.*, 2015; Drewitt and Langston, 2006), or UV reflective paint (Cook *et al.*, 2011; Young *et al.*, 2003; Curry and Kerlinger, 2000; Johnson *et al.*, 2007). UV reflective paint would not reduce motion smear but help in 'flight around' behaviour (as observed by Curry and Kerlinger (2000)) as at least 30 species can see UV light (Johnson *et al.*, 2007) and can be helpful in increased visibility under a variety of conditions (Johnson *et al.*, 2007). However, this topic deserves further investigation as some have shown no statistically significant differences between fatality rates for UV and non-UV turbines (as observed by Young *et al.* (2003)). There is also recommendation of lowering the rotor speed or repowering to larger turbines for increased visibility (Cook *et al.*, 2011; Dai *et al.*, 2015). In regards to turbine colour, there was an investigation in Germany by Dürr (2011) into tower colouration relevancy with bird collisions. He recorded 37 bird deaths at all grey- and white-coloured turbine towers and no deaths at those with a green-coloured bottom gradient fading into white or grey upwards, thus determining turbine colouration is significant. This can be particularly significant for *breeding birds* as they do not see the light turbines as an obstacle when they take off in flight from the ground nearby, thus increasing their collision risk with the tower.

In summary, strong recommendations have been made and are currently in use (i.e. tubular towers) but there are still variations in turbine design. Both onshore and offshore, mitigation relating to the height of the rotor swept area needs to be determined based on the conservation priorities relating to the species most likely to be affected. For increased visibility, it is recommended to use a variety of methods together as the largest problem of visibility occurs during poor weather conditions (Johnson *et al.*, 2007). Using inverse LED plates, letters, and numbers, self-reflective material are other suggested methods (Blew *et al.*, 2013). Metadata from facility designs could give better insight into how efficient colouration, heights, patterns, and visibility factors influence wildlife.

## Construction Minimisation

Construction has a higher concentration of human activity, vehicle transportation, and noise as well as a general loss of the environment, thus mitigation measures which differ during operation and maintenance are needed. Additionally, construction impacts not only include the erection of the turbine, but also the creation and use of roads, substations, and maintenance facilities (Lovich and Ennen, 2013); thus, mitigation should include measures needed for these additional impacts (Rodrigues *et al.*, 2006). It is important to note, construction impacts are not always limited during this period, and can overlap or persist into the operational period. Mitigation measures during this time can be establishing environmental rules for contractors or establishing efficient supervision (Ledec *et al.*, 2011), instituting restrictions of movement or activity during specific periods (i.e. time and seasons) to reduce disturbance (Drewitt and Langston, 2006), and establishing barriers to not only limit wildlife from coming into the facility but also limit human activity from expanding beyond the workspace (Pearce-Higgins *et al.*, 2012). Barriers also include noise mitigation systems, particularly for offshore wind facilities.

For instance, *bird* populations can be impacted during construction and some do not recover after, as was observed in the UK by Pearce-Higgins *et al.* (2012). Analysing 10 bird species between 18 wind farm sites and 12 reference sites, results exhibited the main negative effects on upland species populations is through disturbance displacement during construction, yet there were some positive effects after construction on a couple of species as the vegetation had shifted benefitting their survival. Conclusively, they recommend constructing barriers or screens to limit the disturbance zone, or establish times or places to avoid during breeding times (Pearce-Higgins *et al.*, 2012), but do not evaluate the effectiveness of each. An investigation by Shewring *et al.* (2015) provides a best practice measure during the construction period establishing exclusion zones based on active nesting sites of nightjar (*Caprimulgus europaeus*) in Wales, minimising disruption or any damage.

For *bats*, EUROBATS (Rodrigues *et al.*, 2006, 2014) established guidelines for the planning process and impact assessments, including the construction period. They recommend local knowledge on the site and species that could become displaced and construction only be planned during times of the day or parts of the year when bats are least active and not in hibernation (Rodrigues *et al.*, 2014). As their loss of roost sites would occur during construction, an additional recommendation from English Nature (Mitchell-Jones, 2004) includes establishing alternative roosts for species to return (Rodrigues *et al.*, 2006).

For *non-volant species*, the destruction and modification of wildlife habitats, e.g. ground disturbance, is highest (Lovich and Ennen, 2013): Soil compaction from heavy machinery can collapse burrows and crush small wildlife (Lovich and Ennen, 2011); roads can affect species richness and increase the possibility of vehicle strikes (Bissonette and Rosa, 2009; Lovich and Ennen, 2013). Conclusively, there is no empirical research into how to mitigate any of these impacts during construction on wildlife around (and to) wind facilities or specific turbines. There are, however, brief recommendations from two sources for two different species: One for reindeer (*Rangifer tarandus*) in Norway, where construction should occur during the time of the year when they are not in the area (May *et al.*, 2012), and the second for the Iberian wolf (*Canis lupus signatus*) in Portugal with recommendations to close network roads to reduce traffic and human disturbance and to protect breeding sites ($>2$ km radius) during site selection and construction period (Álvares *et al.*, 2011).

*Offshore* behavioural impacts have shown that most impacts occur during construction (Verfuß, 2014; Scheidat *et al.*, 2011; Russell *et al.*, 2015). Research has provided some insight into mitigation measures such as spatial and temporal closure of areas (e.g. vessel restrictions (Simmonds and Brown, 2010)), deterrence of species at risk (Lucke *et al.*, 2011; Bergström *et al.*, 2014), and noise mitigation systems (NMSs) to avoid acute injury on marine mammals (Bellmann *et al.*, 2015). It is recommended to establish restrictions during specific periods (e.g. breeding, migration, spawning, recruitment, calving, and feeding) to reduce disturbance (Drewitt and Langston, 2006; Bergström *et al.*, 2014; Sea Mammal Research Unit, 2009). For example, the German Federal Ministry for the Environment (BMUB) developed a "noise prevention concept" providing recommendations to avoid disturbing and killing of harbour porpoises. It is prohibited to disturb them during their sensitive breeding season (May–August). Outside of this season, a sufficient noise exposure buffer is still required and only 10% of the EEZ should be within the construction noise impact zone (BMUB, 2013). Other recommendations state boats, helicopters, and personnel use timed and specific routes to reduce disturbance (Drewitt and Langston, 2006; Simmonds and Brown, 2010). One investigation by Hammar *et al.* (2014) on Kattegat Atlantic cod (*Gadus morhua*) in the Baltic Sea and the North Sea advises a specific time period (December–June) in which pile-driving and construction activities be avoided.

Regarding NMSs, there is no 'off-the-shelf' method for minimising sound impacts during construction, namely during pile-driving (i.e. when towers are installed into the seabed) (Matuschek and Betke, 2009). Thus, precautionary actions have been established as well as technological advances which can deter wildlife away from the area before harmful noise impacts occur, and to reduce sound impacts when they are occurring. Recommendation primary to the use of mitigation technology include adjusting piling energy based on soil properties to reduce piling noise or impulse prolongation, altering the shape of sound impulses and thus reducing noise lengths (Verfuß, 2014). In Germany, the BMUB does not only set standards regarding spatial and temporal construction restrictions, but also deterrence measures and NMSs (BMUB, 2013).

In addition to NMSs, the use of 'soft start' (or 'ramp-up') has been recommended to gradually increase sound intensity, giving marine wildlife time to leave the area (Bailey *et al.*, 2014; Teilmann *et al.*, 2012; Tougaard *et al.*, 2012). However, it is important to note, soft start has been commonly implemented (Sea Mammal Research Unit, 2009) but lacks empirical research into its effectiveness. This can be a concern, as harbour seals (*Phoca vitulina*) may not be able to move away quick enough before noise levels reach auditory damage (as observed by Russell *et al.* (2014, 2015)). Additionally, the use of deterrents before pile-driving have been recommended, including an acoustic 'startle' system, pingers, sealscarers, compact autonomous military devices, and loudspeakers (Madsen *et al.*, 2006; Gordon, 2012; Brandt *et al.*, 2011), but the effectiveness of each is not well known. Additionally, the use of sealscarers may not be as effective today due to more effective noise mitigation techniques as stated by Brandt *et al.* (2013, 2014).

New technologies, such as FaunaGuard (acoustic deterrence device), are becoming implemented at OWF, but results of their effectiveness are not yet available (van der Meij *et al.*, 2015). Other means can be used based on passive acoustic monitoring, or Marine Mammal Observers (MMOs) (Bailey *et al.*, 2010, 2014; Thompson *et al.*, 2010) to reliably detect the presence of animals in real time and to alert the OWF operator when particular species are in the area and to halt construction activities. Höschle *et al.* (2015) tested a Wireless Detection System (WDS) with porpoises within 200 m distance during the installation of 48 piles in the German North Sea, providing another technique to deter species away before pile-driving. For seals, Gordon *et al.* (2007) stress that neither visual nor acoustic monitoring are effective detecting methods as they do not often vocalise and can be hard to see at surface. As for secondary mitigation measures, there are a number of technological advances that have reduced noise impacts, such as bubble curtains, shell-in-shell systems or castings, hydro sound damper (HSD), and cofferdams (Verfuß, 2014; Bellmann *et al.*, 2015). The use of bubble curtains (Big Bubble Curtain [BBC], in particular) is considered most effective through research investigations, particularly with harbour porpoises (*Phocoena phocoena*) (Matuschek and Betke, 2009; Würsig *et al.*, 2000; Koschinski and Lüdemann, 2013; Lucke *et al.*, 2011; Wilke *et al.*, 2012; Schubert *et al.*, 2015). Schubert *et al.* (2015) investigated that a BBC reduced the disturbed area by 90% from 700 km$^2$ to only 70 km$^2$. Bellebaum *et al.* (2015) and Philipp (2015) investigated different NMSs and found that a combination of Noise Mitigation Screen (IHC-NMS) and BBC methods can be most effective. While there is no 100% noise mitigation measure, it is important to take this into account offshore as even little noise can have an impact on communication, behaviour, foraging, and reproduction of marine mammal populations (Dähne *et al.*, 2013).

One concern offshore, not only during construction, is the cumulative effects noise impacts can have on marine mammals, fish, and benthos (Pine *et al.*, 2014; van Opzeeland, 2014). Another concern is the influence of electromagnetic (EM) fields and what mitigation measures can be most effective (Gill *et al.*, 2014; Bergström *et al.*, 2014; Öhman *et al.*, 2007). These are areas of further study, as well as incorporating mitigation measures into the construction phase without delaying the process or extending beyond economic constraints.

## Discussion

In providing a comprehensive understanding of where current research and practice lies, a significant point to be made is the lack of evidence into the efficacy of each mitigation type. This is primarily due to the lack of research and varied research methodologies. Nevertheless, Appendix A provides synoptical tables of current peer-reviewed mitigation research at all stages for all relevant species (Tables A.1 and A.2), visualising where the gaps in research are persistent. Below, each mitigation type is construed based on the peer-reviewed and grey literature within planning, siting and construction:

(1) In terms of *macro- and micro-siting*, these phases are key in avoiding critical habitats during the planning stage. Sensitivity mapping, regional planning, and local zoning can be effective forms in reducing impacts, but research understanding the balance between macro- and micro-siting could be beneficial in future planning. Offshore, similar can be done in establishing a strategic marine planning framework allowing more efficient opportunities for adopting new areas and licensing for wind facilities, as can be seen in Scotland with the development of a Sectoral Marine Plan (see Sec. 3.2) (Davies and Pratt, 2014).

(2) *Facility characteristics* show some investigative research into the design and height of wind facilities and their increased visibility, but further empirical evidence is needed. With the wind industry continuing to grow their turbines in height and rotor diameter for more efficient energy generation, research must adapt and provide meaningful recommendations. In addition, these type of mitigation measures should continue to line up with other requirements (e.g. aviation and shipping lighting) as well as fall in line with public interests and agreements (e.g. turbine colour).

(3) Reduction measures during *construction* focus most on sound barriers offshore for marine mammals and lack for other species groups. This can be due to research and monitoring focusing on impacts during construction, so continued research into effective measures is needed. Measures can be better implemented if more standards during the construction stage are given, e.g. one concern is the lack of EU standards for offshore noise mitigation measures (Müller and Zerbs, 2013).

Based on Appendix A, Table 1 provides a numerical table of peer-reviewed sources aligned as 'recommendation', 'observation', and 'investigation'. However, we further this in categorising the measures and species group that are 'known' (in black) when there are three or more investigations, 'somewhat known' (in dark grey) when there is at least one observation or one investigation, 'unknown' (in white) when there is no research at all, and 'unknown but recommended' (in light grey) when there is no observational or investigative research.

In regards to this visualisation, it is important to acknowledge how peer-reviewed research lacks perspective in the current state of knowledge, as reports

Table 1. Mitigation measures and species group — what is known (in black), somewhat known (in dark grey), unknown (in white), and unknown but recommended (in light grey). Based on over 105 peer-reviewed sources, numbers are aligned as recommendation, observation, or investigation.

| Wind energy measures and species groups | Migratory bats | Bats (land-based and general) | Migratory birds | Birds (land-based and general) | Raptors | Seabirds | Marine mammals | Fish and benthos |
|---|---|---|---|---|---|---|---|---|
| **Use areas of low spatial resistance** | 0 | 1,0,0 | 1,0,2 | 5,1,0 | 0 | 2,0,0 | 0 | 0 |
| **Avoid high-quality habitats, sig. topography** | 0,1,0 | 2,0,2 | 1,0,0 | 3,0,1 | 3,1,1 | 0 | 0 | 0 |
| **Turbine arrangement and placement** | 0 | 1,0,1 | 1,0,0 | 4,0,0 | 0 | 0,1,0 | N/A | N/A |
| **Facility design and size** | 0 | 1,0,2 | 0 | 2,0,1 | 0,0,1 | 1,0,1 | 0 | N/A |
| **Increased visibility** | 0 | 1,3,0 | 1,0,0 | 4,0,1 | 1,0,0 | 0 | N/A | N/A |
| **Construction time restrictions** | 0 | 0 | 0 | 1,1,0 | 0 | 0 | 3,0,0 | 0,0,1 |
| **Construction sound, physical barriers** | N/A | N/A | N/A | 0 | 0 | N/A | 3,1,2 | 0 |

and grey literature have been substantial in developing and understanding mitigation measures. A similar table is found in "Mitigation Measures for Wildlife in Wind Energy Development, Consolidating the State of Knowledge — Part 2: Operation, Decommissioning." Certain notable approaches have a higher coverage through grey literature. One example is land management for raptors in Germany, as much research was initiated from field experts improving management strategies based on experience, and not from scientific research. Immediate field application indicated if measures were successful or not. Thus, this is an important documentation of measures directly implemented in the field that have not yet been scientifically investigated and published.

The discussion on mitigation topics of operation and decommissioning are within the article *Mitigation Measures for Wildlife in Wind Energy Development, Consolidating the State of Knowledge — Part 2: Operation, Decommissioning*, as well as an outlook for the future in terms of all land-based and offshore mitigation measures for wildlife in wind energy development.

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# Appendix A

Table A.1. Peer-review sources table dependent on measures, species, and category — birds and bats (not including seabirds). "General" stands for the overall discussion of the measure (no particular species group).

| Wind energy measures | | Migratory bats | Bats (land-based and general) | Migratory birds | Birds (land-based and general) | Raptors | |
|---|---|---|---|---|---|---|---|
| *Macro-siting* | *Use areas of low spatial resistance* | | [6] | [1] | [2–6] | | Recommendation |
| | | | | | [7] | | Observation |
| | | | | [8, 9] | | | Investigation |
| | *Avoid sensitive areas* | | [10, 11] | [12] | [13–15] | [16–18] | Recommendation |
| | | [19] | | | | [20] | Observation |
| | | | [21, 22] | | [23] | [24] | Investigation |
| *Micro-siting* | *Turbine arrangement and placement* | | [25] | [12] | [2, 13, 26, 25] | | Recommendation |
| | | | | | | | Observation |
| | | | [27] | | | | Investigation |
| *Facility characteristics* | *Facility design and size* | | [6] | | [2,13] | | Recommendation |
| | | | | | | | Observation |
| | | | [28, 29] | | [30] | [31] | Investigation |
| | *Increased visibility* | | [25] | [2] | [13, 32, 33, 25] | [2] | Recommendation |
| | | | [34–36] | | | | Observation |
| | | | | | [37] | | Investigation |

Table A.1. (*Continued*)

| Wind energy measures | | Migratory bats | Bats (land-based and general) | Migratory birds | Birds (land-based and general) | Raptors | |
|---|---|---|---|---|---|---|---|
| *Construction* | *Restrictions during specific periods* | | | | [13] | | Recommendation |
| | | | | | [38] | | Observation |
| | | | | | | | Investigation |
| | ***Barriers (physical and sound)*** | **No peer-reviewed research** | | | | | |
| *Avoid attraction* | *Land management* | | [39, 40] | [4] | | [16, 41] | Recommendation |
| | | | | | | | Observation |
| | | | | | | [42, 43] | Investigation |
| | *Lighting intensity* | | | | [2, 26] | | Recommendation |
| | | [21, 35] | [36, 45] | | [44, 45] | | Observation |
| | | | | | [46] | | Investigation |
| *Avoidance-luring* | *Habitat enhancement* | | [10] | | [13] | [2, 16, 43] | Recommendation |
| | | | | | | | Observation |
| | | | | | | | Investigation |
| | *Habitat replacement* | | [10] | | | [2, 5, 47, 6] | Recommendation |
| | | | | | | | Observation |
| | | | [48] | | | [47, 49, 50] | Investigation |
| *Deterrence* | *Acoustic* | | [51] | | [2, 14]<br>**General:** [52, 53] | | Recommendation |

Table A.1. (*Continued*)

| Wind energy measures | | Migratory bats | Bats (land-based and general) | Migratory birds | Birds (land-based and general) | Raptors | |
|---|---|---|---|---|---|---|---|
| | | | | | | | Observation |
| | | | | | | | Investigation |
| | *Electromagnetic* | | | | [2] | | Recommendation |
| | | | | | | | Observation |
| | | | [54, 55] | | | | Investigation |
| | ***Visual*** | **No peer-reviewed research** | | | | | |
| *Operational minimisation* | *High abundance and high risk of collision* | [56] | [11, 57, 58, 6] | [4] | **General:** [59, 6] | | Recommendation |
| | | | | | | [60, 61] | Observation |
| | | | [62–67] | | | [68] | Investigation |
| *Decommissioning and repowering* | *Dismantling and repowering* | | | | [2, 6, 61] | [42, 69]<br>**General:** [56] | Recommendation |
| | | | | | | | Observation |
| | | | [41, 70] | | [30, 41, 70] | | Investigation |
| | ***Phased development*** | **No peer-reviewed research** | | | | | |
| | *Relocation* | | | | | [13, 61] | Recommendation |
| | | | | | | | Observation |
| | | | | | | | Investigation |

Table A.2. Sources table dependent on measure, species, and category — Reptiles and amphibians, terrestrial mammals, seabirds, marine mammals, and fish and benthos. “General” stands for the overall discussion of the measure “offshore”; “Marine birds” stands for seabirds and offshore migratory birds collectively.

| Wind energy measures | | Reptiles and amphibians | Terrestrial mammals | Seabirds | Marine mammals | Fish and benthos | |
|---|---|---|---|---|---|---|---|
| *Macro-siting* | *Use areas of low spatial resistance* | | | [71, 72] | | | Recommendation |
| | | [73, 74] | | | | | Observation |
| | | | | | | | Investigation |
| | ***Avoid sensitive areas*** | **No peer-reviewed research** | | | | | |
| *Micro-siting* | *Turbine arrangement and placement* | | | | | | Recommendation |
| | | | | [75] | | | Observation |
| | | | | | | | Investigation |
| *Facility characteristics* | *Facility design and size* | | | **Marine birds:** [76] | | | Recommendation |
| | | | | | | | Observation |
| | | | | **Marine birds:** [77] | | | Investigation |
| | ***Increased visibility*** | **No peer-reviewed research** | | | | | |
| *Construction* | *Restrictions during specific periods* | | | | **General:** [13, 78, 79] | | Recommendation |
| | | | | | | | Observation |
| | | | | | | [80] | Investigation |
| | *Barriers (physical and sound)* | | | | **General:** [81–83] | | Recommendation |
| | | | | | [84] | | Observation |
| | | | | | [85, 86] | | Investigation |
| *Avoid attraction* | *Land management* | | | | | | Recommendation |
| | | | | | | | Observation |
| | | [87] | | | | | Investigation |
| | ***Lighting intensity*** | **No peer-reviewed research** | | | | | |

Table A.2. (*Continued*)

| Wind energy measures | | Reptiles and amphibians | Terrestrial mammals | Seabirds | Marine mammals | Fish and benthos | |
|---|---|---|---|---|---|---|---|
| *Avoidance-luring* | *Habitat enhancement* | | [88] | | | | Recommendation |
| | | | | | | | Observation |
| | | | | | | | Investigation |
| | *Habitat replacement* | | | | **General:** [89] | [90–92] | Recommendation |
| | | | | | | | Observation |
| | | | | [93] | [94] | [95–97] | Investigation |
| *Deterrence* | *Acoustic* | | | | [98–102] | | Recommendation |
| | | | | | | | Observation |
| | | | | | | | Investigation |
| | *Electromagnetic* | | | | [103, 104] | | Recommendation |
| | | | | | | | Observation |
| | | | | | | | Investigation |
| | ***Visual*** | **No peer-reviewed research** | | | | | |
| *Operational minimisation: Curtailment* | *High abundance and high risk of collision* | | | **Marine birds:** [12, 71] | | | Recommendation |
| | | | | [105] | | | Observation |
| | | | | [106, 107] | | | Investigation |
| *Decommissioning and repowering* | *Dismantling and repowering* | | | | | **General:** [108] | Recommendation |
| | | | | | | | Observation |
| | | | | | | | Investigation |
| | ***Phased development*** | **No peer-reviewed research** | | | | | |
| | ***Relocation*** | **No peer-reviewed research** | | | | | |

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