Impacts of onshore wind energy production on birds and bats: recommendations for future life cycle impact assessment developments

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Abstract

Purpose: Models for quantifying impacts on biodiversity from renewable energy technologies are missing within life cycle impact assessment (LCIA). We aim to provide an overview of the effects of wind energy on birds and bats, with a focus on quantitative methods. Furthermore, we will investigate and provide the necessary background for how these can in future be integrated into new developments of LCIA models.

Methods: We reviewed available literature summarizing the effects of wind energy developments on birds and bats. We provide an overview over available quantitative assessment methods that have been employed outside of the LCIA framework to model the different impacts of wind energy developments on wildlife. Combining the acquired knowledge on impact pathways and associated quantitative methods, we propose possibilities for future approaches for a wind energy impact assessment methodology for LCIA.

Results and discussion: Wind energy production has impacts on terrestrial biodiversity through three main pathways: collision, disturbance, and habitat alterations. Birds and bats are throughout the literature considered the most affected taxonomic groups, with different responses to the before-mentioned impact pathways. Outside of the LCIA framework, current quantitative impact assessment prediction models include collision risk models, species distribution models, individual-based models and population modelling approaches. Developed indices allow scaling of species-specific vulnerability to mortality, disturbance and/or habitat alterations.

Conclusion: Although insight into the causes behind collision risk, disturbance and habitat alterations on bats and birds is still limited, the current knowledge base enables the development of a robust assessment tool. Modelling the impacts of habitat alterations, disturbance and collisions within an LCIA framework is most appropriate using species distribution models as those enable the estimation of species' occurrences across a region. Although local scale developments may be more readily feasible, further up-scaling to global coverage is recommended to allow comparison across regions and technologies, and to assess cumulative impacts.

Keywords: collision, disturbance, habitat alteration, quantitative models, wind turbine, LCIA

1. Introduction

Wind energy has emerged as a promising alternative to fossil fuels in an attempt to halt climate change, with an annual average growth rate of 24.3% from 1990 to 2014 (IEA 2016). In 2013 it represented 2.5% of the global electricity supply, and it is expected to grow to between 15-18% by 2050 (International Energy Agency 2013). However, research has shown that wind farms, both onshore and offshore, can cause direct and indirect damage to wildlife (e.g., Edenhofer et al., 2012; Rydell et al., 2012; Schuster, Bulling, & Köppel, 2015). For onshore wind energy, this research describes bats and birds in particular to be vulnerable to collision, disturbance and habitat alterations during the construction and operational stages. Even if this damage may be relatively low today in comparison to other energy sources (Sovacool 2013), the cumulative impacts due to the installation of projected wind farms may significantly affect more vulnerable populations (Carrete et al. 2009; Masden et al. 2010a; Schaub 2012). Wind power might also come as an additional impact to already existing environmental impacts, contributing critically to increased impacts upon specific species and populations. For the impacts of wind energy different impact assessments exist, however, these are all site-, species- or impact- specific and a globally applicable tool is still lacking.

Life cycle assessment (LCA) is an environmental impact assessment tool, which is widely used to evaluate and compare the environmental performance of products or services through their whole life cycle by using different impact categories, such as climate change, ecotoxicity or land use (Hauschild and Huijbregts 2015). LCA has been used to evaluate and compare environmental impacts associated with different energy production systems, but typically focuses on greenhouse gas emissions (Evans et al. 2009). Martínez et al. (2009) performed a LCA of a multi-megawatt wind turbine, analyzing the manufacturing, use, disposal, and transport stages throughout several impact categories (e.g., global warming carcinogens, acidification). The authors show that manufacturing of the components is the largest contributor to the impacts of a wind turbine, which was supported by a study by Arvesen and Hertwich (2012). However, none of these studies took into account impacts on biodiversity, due to insufficient or lacking impact assessment models. Including biodiversity will likely increase the contribution of the construction and operational stages of a wind farm to its overall impacts, although the magnitude of it is unknown. Even with recent developments in incorporating biodiversity related impacts in LCA (e.g., Azevedo et al. 2013; Chaudhary et al. 2015; Verones et al. 2016; Cosme et al. 2017), currently available life cycle impact assessment (LCIA) models do not cover wind energy specific impacts on biodiversity.

In an attempt to cover the lack of biodiversity impacts from renewable energy production, we aim to summarize the existing knowledge base and its applicability for the future development of LCIA models covering the impacts of wind energy on biodiversity. New developments of LCIA models should take into consideration the varying vulnerability among different species groups to each type of impact. Focusing on onshore wind energy, we provide an overview of the main impact pathways affecting two major taxonomic groups, bats and birds, showing the most relevant state mechanisms and conditional variables that should be considered in the development of an impact assessment model. Although other authors have qualitatively reviewed this topic before, there is yet a lack for a summary of quantitative methods and a link to LCIA. Therefore, we present the most commonly used environmental impact assessment tools in the wind energy sector, as well as recent developments in these. Finally, we explore how these can be used as a basis to develop future LCIA models and provide recommendations for the next steps in the direction of these model developments.

2. Methods

Several authors (Drewitt and Langston 2006; Kunz et al. 2007b; Rydell et al. 2012; Langston 2013; Marques et al. 2014; Dai et al. 2015; Wang et al. 2015; Schuster et al. 2015) have comprehensively reviewed the effects of wind energy on biodiversity from an ecological point of view. These served as a gateway to a more refined search within the subsections covered in each article (e.g., articles focusing on one species or group of species, or on a particular impact pathway). Despite the availability of several reviews, there was only one article focusing on quantitative models; regarding avian collision risk models (Masden and Cook 2016).

We searched for available peer-reviewed and "grey" literature on the topic of impacts of wind energy on wildlife published up until the date of final submission. Using mainly Google Scholar (Google 2017) and Oria (Bybsys 2017) we began by using key terms including, but not limited to, "wind energy", "wind power" "biodiversity", "LCA", "impacts", "assessment", "birds", "bats", "collision", "displacement", "disturbance", "avoidance", "habitat loss", "habitat alterations". For an overview of available quantitative models, we mainly used Google Scholar to conduct our search, using key terms such as "collision risk", "model", "quantifying", "quantitative", "habitat loss", "avian", "displacement", "bat", "species distribution" and "wind energy". When searching for available LCA related methodologies, we also included the key terms "LCA", "LCIA", "Life Cycle Assessment", and "Life Cycle Impact Assessment", in addition to the previous terms. For each article, we went through its reference list in search for other relevant studies. The most highly cited literature was taken as a basis for understanding the topic. Mendeley (Mendeley Ltd. 2016) and Elsevier (Elsevier 2017) also proved to be valuable sources of knowledge by linking previous searches to related articles and providing recommendations on relevant articles. "Grey" literature was also considered in this review, consisting mainly of technical reports from highly credited institutions or companies working on the topic at hand because of either the reports' high number of citations or very high relevance to this study. Some articles were excluded from this review, as they were already well described in other reviews and would not contribute any additional content to this article. We also excluded articles describing non-predictive quantitative methods, i.e. those that would not contribute to the development of LCIA models. In total, we reviewed 138 articles.

3. Effects of wind energy development on biodiversity

Knowledge on the effects of wind energy on biodiversity at a species level, and how these reflect impacts on a population level (May et al. 2017), is the first step to adequately quantify impacts, outside and within the LCA framework. Drewitt and Langston (2006), as well as many other authors, identified collision, disturbance, as well as habitat loss and change as the main effects from wind power on birds, both on- and offshore. For bats, Brinkmann (2006) stated that collision is likely the main cause of impacts.. Schuster et al. (2015) consolidated literature on effects from wind power on birds and bats, with a focus on both taxa. We note that disturbance and displacement are two similar terms that may be used interchangeably in wind energy impact assessment literature, and should therefore be clarified. As defined by Furness et al. (2013) disturbance relates to the added expenditure of resources by animals to avoid a wind farm and associated activity. Displacement refers to the reduced number of animals occurring in the wind farm area and its vicinity. We also follow this terminology in this article.

3.1. Collision

Collision risk, or the probability of mortality due to collision of all individuals intersecting with a wind turbine, occurs during the operational life cycle stage of a wind farm. Species that generally do not exercise avoidance behavior towards human-made structures, specifically wind turbines, are at risk of colliding with turbine blades, or the monopoles (Kunz et al. 2007a). Cook et al. (2014), and later May (2015), described three main types of bird avoidance behavior, according to the scale of its occurrence. Two of these, meso- and micro-avoidance, take place inside the wind farm space, and therefore directly affect collision risk. Meso-avoidance is described by May (2015) when birds evade the wind turbines individually by anticipating or reacting to their presence. However, the longer it takes the bird to do this (i.e. the closer it gets to the wind turbine before it responds to the obstacle), the more likely it is to collide. He explains that at this point, birds may still narrowly escape the turbine structure, which the author classifies as a micro-scale avoidance. The bird may also avoid the wind farm altogether (macro avoidance), in which case it will either lead to no response (if the avoidance does not alter the birds' habitat use), or displacement through disturbance. Different variables contribute to the collision risk of birds and bats, and have been observed to be site-, species- and turbine-specific (Drewitt and Langston 2006; Marques et al. 2014; Hein and Schirmacher 2016). Some studies show that wind turbine collisions only account for a considerably small percentage of total bird mortality (Erickson et al. 2005; Calvert et al. 2013; Sovacool 2013). This may appear as an argument to reduce efforts to mitigate impacts of wind energy development on wildlife. However, the different authors agree that fatalities from wind energy come in addition to other sources of mortality. In other words, it is not only the main source of a species mortality that should be looked into (while ignoring other causes), as even smaller additions to a population's mortality rate can have severe consequences, especially to species with slow life-history traits (i.e., long lifespans, few offspring and late maturity) such as raptors or bats.

3.2. Disturbance

Displacement can be considered as reduced flight activity within the wind farm area due to a functional loss in habitat (May 2015). This is true for not only resident species, but also migratory species through loss of stopover sites. It may also lead to a higher expenditure of energy for species that need to alter their flight path to avoid the wind farm (also known as "barrier effect"), which may potentially have consequences on population health if a high number of wind farms is to be avoided (Masden et al. 2009; Masden et al. 2010b). The extent and severity of disturbance and consequent displacement is dependent on site and species characteristics (Drewitt and Langston 2006), and some authors consider displacement to be potentially more threatening for birds than collision (Kuvlesky et al. 2007). Pearce-Higgins et al. (2012) show how the construction stage of wind farms may have a greater displacement impact on bird populations than the operational stage. Nevertheless, indirect impacts of wind energy production remain greatly understudied, making their quantification very challenging (May 2015). Bird displacement from wind farms has been shown to translate into the avoided habitat effectively being lost (Pedersen and Poulsen 1991; Larsen and Madsen 2000; Pearce-Higgins et al. 2008; Pearce-Higgins et al. 2009; Garvin et al. 2011; Petersen et al. 2011; May et al. 2013). However, some species may return to their original habitat with time, becoming habituated to the presence of the wind farm (Madsen and Boertmann 2008). Masden et al. (2009) evaluated this deviation and concluded that although avoidance of a single wind farm may be negligible in terms of energy cost, there may be a harmful cumulative effect over the avoidance of several wind farms.

Bats, on the other hand, appear to either be undisturbed by wind turbines and even in some cases attracted to them, which thereby can increase the number of collisions (Rydell et al. 2012). Kunz et al. (2007b) present several hypotheses that may explain bat attraction to turbines. Most of these are related to a potential attraction to insects drawn to the wind turbines or associated altered landscape, which is also supported by other authors (Brinkmann 2006; Rydell et al. 2010a). Another hypothesis presented by Kunz et al. (2007b), is that tree-roosting bats are attracted to the turbines that they perceive as potential roosts. This is further described in the work of Cryan et al. (2014), as well as other observed bat behaviors around wind turbines in an experimental setting. Nevertheless, Rydell et al. (2012) note that indirect effects of wind energy on bats are relatively small, while possible the most relevant on birds.

3.3. Habitat alterations

Construction of wind turbines, like any infrastructure development, alters habitats at and surrounding the construction sites. However, the extent of this effect may vary depending on the original setting. For instance, habitat alteration effects may be more pertinent in e.g. forested and/or pristine wilderness areas, versus multiple-use landscapes with pre-existing anthropogenic influences. Specialist species, i.e. species with a narrow range of usable habitats (high habitat specificity) are more vulnerable (Swihart et al. 2003; Munday 2004; de Baan et al. 2013), and therefore potentially suffer a higher impact than more wide-ranging and generalist species.

Apart from the direct loss of habitat for certain species where the turbines are placed, the tall structure of the turbines may be mistaken for previous natural structures such as trees, which, as described in the previous section, may attract certain species and lead to increased collision risk (i.e., an ecological trap; May 2015). In addition, roads and power lines associated with the wind farm may cause habitat fragmentation, which can be particularly damaging in previously unaltered areas (Rydell et al. 2012). Although these alterations can reduce habitat suitability for some species, other species may find these new conditions more favorable (Hötker et al. 2006). In turn, increased densities of benefiting species may attract predators, such as bats or birds of prey, which may end up suffering higher collision rates while hunting. Smallwood et al. (2007), for instance, showed how increased densities of ground squirrels near the base of wind turbines attracted burrowing owls closer to the blades, consequently increasing collision risk.

3.4. Conditions influencing effects of wind farms on wildlife

Species-specific conditions

Bat behavior towards wind farms and turbines can be explained with the concept of guilds. Denzinger and Schnitzler (2013) group different bat species based on their use of echolocation, foraging habitats and modes, as well as sensory and motor adaptations. They identify three main guild types, namely open space, edge space and narrow space, which forage at different distances from background structures (such as wind turbines) and may be more or less apt to avoid them. The authors conclude that the foraging and echolocation behaviors of all species within a guild are so similar that a small number of species or observations can be used as proxy for the whole guild with high certainty.

Birds' sensory capabilities, as well as behavior, may play a significant role in their response to a wind farm or turbine (e.g., Marques et al. 2014; May et al. 2015). Moreover, the morphology of birds appears to be a determinant parameter for collision risk (e.g., Bevanger 1994; Janss 2000; Herrera-Alsina et al. 2013). Rayner (1988) grouped flying birds according to their size, aspect ratio and wing loading and described how these relate to different flight behaviors. The mechanisms behind bird (and bat) flight, and how this in turn reflects in their flight behavior, are further described by Lindhe Norberg (2007).

Environmental conditions

Topographical features of the region influence bat and bird activity. Migrating bats use linear aspects of the landscape for navigation/movement, such as river valleys, tree rows or forest edges (e.g., Ahlén et al. 2009; Furmankiewicz and Kucharska 2009), which could increase collision rates with wind turbines placed in the proximity of these features (Rydell et al. 2010b). Similarly, Johnson et al. (2004) determined a negative correlation between bat activity and distance to woodlands. This knowledge is particularly important for the conservation of tree roosting bats, which may mistake wind turbines to be potential roosting or mating sites (Cryan et al. 2008), as these activities typically take place in tall trees (Cryan et al. 2014). Certain birds, such as raptors, are also known to utilize landscape features enhancing thermal or orographic lift, such as ridgelines or slopes, in order to save energy, making their passages predictable to a certain extent (Duerr et al. 2012). An analysis by Hötker et al. (2006) on collision risk factors showed that habitat type has a significant influence on bird casualty rates, particularly mountain ridges and wetlands.

Season also affects bird and bat behavior, particularly in terms of habitat use and flight activity, and consequentially collision risk. The highest bat fatality rates due to collision are observed during late summer and autumn, during which bat activity is typically at its peak (due to, among other factors, migration periods) (e.g., Brinkmann 2006; Rydell et al. 2010; Baerwald and Barclay 2011a). May et al. (2010, 2011) determined that the white-tailed eagle (*Haliaeetus albicilla)* had considerably higher flight activity in the spring, as well as more fatal collisions with wind turbines. Barrios and Rodríguez (2004) also noted a seasonal variation in the flight frequency of vultures in wind farms, with higher counts, but also variance, during the winter-autumn period. These findings are supported by Smallwood et al. (2009), who evaluated different bird species flying in wind farms at the Altamont Pass Wind Resource Area, USA. Relatively large seasonal variations in bird numbers are associated with migratory behavior, although some of these also coincide with post-breeding periods, when there is an increase of young and inexperienced birds (Drewitt and Langston 2008).

Meteorological conditions, particularly wind speed and direction as well as temperature, are essential in determining the probability of negative effects of a specific site (e.g., by creating orographic and thermal updrafts), influencing the flight behavior and activity of different species (Richardson 1998; Langston 2013; May et al. 2015). In particular, wind, fog and rain have a direct impact on birds' maneuverability, flight height and sensory perception (Langston and Pullan 2003; Arnett et al. 2007). Furthermore, temperature (Arnett et al. 2006) and low wind speeds are positively correlated with bat activity, near wind turbines, and therefore a useful parameter in determining the areas of highest collision risk (e.g., Rydell et al. 2010; Baerwald and Barclay 2011a; Cryan et al. 2014). Brinkmann et al. (2006) report that operating wind turbines only at wind speeds above 5.5 m/s can be an effective measure to reduce bat collision rates with wind turbines. This was also tested and confirmed by Baerwald et al. (2009), at the same start-up speed, with only marginal costs from the decreased electricity production. Similarly, Barrios and Rodríguez (2004) show that wind speed also affects bird collision risk of raptors, with the highest being at wind speeds between 4.6-8.5 m/s, which is consistent with the observations of Smallwood et al. (2009). However, some species are able to fly at speeds considerably higher than these observed limits (Winter 1999), which needs to be taken into consideration when planning such mitigation strategies.

Technological conditions

Finally, type, size and number of wind turbines, as well as layout of wind farms are considered by some authors to be relevant aspects in determining avian and bat collision risk. Smallwood and Thelander (2004) identified tower size, blade tip speed and wind farm layout to be the most relevant factors contributing to golden eagle (*Aquila chrysaetos)* mortality at the Altamont Pass Wind Resource Area (APWRA). Barclay et al. (2007), on the other hand, reported that turbine height did have a significant effect on bats, but not birds, while rotor blade length had no effect on bird or bat fatality rates. de Lucas et al. (2008) also found taller turbines to be linked to a higher number of fatalities, although they could not conclude on the effect of the wind farm layout. Hötker et al. (2006) drew opposing conclusions, determining a statistically insignificant effect of turbine hub height on collision rates. Nevertheless, Hötker et al. (2006) recommend that wind farms should be arranged with turbine arrays parallel to the main flight direction to decrease the risk of collision. Rotor speed has also been identified as a determinant collision risk factor by model developers (e.g., Tucker 1996), such that more rotations per minute imply a higher chance of a bird or bat colliding if it traverses the rotor swept area. This makes turbine designs of inherent slower blade rotation (e.g., vertical axis wind turbine (VAWT)) potentially less deadly to birds and bats (Islam et al. 2013, Santangeli & Katzner 2015). Furthermore, designs that can cause a lower degree of motion smear of the blades may potentially be more detectable by avian species (Hodos 2003).

4. Impact assessment modelling approaches

Integrating wind energy impacts on biodiversity in LCIA not only depends on knowledge on the impacts, but also on how these can be assessed using currently available models. Therefore, and given the current lack of a literature review on the matter, we compiled different predictive modelling approaches used in assessing collision, disturbance and habitat alterations on bird and bat species. We grouped these models by type of method used, noting that each type may cover more than one effect. Table 1 summarizes our findings, and provides an overview on the inputs required for each model type to cover the relevant conditions as described in the previous section. All model types are further detailed in the following paragraphs. At the end of this section, Table 2 summarizes a critical comparison between the different model types, showing the different advantages and disadvantages of each model type for inclusion in LCIA.

Table 1 here

4.1. Collision Risk Models (CRMs)

Masden and Cook (2016) recently reviewed available avian collision risk models. Tucker (1996b) presented the first of these models, calculating collision risk as a ratio between the time spent by a bird flying through the rotor swept area over the time taken by one single rotation of the rotor blades. Similarly, Band et al. (2007) developed a model for onshore wind turbines which associates the risk of collision with the probability of the bird occupying the same space as the turbine blade during its flight through the rotor swept area. This model was then extended to take into account the variable distribution of birds with height within the rotor swept area (Masden and Cook 2016). Also other models have been developed (e.g., Podolsky 2008; Holmstrom et al. 2011; Eichhorn et al. 2012), but in general these take a similar approach to Tucker (1996b) and Band et al. (2007). Bird size, flight characteristics, as well as rotor blade length and speed are typical inputs in this type of models and are combined with the expected number of birds flying within rotor swept height. In another approach, Korner-Nievergelt et al. (2013) used a combination of carcass searches and animal density indices in a mixture model to determine collision rates, yielding results “at least as precise as conventional estimates” from carcass search data. New et al. (2015) developed a predictive CRM based on the assumption of a relationship between pre-construction avian exposure and subsequent fatalities. Among other differences, this model distinguishes itself for the direct inclusion of uncertainty, as well as considering the entire turbine height when calculating the total hazardous volume of a wind turbine. This means that birds in this model are considered to be able to collide when flying under the rotor area, as opposed to most CRMs which only consider rotor blade length. Chamberlain et al. (2006) assessed the effects of estimating and using avoidance rates in the development of a collision risk model, based on the original Band model (Band et al. 2007). Fatality rates derived from estimated avoidance rates may be used for comparative purposes, but the authors underline the urgent need for more specific and empirical avoidance rate studies. Lastly, Calvert et al. (2013) estimated avian mortality, in Canada, due to different sources. The authors developed a stochastic simulation model and compared the effects of mortality at different life stages of different species, as well as across different mortality sources. This model also allowed the assessment of the effects at a population level.

4.2. Species distribution models (SDMs)

Species distribution models are used to determine the probability of occurrence of a species in a given location. Therefore, these can be used to predict avian and bat activity and, together with posterior effect modelling, the likelihood of a negative effect. One interesting application of SDMs is seen in a recent study by Santos et al. (2013), who applied a maximum entropy model (MaxEnt; Phillips et al. 2006), using presence-only data to determine the collision risk associated with wind farms of four different bat species in Portugal. Given a small number of occurrences and a given set of environmental conditions, MaxEnt can be used to identify regions where a species is likely to be present (Pearson et al. 2007), and therefore delineate areas of higher conflict probability. Roscioni et al. (2014) also applied the MaxEnt approach, but rather to determine the impacts of wind energy developments on habitat connectivity for bats. Rebelo and Jones (2010) compared this approach with the ecological niche factor analysis (ENFA) (Hirzel et al. 2002), a similar model which also uses presence-only data, for modelling the potential distribution of a bat species in Portugal. The authors conclude that the differences between the two models make ENFA more appropriate for determining a species' potential distribution, while MaxEnt is better suited for determining a species' realized distribution. Hayes et al. (2015) created seasonally dynamic SDMs to study the impacts on migratory hoary bats (*Lasiurus cinereus)*. Apart from MaxEnt, the authors used four other SDM approaches to model the species' distribution. Bastos et al. (2016) assess the local impacts of wind energy on the skylark (*Alauda arvensis)* populations in Portugal via an index derived from a SDM, showing how this combined framework can be used for predictive impact assessments Elith et al. (2006) summarizes and compares other different modelling methods used in predicting species' distributions from occurrence data.

Bright et al. (2008) presents a bird sensitivity map of 16 protected species in Scotland, in which species distribution data were buffered and rated taking into account foraging ranges, collision risk and susceptibility to disturbance. The SDM was then overlapped with a map of existing or planned wind farm locations in order to provide a proportion of affected bird species by these developments. Similarly, Reid et al. (2015) modelled the movements of bearded vultures (*Gypaetus barbatus)* in southern Africa in terms of habitat use. Other behavior-inclusive SDMs focus on migratory species. Pocewicz et al. (2013) mapped important migratory areas for birds in Wyoming, US, including stopover habitats. The authors combined different geographical features, (such as ridges, streams and likely thermal updraft locations), which directly correlate to increased activity of migratory bird species. Similarly, Liechti et al. (2013) developed a model enabling the determination of areas with predictable high concentration of migratory bird species in Switzerland, which translate to a higher collision risk. Also, with a focus on soaring birds, BirdLife International (2017) developed a sensitivity mapping tool for migratory soaring birds in the Middle East. If migratory paths are known or predictable, siting new wind farms away from them could potentially decrease collisions and displacement effects on those species. These and other applications of species distribution models are further analyzed by Guisan and Thuiller (2005). May et al. (2013) evaluated habitat utilization and displacement of white-tailed eagles using Resource Utilization Functions (RUF), which correlate a species space use to its resource utilization. Other authors also used RUFs to assess potential negative effects on birds from wind energy developments (Mcnew et al. 2014; Miller et al. 2014).

Two models have been developed to quantify the spatial implications of "barrier effects". Masden et al. (2012) details models used to described birds' movement in response to wind farms, based on bird movement data collected post-construction of the wind farm. Masden et al. (2010a) had previously modelled the energy cost of avoidance by several seabirds due to offshore wind farm placement, using the model developed by Pennycuick (2008). The study concluded that the additional energy costs of avoiding the wind farm may be insignificant for some species, but a species-specific approach should be taken when assessing the effects of wind farms on seabirds.

4.3. Individual Based Models (IBMs)

Several individual-based models (IBMs) have been developed for avian impacts. IBMs allow researchers to simulate interactions of individuals with the surrounding environment, as well as their adaptations to environmental changes. Grimm et al. (2006) further describe the concepts behind this tool, potential applications and provide a protocol for further developments, named ODD (‘Overview’, ‘Design concepts’ and ‘Details’). Eichhorn et al. (2012) followed this protocol in their collision risk model of red kites (*Milvus milvus)*. They used landscape grid cells (with habitat characteristics based on West Saxony, Germany), a red kite and a wind turbine as entities in their model, each with their own particular variables. The bird entity is based essentially on its behavior and flight characteristics, as well as probability of collision (based on the Band model) and avoidance. For the wind turbine, position, hub height and rotor blade length were used as inputs. Schaub (2012) also based his model on the red kite species, although not following the same protocol, but nevertheless modelling the effect of a varying number and layout of wind turbines on the population dynamics of the species. Ferreira et al. (2015), also followed the protocol proposed by Grimm et al. (2006), for estimating bat mortality risk at wind farms. As with the model produced by Eichhorn et al. (2012), three entities were selected, referring to landscape, the bat and the wind turbines. Soil-use and altitude of the landscape were included in the first entity, taking into consideration the use for foraging and/or roosting by bats. Wind speed, temperature and species behavior determined the inputs of the bats entity. As for the turbines, the authors also included the variable of blade length, but not height. Masden (2010) developed an IBM following the ODD protocol to evaluate changes in collision mortality and habitat-related productivity in hen harriers (*Circus cyaneus)* due to technological conditions. From her results, the author concludes that the impacts of wind turbines on hen harriers depended not only on the number of turbines, but also their location, suggesting the need for knowledge on a species’ ecology in wind energy development planning. A recent work by Warwick-Evans et al. (2017) shows the use of the ODD protocol to study the effect of wind turbines on body mass, mortality rate and breeding success of Northern gannets (*Morus bassanus)*. The authors state that this is the most complex and comprehensive model of its kind yet, and has the potential to be adapted for other seabird populations and other types of impacts from spatial change.

4.4. Population models

Widely used in ecology, population viability analyses (PVA) estimate the probability of a population or species becoming extinct in a given period of time, and based on a number of case-dependent variables together with demographic parameters (Beissinger and McCullough 2002). Multiple authors have used the program VORTEX (Lacy and Pollak 2014), an IBM used for PVA, to simulate the effects of avian mortality from wind farms on population dynamics of different species (Hötker et al. 2006; Carrete et al. 2009; García-Ripollés and López-López 2011; Rushworth and Krüger 2014). This type of modeling is mainly based on demographic parameters (e.g., mortality rates, population size, age at first reproduction), although some environmental variables such as carrying capacity can be incorporated. Sanz-Aguilar et al. (2015) designed a PVA without using VORTEX, using instead linear regression and

R based scripts to determine stochastic population growth. Nevertheless, their model is based on demographic parameters. Erickson et al. (2015), using branching process models, delivered a predictive model for the probability of extinction of four representative species: two bats and two birds. Although branching process models are in essence individual-based models, this output is characteristic of PVAs, and based on population dynamics. Rydell et al. (2012) presented a simple, deterministic population model based on population size, survival rates, fecundity and number of turbines. The mortality from wind turbines is a simple subtractive factor in the equation, dependent only on the annual mortality at each turbine and the number of turbines. Bellebaum et al. (2013) estimated mortality thresholds for red kites in Germany using a potential biological removal (PBR) model. They affirm that PBR models are needed to enable more precise estimations of thresholds for the added mortality from wind energy developments. In his PhD thesis, Dahl (2014) used a different approach and presented an age-structured matrix-based population model for the white-tailed eagle in Smøla, Norway. This model focused on the demographic parameters of the population in study, including not only survival rates but also reproductive success. In a report by Grünkorn et al. (2016), matrix and elasticity models were used to identify consequences of bird mortality at a population level, for three raptor species, taking into account age-specific mortality and reproduction rates. Lastly, Cook and Robinson (2017) recently published an article where they present a framework for assessing wind energy impacts at a population level using Leslie matrix models. These models consider a generic seabird species with characteristics derived from literature. Of note is the evaluation of decision criteria previously summarized by Green et al. (2016). The authors highlight the need for transparency when it comes to the use of demographic values of populations. However, it would be very difficult, if not impossible at the moment, to obtain demographic data for a large number of species at scales relevant to LCIA.

4.5. Index-based models

Data scarcity can be a constraint when modelling ecological processes, especially at higher scales when many different species are involved. To overcome this obstacle, index-based models can potentially be used as proxies, delivering score-based outputs on effects rather than, for instance, a number of individuals affected. Data requirements are lower, and often based on what is known of a species in terms of e.g., behavior, morphology, habitat use. Garthe and Hüppop (2004) developed a vulnerability index for species affected by offshore wind power farms, with a focus on German seas, based on different seabird characteristics as well as their conservation status. More recently, Furness et al. (2013) constructed similar indexes for collision and displacement impacts on Scottish marine birds. Although somewhat simplistic in its nature, this type of sensitivity indexes can be used to identify important impact sources, as well as map areas of higher risk, even when experimental data is not widely available. Using the indexes from these publications, Busch and Garthe (2016) developed a novel method for assessing displacement combining a matrix of potential displacement and mortality levels of seabirds from offshore wind farms with a potential biological removal (PBR) model (Wade 1998). Perhaps one of the methodologies that encompasses the most impacts of wind energy on bats and birds to date was designed by Diffendorfer et al. (2015). The methodology prioritizes species based on previously gathered data, combining each species' conservation status, as well as its relative risks from collision fatalities and habitat modification. The consequent impacts at a population level are then evaluated with the methodology's demographic and PBR models. The authors followed-up on this work, this time focusing on prioritizing bird taxonomic orders according to their impact risk indexes (Beston et al. 2016).

Table 2 goes here

5. On modeling biodiversity impacts from wind energy production in LCIA

The integration of wind energy impacts on biodiversity in LCIA should include all three aforementioned impact pathways: collision, disturbance and habitat alterations. Figure 1 illustrates how the impact pathways can conceptually be integrated into a logical assessment flow (conditions – state – effect – impact), and the potential contribution of the different prediction models to quantify these. We propose that separate characterization factors should be developed for the three impact pathways and both birds and bats. All bat and bird species should be grouped into guilds or groups depending on their morphology and behavior, in order to cover as many species as possible without requiring all information for every individual species (which may not be available). However, a final impact score should include all the impacts on all species groups together, expressed in common LCIA units such as potentially disappeared fraction of species (PDF) as recommended by the UNEP-SETAC Life Cycle Initiative (Verones et al. 2017). Verones et al. (2015) propose four different options to aggregate land and water use impact scores into a single score: equal weight for species, equal weight for taxa and two options with special consideration of species' vulnerability. Similar approaches could be used to combine impact scores for bats and birds, over the main impact pathways, into one score compatible with current LCIA methodologies. These options are particularly relevant when deciding if and which taxonomic groups between birds and bats should be given a higher impact score from wind energy developments.

The three impact pathways generally affect a species' probability of occurrence at a specific site. Whereas habitat alterations may lead to the loss of presence of a species at a site, displacement and collision reduce the number of individuals and thereby indirectly the probability of occurrence. Spatial estimation of species probability of occurrence can be done using SDMs. Harte et al. (2009) presents an approach on species-area relationships that estimates the number of species in a certain area through correlation of species richness with probability of occurrence. With such estimates, and knowing at which sites wind turbines are located, GIS tools can be used to quantify effects from wind energy developments in a spatially explicit manner. Estimating an altered probability of occurrence due to the expected effect, e.g. using respectively flight initiation distances (Blumstein 2006)and collision risk models (e.g. Tucker 1996, Band 2007), the expected loss of occurrence at a site can be determined,. MaxEnt, for instance, is a SDM that derives a score in each map cell proportional to the probability of occurrence of a species. Summing scores across species renders insight into the species richness at a site, allowing the calculation of regional and potentially global PDFs. An impact score can then be derived by applying species-area relationship models (SARs), which are already used in LCIA. Unlike classical SARs, which consider all biodiversity to be lost when habitat is changed, countryside SARs (Pereira and Daily 2009) factor in habitat suitability for a given species. This habitat suitability factor is analogous to the proposed use of MaxEnt scores. In addition, estimating a species distribution rather than directly using binary presence-absence range map is an improvement in terms of ecological significance.

Only in cases where population size and species distribution are known (either empirically or through estimation), can the number of affected individuals in each cell be determined. With such data, other approaches such as PVAs and IBMs also become feasible for developing (regional) LCIA models. Furthermore, if a relation between the area (or number of individuals) lost and probability of extinction is known, one can potentially quantify results directly in terms of PDF and therefore easily integrate the results in LCIA. However, to our knowledge, such relations are not known, and population data is scarce for a large number of species. As a generic approach for inclusion within the LCIA framework, such models are therefore deemed less appropriate. Although IBMs would give the most detail, they are in general too complex and data intensive to be able to cover a large number of species and spatial distribution. Nevertheless, future research can be done to further develop or adapt CRMs or index-based models in order to obtain a descriptive result of a fraction of species lost, or another justifiable unit in LCIA.

It is important to note that the three identified impact pathways are hierarchical. Displacement of individuals only occurs outside the area of habitat alteration. Only individuals which were not displaced face the risk of collision with turbines. This hierarchy should be taken into account to avoid double counting. However, species are known to respond behaviorally to these risks through avoidance, reducing the risk of an impact to occur (May 2015). Attraction of bats, or birds, towards wind turbines may on the contrary lead to increased occurrence and thereby a higher risk of collisions. Such pertinent avoidance and attraction effects should therefore also be taken into account.

Furthermore, it is necessary to take into consideration that different species or populations may be more vulnerable to an effect than others. Understanding a species' or species group's behavior and population dynamics is key to adequately integrating vulnerability at an impact level. (Verones et al. 2013) added a vulnerability score to their LCIA characterization factors for biodiversity impacts from water consumption. The authors developed this score from species geographical distribution ranges together with IUCN threat levels. More variables could be added in order to adapt this method to other types of impacts on biodiversity, such as those from onshore wind energy on bats and birds. It is also important to keep the spatial scale that the methodologies are developed for in mind. Characterization factors developed for a certain region may not be applicable in another, due to differences in species composition, vulnerability, as well as technical and environmental characteristics. Furthermore, data may not be available for every region in the same quantity or quality, which therefore adds uncertainty to methodologies developed at a global scale. In addition, scaling up or down (i.e., going from a local to a global spatial scale, or vice-versa) must take into consideration that species composition, as well as environmental variables, may change in the process. Wessman (1992) further develops on the issues of scaling, discussing the matter of extrapolation of environmental or ecological information in modelling approaches.

Irrespective of the approach used to quantify the impacts in question, various types of data are required (Table 1). Several existing databases cover some of these information needs (e.g., species data, turbine characteristics and locations, environmental data), while other types of data may require the use of allometric relationships (e.g., bird wing loading from body mass). Empirical species-related data at a global level can be obtained from BirdLife International (2016) on birds, while IUCN (2016) provides data on many other species groups, including threat status and range maps. For occurrence data, GBIF (2016) provides an open access database describing more than 1.6 million species. In addition, Wilman et al. (2014) compiled a great amount of data on animal diet and mass for all extant bird and mammal species, which can potentially be used to estimate important morphological parameters such as wing loading and aspect ratio using allometric relationships (Lindhe Norberg 2007). Lack of species data can also potentially be coped with by using better-known species, with similar characteristics, as proxies for a larger group (Denzinger and Schnitzler 2013). Such data can be used to, for instance, rank species according to characteristics that render them more vulnerable to the different effects of wind energy developments. Environmental data, such as wind speed and topography, may be required to predict a species' occurrence, especially when using SDM software such as MaxEnt. Temperature and wind speed data can be acquired from databases such as the NASA Langley Research Center Atmospheric Science Data Center Surface meteorological and Solar Energy (SSE) web portal (NASA 2016), among others. The U.S. Geological Survey (2016) provides remote sensing data, including digital terrain models. Technological data may be available through direct contact with the operating company, or local datasets. Remote sensing databases such as the CORINE Land Cover (Heymann et al. 2000) can provide information for present land cover types, which can also aid in the prediction of a species' preferred habitat. Knowledge on a species' flight initiation distance allows the determination of the extent of area disturbed for that species, although no database currently exists to provide these distances for a large number of bird species (but see Blumstein 2006). Lastly, although many of these databases provide relatively generic data, local datasets may also exist with higher resolution or more accurate data (e.g., in Norway: Artsdatabanken 2017; Kartverket 2017; NVE 2017) to complement larger databases.

Figure 1 goes here

6. Conclusions and recommendations

Available literature on the impacts of wind energy on biodiversity allowed this article to focus on two main research gaps: a lack of a review on predictive quantitative methods on the topic, and a lack of attempts to develop a methodology for LCIA to address this type of impacts. This is a first effort to provide the necessary background knowledge for the development of said LCIA methodology, in terms of the effects of wind energy on birds and bats and how these are modelled outside of LCA. Based on the results in this study, we can now start to develop LCIA models for assessing impacts of onshore wind power on birds and bats.

Collision, displacement and habitat alterations have been identified as the main impacts of wind energy on wildlife in numerous articles. According to current research, birds and bats are the most susceptible species groups to these effects for onshore wind turbines. As their responses to wind energy developments are considerably different, models should be developed separately for each of the two species groups. In addition, assessment of these species should take into consideration that within the two taxonomic groups there is considerable behavioral and morphological variation, especially among bird species.

Existing predictive models for the three main impact pathways show that quantitative estimations can be performed. GIS tools and remote sensing have proven invaluable in spatially differentiating areas of variable risk. More specifically, SDMs are widely used for determining areas of higher probability of conflict with biodiversity. This type of modelling has proven especially important in collision risk modelling, given the existing scarcity of data usually required by the more complex CRMs. However, an application of SDMs at a global scale for estimating wind energy impacts on biodiversity is still lacking. Index-based models offer a clear, simplistic approach to not only scale impacts according to the species' sensitivity, but to include certain aspects that are often excluded from assessments, particularly those related to a species vulnerability (e.g., life-history traits, behavior).

Inclusion of the three main pathways for impacts of wind energy on biodiversity in LCIA requires adaptation of these quantitative methods to the methodologies used in the LCA framework. In other words, results must be compatible with those of other ecosystem-related impact categories, which should be communicated in units of PDF (Verones et al. 2017). As an example, in order for a number of fatalities to be integrated, knowledge of a total number of individuals would be needed, so that a percentage loss of each species is obtained. This integration must be spatially explicit, with the support of GIS tools, given the variability between regions or countries in terms of ecosystem composition and wind energy technology. We suggest local characterization factors be constructed first, as data requirements should be lower and more accessible. Once a working model is in place, it should then be followed by an attempt of upscaling to a global level, taking into consideration data and technological constraints of up-scaling models. In either case, we point out that modelling habitat alterations, together with or followed by disturbance, is more readily feasible compared to collision. Modelling the first two impact pathways relies strongly on available GIS tools and remote sensing data, as well as knowledge of each species group's general behavior towards wind turbines. SDMs show promise in their ability to tackle this set of impacts, and can be combined with currently used SARs in order to directly obtain characterization factors in units of PDF, as described before. Vulnerability should be introduced at this point for instance by means of indexes, in order to weigh species according to how strongly they are affected.

The proposed LCIA development is not only a step towards more comprehensive impact assessments in LCA, but also outside of it. Most of the reviewed quantitative methods focused on only one or two of the three main impact pathways and at relatively small scales. Also, many studies are based on small samples or on few species that are not representative for all birds or bats (Sovacool 2013). This underlines the importance of grouping species after e.g. morphological similarities and creating archetypes for environmental conditions when data for all species and conditions is not available. Furthermore, there is still a lack of impact quantification relative to the energy produced by each turbine or wind farm. This hinders the possibility of an adequate comparison between wind energy production and other types of energy production, as well as between wind farms with variable production efficiencies. LCA has the potential to, in future, cover all these gaps, as well as integrate impacts on biodiversity from other energy sources.

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References

Ahlén I, Baagøe HJ, Bach L (2009) Behavior of Scandinavian Bats During Migration and Foraging At Sea. 90:1318–1323.

Arnett EB, Hayes JP, Huso MMP (2006) Patterns of pre-construction bat activity at a proposed wind facility in south-central Pennsylvania: 2005 Annual Report. An Annu Rep Prep Bats Wind Energy Coop 46 pp. doi: 10.1017/S0001972000001765

Arnett EB, Inkley DB, Larkin RP, et al (2007) Impacts of wind energy facilities on wildlife and wildlife habitat. Wildlife Society Technical Review 07- 2.

Artsdatabanken (2017) Artsdatabanken.

Arvesen A, Hertwich EG (2012) Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. Renew Sustain Energy Rev 16:5994–6006. doi: 10.1016/j.rser.2012.06.023

Azevedo LB, Henderson, Andrew, van Zelm R, et al (2013) Assessing the importance of spatial variability versus madel choices in life cycle impact assessment: The case of freshwater eutrophication in Europe. Am Chem Soc 47:13565–13570.

Baerwald EF, Barclay RMR (2011) Patterns of activity and fatality of migratory bats at a wind energy facility in Alberta, Canada. J Wildl Manage 75:1103–1114. doi: 10.1002/jwmg.147

Baerwald EF, Edworthy J, Holder M, Barclay RMR (2009) A Large-Scale Mitigation Experiment Fatalities at Wind Energy Facilities. J Wildl Manage 73:1077–1081. doi: 10.2193/2008-233

Band MW, Madders M, Whitfield DP (2007) Developing field and analytical methods to assess avian collision risk at wind farms. Birds Wind farms risk Assess Mitig 259–275.

Barclay RMR, Baerwald EF, Gruver JC (2007) Variation in bat and bird fatalities at wind energy facilities: assessing the effects of rotor size and tower height. Can J Zool 85:381–387. doi: 10.1139/Z07-011

Barrios L, Rodríguez A (2004) Behavioural and environmental correlates of soaring-bird mortality an an-shore wind turbines. J Appl Ecol 41:72–81. doi: 10.1111/j.1365-2664.2004.00876.x

Bastos R, Pinhancos A, Santos M, et al (2016) Evaluating the regional cumulative impact of wind farms on birds: how can spatially explicit dynamic modelling improve impact assessments and monitoring? J Appl Ecol

53:1330–1340. doi: 10.1111/1365-2664.12451

Beissinger SR, McCullough DR (2002) Population viability analysis. University of Chicago Press

Bellebaum J, Korner-Nievergelt F, Dürr T, Mammen U (2013) Wind turbine fatalities approach a level of concern in a raptor population. J Nat Conserv 21:394–400. doi: 10.1016/j.jnc.2013.06.001

Beston JA, Diffendorfer JE, Loss SR, Johnson DH (2016) Prioritizing avian species for their risk of population-level consequences from wind energy development. PLoS One. doi: 10.1371/journal.pone.0150813

Bevanger K (1994) Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. Ibis (Lond 1859) 136:412–425. doi: 10.1111/j.1474-919X.1994.tb01116.x

BirdLife International (2017) Soaring Bird Sensitivity Map. http://migratorysoaringbirds.undp.birdlife.org/en/sensitivity-map.

BirdLife International (2016) BirdLife Data Zone. http://www.birdlife.org/datazone/home. Accessed 12 Dec 2016

Blumstein DT (2006) Developing an evolutionary ecology of fear: How life history and natural history traits affect disturbance tolerance in birds. Anim Behav 71:389–399. doi: 10.1016/j.anbehav.2005.05.010

Bright J, Langston RHW, Bullman R, et al (2008) Map of bird sensitivities to wind farms in Scotland: A tool to aid planning and conservation. Biol Conserv 141:2342–2356. doi: 10.1016/j.biocon.2008.06.029

Brinkmann R (2006) Survey of possible operational impacts on bats by wind facilities in Southern Germany. A Rep ordered by Adm Dist Freibg - Dep 56 Conserv Landsc Manag 63 pp.

Brinkmann R, Mayer K, Kretzschmar F, Witzlebeben J V. (2006) Auswirkungen von Windkraftanlagen auf Fledermäuse. 11.

Busch M, Garthe S (2016) Approaching population thresholds in presence of uncertainty : Assessing displacement of seabirds from offshore wind farms. Environ Impact Assess Rev 56:31–42. doi: 10.1016/j.eiar.2015.08.007

Bybsys (2017) Oria.

Calvert AM, Bishop C a, Elliot RD, et al (2013) A Synthesis of Human-related Avian Mortality in Canada Synthèse des sources de mortalité aviaire d ' origine anthropique au Canada. Avian Conserv Ecol 8:11. doi: http://dx.doi.org/10.5751/ACE-00581-080211

Carrete M, Sánchez-Zapata J a., Benítez JR, et al (2009) Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. Biol Conserv 142:2954–2961. doi: 10.1016/j.biocon.2009.07.027

Chamberlain DE, Rehfisch MR, Fox AD, et al (2006) The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. Ibis (Lond 1859) 148:198–202. doi: 10.1111/j.1474-919X.2006.00507.x

Chaudhary A, Verones F, De Baan L, Hellweg S (2015) Quantifying Land Use Impacts on Biodiversity: Combining Species-Area Models and Vulnerability Indicators. Environ Sci Technol 49:9987–9995. doi: 10.1021/acs.est.5b02507

Cook ASCP, Humphreys EM, Masden EA, Burton NHK (2014) The Avoidance Rates of Collision Between Birds and Offshore Turbines. 5:33. doi: 10.7489/1616-1

Cook ASCP, Robinson RA (2017) Towards a framework for quantifying the population-level consequences of anthropogenic pressures on the environment: The case of seabirds and windfarms. J Environ Manage 190:113–121. doi: 10.1016/j.jenvman.2016.12.025

Cosme N, Jones MC, Cheung WWL, Larsen HF (2017) Spatial differentiation of marine eutrophication damage indicators based on species density. Ecol Indic 73:676–685. doi: 10.1016/j.ecolind.2016.10.026

Cryan PM, Barclay RMR, Arnett EB, et al (2008) Mating Behavior as a Possible Cause of Bat Fatalities at Wind Turbines. An Annu Rep Prep Bats Wind Energy Coop 14:1330–1340. doi: 10.3161/150811012X661756

Cryan PM, Gorresen PM, Hein CD, et al (2014) Behavior of bats at wind turbines. Proc Natl Acad Sci 111:15126–15131. doi: 10.1073/pnas.1406672111

Dahl EL (2014) Population dynamics in white-tailed eagle at an on-shore wind farm area in coastal Norway.

Dai K, Bergot A, Liang C, et al (2015) Environmental issues associated with wind energy – A review. Renew Energy 75:911–921. doi: 10.1016/j.renene.2014.10.074

de Baan L, Mutel CL, Curran M, et al (2013) Land use in life cycle assessment: global characterization factors based on regional and global potential species extinction. Environ Sci Technol 47:9281–90. doi: 10.1021/es400592q

de Lucas M, Janss GFE, Whitfield DP, Ferrer M (2008) Collision fatality of raptors in wind farms does not depend on raptor abundance. J Appl Ecol 45:1695–1703. doi: 10.1111/j.1365-2664.2008.01549.x

Denzinger A, Schnitzler HU (2013) Bat guilds, a concept to classify the highly diverse foraging and echolocation behaviors of microchiropteran bats. Front Physiol 4 JUL:1–15. doi: 10.3389/fphys.2013.00164

Diffendorfer JE, Beston JA, Merrill MD, et al (2015) Preliminary Methodology to Assess the National and Regional Impact of U.S. Wind Energy Development on Birds and Bats.

Drewitt AL, Langston RHW (2006) Assessing the impacts of wind farms on birds. Ibis (Lond 1859) 148:29–42.

Drewitt AL, Langston RHW (2008) Collision effects of wind-power generators and other obstacles on birds. Ann N Y Acad Sci 1134:233–266. doi: 10.1196/annals.1439.015

Duerr AE, Miller TA, Lanzone M, et al (2012) Testing an emerging paradigm in migration ecology shows surprising differences in efficiency between flight modes.

Edenhofer O, Pichs-Madruga R, Sokona Y, et al (2012) Renewable energy sources and climate change mitigation:

special report of the Intergovernmental Panel on Climate Change.

Eichhorn M, Johst K, Seppelt R, Drechsler M (2012) Model-based estimation of collision risks of predatory birds with wind turbines. Ecol Soc. doi: org/10.5751/ES-04594-170201

Elith J, Graham CH, Anderson RP, et al (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography (Cop) 29:129–151. doi: 10.1111/j.2006.0906-7590.04596.x

Elsevier (2017) Elsevier.

Erickson RA, Eager EA, Stanton JC, et al (2015) Assessing local population vulnerability with branching process models: an application to wind energy development. Ecosphere 6:art254. doi: 10.1890/ES15-00103.1

Erickson WP, Johnson GD, Young Jr DP (2005) A Summary and Comparison of Bird Mortality from Anthropogenic Causes with an Emphasis on Collisions. USDA For Serv Gen Tech PSW-GTR-19:1029–1042. doi: Erickson, Wallace P, Gregory D Johnson, and David P Young Jr. 2005. "A Summary and Comparison of Bird Mortality from Anthropogenic Causes with an Emphasis on Collisions."

Evans A, Strezov V, Evans TJ (2009) Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 13:1082–1088. doi: 10.1016/j.rser.2008.03.008

Ferreira D, Freixo C, Cabral JA, et al (2015) Do habitat characteristics determine mortality risk for bats at wind farms? Modelling susceptible species activity patterns and anticipating possible mortality events. Ecol Inform 28:7–18. doi: 10.1016/j.ecoinf.2015.04.001.

Furmankiewicz J, Kucharska M (2009) Migration of Bats Along a Large River Valley in Southwestern Poland. J Mammal 90:1310–1317. doi: 10.1644/09-MAMM-S-099R1.1

Furness RW, Wade HM, Masden EA (2013) Assessing vulnerability of marine bird populations to offshore wind farms. J Environ Manage 119:56–66. doi: 10.1016/j.jenvman.2013.01.025

García-Ripollés C, López-López P (2011) Integrating effects of supplementary feeding, poisoning, pollutant ingestion and wind farms of two vulture species in Spain using a population viability analysis. J Ornithol 152:879–888. doi: 10.1007/s10336-011-0671-8

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. doi: 10.1111/j.0021-8901.2004.00918.x

Garvin JC, Jennelle CS, Drake D, Grodsky SM (2011) Response of raptors to a windfarm. J Appl Ecol 48:199–209. doi: 10.1111/j.1365-2664.2010.01912.x

GBIF (2016) Global Biodiversity Information Facility.

Google (2017) Google Scholar.

Green RE, Langston RHW, McCluskie A, et al (2016) Lack of sound science in assessing wind farm impacts on seabirds. J Appl Ecol 53:1635–1641. doi: 10.1111/1365-2664.12731

Grimm V, Berger U, Bastiansen F, et al (2006) A standard protocol for describing individual-based and agent-based models. Ecol Modell 198:115–126. doi: 10.1016/j.ecolmodel.2006.04.023

Grünkorn T, Blew J, Coppack T, et al (2016) Ermittlung der Kollisionsraten von (Greif)Vögeln und Schaffung planungsbezogener Grundlagen für die Prognose und Bewertung des Kollisionsrisikos durch Windenergieanlagen (PROGRESS). 338.

Guisan A, Thuiller W (2005) Predicting species distribution: Offering more than simple habitat models. Ecol Lett 8:993–1009. doi: 10.1111/j.1461-0248.2005.00792.x

Harte J, Smith AB, Storch D (2009) Biodiversity scales from plots to biomes with a universal species-area curve. Ecol Lett 12:789–797. doi: 10.1111/j.1461-0248.2009.01328.x

Hauschild MZ, Huijbregts MAJ (2015) Life cycle impact assessment.

Hayes MA, Cryan PM, Wunder MB (2015) Seasonally-dynamic presence-only species distribution models for a cryptic migratory bat impacted by wind energy development. PLoS One 10:1–20. doi: 10.1371/journal.pone.0132599

Hein C, Schirmacher M (2016) Impact of wind energy on bats : a summary of our current knowledge. Human–Wildlife Interact 10(1)19–27, 10:19–27.

Herrera-Alsina L, Villegas-Patraca R, Eguiarte LE, Arita HT (2013) Bird communities and wind farms: A phylogenetic and morphological approach. Biodivers Conserv 22:2821–2836. doi: 10.1007/s10531-013-0557-6

Heymann Y, Steenmans C, Croissille G, Bossard M (2000) CORINE land cover technical guide. Off Publ Eur Communities 1–94.

Hirzel AH, Hausser J, Chessel D, Perrin AN (2002) Ecological-Niche Factor Analysis: How To Compute Habitat-Suitability Maps Without Absence Data? Ecology 83:2027–2036. doi: 10.1890/0012-9658(2002)083[2027:ENFAHT]2.0.CO;2

Hodos W (2003) Minimization of motion smear: reducing avian collisions with wind turbines. Subcontract Rep period Perform July 12, 1999 - August 31, 2002 43.

Holmstrom L a., Hamer TE, Colclazier EM, et al (2011) Assessing Avian-Wind Turbine Collision Risk: An Approach Angle Dependent Model. Wind Eng 35:289–312. doi: 10.1260/0309-524X.35.3.289

Hötker H, Thomsen K, Jeromin H (2006) Impacts on biodiversity of exploitation of renewable energy sources: the example of birds and bats - facts, gaps in knowledge, demands for further research, and ornithological guidelines for the development of renewable energy exploitation. Michael-Otto-Institut im NABU, Berghusen 1–65.

IEA (2016) Key Renewables Trends - Excerpt from: Renewables information.

International Energy Agency (2013) Technology roadmap - Wind energy. Technol Roadmap 58.

IUCN (2016) The IUCN Red List of Threatened Species - Version 2016-1. http://www.iucnredlist.org. Accessed 20 Jul 2016

Janss GFE (2000) Avian mortality from power lines: A morphologic approach of a species-specific mortality. Biol Conserv 95:353–359. doi: 10.1016/S0006-3207(00)00021-5

Johnson GD, Perlik MK, Erickson WP, Strickland MD (2004) Bat activity, composition, and collision mortality at a large wind plant in Minnesota. Wildl Soc Bull 32:1278–1288. doi: 10.2193/0091-7648(2004)032[1278:BACACM]2.0.CO;2

Kartverket (2017) Geonorge. https://www.geonorge.no/. Accessed 28 Jul 2017

Korner-Nievergelt F, Brinkmann R, Niermann I, Behr O (2013) Estimating Bat and Bird Mortality Occurring at Wind Energy Turbines from Covariates and Carcass Searches Using Mixture Models. PLoS One 8:e67997. doi: 10.1371/journal.pone.0067997

Kunz TH, Arnett EB, Cooper BM, et al (2007a) Assessing Impacts of Wind-Energy Development on Nocturnally Active Birds and Bats: A Guidance Document. J Wildl Manage 71:2449–2486. doi: 10.2193/2007-270

Kunz TH, Arnett EB, Erickson WP, et al (2007b) Ecological impacts of wind energy development on bats: Questions, research needs, and hypotheses. Front Ecol Environ 5:315–324. doi: 10.1890/1540-9295(2007)5[315:EIOWED]2.0.CO;2

Kuvlesky WP, Brennan LA, Morrison ML, et al (2007) Wind Energy Development and WIldlife Conservation: Challenges and Opportunities. J Wildl Manage 71:2487–2498. doi: 10.2193/2007-248

Lacy RC, Pollak JP (2014) Vortex: A stochastic simulation of the extinction process.

Langston RHW (2013) Birds and wind projects across the pond: A UK perspective. Wildl Soc Bull 37:5–18. doi: 10.1002/wsb.262

Langston RHW, Pullan JD (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. 58.

Larsen JK, Madsen J (2000) Effects of wind turbines and other physical elements on field utilization by pink-footed geese (Anser brachyrhynchus): A landscape perspective. Landsc Ecol 15:755–764. doi: 10.1023/A:1008127702944

Liechti F, Guélat J, Komenda-Zehnder S (2013) Modelling the spatial concentrations of bird migration to assess conflicts with wind turbines. Biol Conserv 162:24–32. doi: 10.1016/j.biocon.2013.03.018

Lindhe Norberg UM (2007) Flight and scaling of flyers in nature.

Madsen J, Boertmann D (2008) Animal behavioral adaptation to changing landscapes: Spring-staging geese habituate to wind farms. Landsc Ecol 23:1007–1011. doi: 10.1007/s10980-008-9269-9

Marques AT, Batalha H, Rodrigues S, et al (2014) Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. Biol Conserv 179:40–52. doi: 10.1016/j.biocon.2014.08.017

Martínez E, Sanz F, Pellegrini S, et al (2009) Life cycle assessment of a multi-megawatt wind turbine. Renew Energy 34:667–673. doi: 10.1016/j.renene.2008.05.020

Masden EA (2010) Assessing the cumulative impacts of wind farms on birds.

Masden EA, Cook ASCP (2016) Avian collision risk models for wind energy impact assessments. Environ Impact Assess Rev 56:43–49. doi: 10.1016/j.eiar.2015.09.001

Masden EA, Fox AD, Furness RW, et al (2010a) Cumulative impact assessments and bird/wind farm interactions: Developing a conceptual framework. Environ Impact Assess Rev 30:1–7. doi: 10.1016/j.eiar.2009.05.002

Masden EA, Haydon DT, Fox AD, et al (2009) Barriers to movement: Impacts of wind farms on migrating birds. ICES J Mar Sci 66:746–753. doi: 10.1093/icesjms/fsp031

Masden EA, Haydon DT, Fox AD, Furness RW (2010b) Barriers to movement: Modelling energetic costs of avoiding marine wind farms amongst breeding seabirds. Mar Pollut Bull 60:1085–1091. doi: 10.1016/j.marpolbul.2010.01.016

Masden EA, Reeve R, Desholm M, et al (2012) Assessing the impact of marine wind farms on birds through movement modelling. J R Soc Interface 9:2120–30. doi: 10.1098/rsif.2012.0121

May R (2015) A unifying framework for the underlying mechanisms of avian avoidance of wind turbines. Biol Conserv 190:179–187. doi: 10.1016/j.biocon.2015.06.004

May R, Bevanger K (2011) Proceedings: Conference on Wind Energy and Wildlife Impacts, 2-5 May 2011, Trondheim, Norway.

May R, Gill AB, Köppel J, et al (2017) Future Research Directions to Reconcile Wind Turbine–Wildlife Interactions. In: Wind Energy and Wildlife Interactions. Springer, pp 255–276

May R, Hoel PL, Langston RHW (2010) Collision risk in white-tailed eagles.

May R, Nygård T, Dahl EL, Bevanger K (2013) Habitat utilization in white-tailed eagles (*Haliaeetus albicilla*) and the displacement impact of the Smøla wind-power plant. Wildl Soc Bull 37:75–83. doi: 10.1002/wsb.264

May R, Reitan O, Bevanger K, et al (2015) Mitigating wind-turbine induced avian mortality: Sensory, aerodynamic and cognitive constraints and options. Renew Sustain Energy Rev 42:170–181. doi: 10.1016/j.rser.2014.10.002

Mcnew LB, Hunt LM, Gregory AJ, et al (2014) Effects of wind energy development on nesting ecology of greater prairie-chickens in fragmented grasslands. Conserv Biol 28:1089–1099. doi: 10.1111/cobi.12258

Mendeley Ltd. (2016) Mendeley.

Miller TA, Brooks RP, Lanzone M, et al (2014) Assessing risk to birds from industrial wind energy development via paired resource selection models. Conserv Biol 28:745–755. doi: 10.1111/cobi.12227

Munday PL (2004) Habitat loss, resource specialization, and extinction on coral reefs. Glob Chang Biol 10:1642–1647. doi: 10.1111/j.1365-2486.2004.00839.x

NASA (2016) NASA Langley Research Center Atmospheric Science Data Center - Surface meteorology and Solar Energy (SSE). https://eosweb.larc.nasa.gov/project/sse/sse_table. Accessed 20 Jul 2016

New L, Bjerre E, Millsap B, et al (2015) A Collision Risk Model to Predict Avian Fatalities at Wind Facilities: An Example Using Golden Eagles, Aquila chrysaetos. PLoS One 10:e0130978. doi: 10.1371/journal.pone.0130978

NVE (2017) NVE Kartkatalog. http://gis3.nve.no/kartkatalog/metadatahg_datasett.html. Accessed 28 Jul 2017

Pearce-Higgins J, Stephen L, Langston RHW, Bright J (2008) Assessing the cumulative impacts of wind farms on peatland birds: a case study of golden plover Pluvialis apricaria in Scotland. Mires Peat 4:1–13.

Pearce-Higgins JW, Stephen L, Douse A, Langston RHW (2012) Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. J Appl Ecol 49:386–394. doi: 10.1111/j.1365-2664.2012.02110.x

Pearce-Higgins JW, Stephen L, Langston RHW, et al (2009) The distribution of breeding birds around upland wind farms. J Appl Ecol 1323–1331. doi: 10.1111/j.1365-2664.2009.01715.x

Pearson RG, Raxworthy CJ, Nakamura M, Townsend Peterson a. (2007) Predicting species distributions from small numbers of occurrence records: A test case using cryptic geckos in Madagascar. J Biogeogr 34:102–117. doi: 10.1111/j.1365-2699.2006.01594.x

Pedersen MB, Poulsen E (1991) Impact of a 90m/2MW wind turbine on birds: avian responses to the implementation of the Tjaereborg wind turbine at the Danish Wadden Sea. Danske Vildtundersogelser 47:1–44.

Pennycuick CJ (2008) Modelling the Flying Bird. Elsevier

Pereira HM, Daily GC (2009) Modeling Biodiversity Dynamics in Countryside Landscapes Published by : Ecological Society of America Stable URL : http://www.jstor.org/stable/20069170 Your use of the JSTOR archive indicates your acceptance of JSTOR â€™ s Terms and Conditions of Use , avai. 87:1877–1885.

Petersen IK, Monique M, Rexstad EA, et al (2011) Comparing pre- and post-construction distributions of long-tailed ducks Clangula hyemalis in and around the Nysted offshorewind farm, Denmark: a quasi-designed experiment accounting for imperfect detection, local surface features and autocorrelation. 1–16.

Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. Ecol

Modell 190:231–259. doi: 10.1016/j.ecolmodel.2005.03.026

Pocewicz A, Estes-Zumpf WA, Andersen MD, et al (2013) Mapping Migration: Important places for Wyoming's migratory birds. 1–16.

Podolsky R (2008) Method of and article of manufacture for determining probability of avian collision. US Pat 7,315,799 1:14pp.

Rayner JM V. (1988) Form and function in avian flight. Curr. Ornithol. vol.5 1–66.

Rebelo H, Jones G (2010) Ground validation of presence-only modelling with rare species: a case study on barbastelles *Barbastella barbastellus* (Chiroptera: Vespertilionidae). J Appl Ecol 47:410–420. doi: 10.1111/j.1365-2664.2009.01765.x

Reid T, Krüger S, Whitfield DP, Amar A (2015) Using spatial analyses of bearded vulture movements in southern Africa to inform wind turbine placement. J Appl Ecol 52:881–892. doi: 10.1111/1365-2664.12468

Richardson WJ (1998) Bird migration and wind turbines: Migration timing, flight behaviour and collision risk. Proc Natl Avian- Wind Power Plan Meet III 132–140.

Roscioni F, Rebelo H, Russo D, et al (2014) A modelling approach to infer the effects of wind farms on landscape connectivity for bats. Landsc Ecol 29:891–903. doi: 10.1007/s10980-014-0030-2

Rushworth I, Krüger S (2014) Wind farms threaten southern Africa's cliff-nesting vultures. Ostrich 85:13–23. doi: 10.2989/00306525.2014.913211

Rydell J, Bach L, Dubourg-Savage M-J, et al (2010a) Mortality of bats at wind turbines links to nocturnal insect migration? Eur J Wildl Res 56:823–827. doi: 10.1007/s10344-010-0444-3

Rydell J, Bach L, Dubourg-Savage M-J, et al (2010b) Bat Mortality at Wind Turbines in Northwestern Europe. Acta Chiropterologica 12:261–274. doi: 10.3161/150811010X537846

Rydell J, Engström H, Swedish T, et al (2012) The effect of wind power on birds and bats power - a synthesis.

Santos H, Rodrigues L, Jones G, Rebelo H (2013) Using species distribution modelling to predict bat fatality risk at wind farms. Biol Conserv 157:178–186. doi: 10.1016/j.biocon.2012.06.017

Sanz-Aguilar A, Sánchez-Zapata JA, Carrete M, et al (2015) Action on multiple fronts, illegal poisoning and wind farm planning, is required to reverse the decline of the Egyptian vulture in southern Spain. Biol Conserv 187:10–18. doi: 10.1016/j.biocon.2015.03.029

Schaub M (2012) Spatial distribution of wind turbines is crucial for the survival of red kite populations. Biolgical Conserv 155:111–118. doi: 10.1016/j.biocon.2012.06.021

Schuster E, Bulling L, Köppel J (2015) Consolidating the State of Knowledge: A Synoptical Review of Wind Energy's Wildlife Effects. Environ Manage 56:300–331. doi: 10.1007/s00267-015-0501-5

Smallwood KS, Rugge L, Morrison ML (2009) Influence of Behavior on Bird Mortality in Wind Energy Developments. J Wildl Manage 73:1082–1098. doi: 10.2193/2008-555

Smallwood KS, Thelander CG (2004) Developing methods to reduce bird mortality in the Altamont Pass Wind Resource Area.

Smallwood KS, Thelander CG, Morrison ML, Rugge LM (2007) Burrowing Owl Mortality in the Altamont Pass Wind Resource Area. J Wildl Manage 71:1513–1524. doi: 10.2193/2006-307

Sovacool BK (2013) The avian benefits of wind energy: A 2009 update. Renew Energy 49:19–24. doi: 10.1016/j.renene.2012.01.074

Swihart RK, Gehring TM, Kolozsvary MB, Nupp TE (2003) Responses of'resistant'vertebrates to habitat loss and fragmentation: the importance of niche breadth and range boundaries. Divers Distrib 9:1–18. doi: 10.1046/j.1472-4642.2003.00158.x

Tucker VA (1996a) Using a Collision Model to Design Safer Wind Turbine Rotors for Birds. J. Sol. Energy Eng. 118:263.

Tucker V a. (1996b) A Mathematical Model of Bird Collisions With Wind Turbine Rotors. J Sol Energy Eng 118:253. doi: 10.1115/1.2871788

U.S. Geological Survey (2016) Earth Resources Observation and Science (EROS) Center. http://eros.usgs.gov/. Accessed 20 Jul 2016

Verones F, Bare J, Bulle C, et al (2017) LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. J Clean Prod 161:957–967. doi: 10.1016/j.jclepro.2017.05.206

Verones F, Huijbregts MAJ, Chaudhary A, et al (2015) Harmonizing the assessment of biodiversity effects from land and water use within LCA. Environ Sci Technol 49:3584–3592. doi: 10.1021/es504995r

Verones F, Pfister S, van Zelm R, Hellweg S (2016) Biodiversity impacts from water consumption on a global scale for use in life cycle assessment. Int J Life Cycle Assess 1–10. doi: 10.1007/s11367-016-1236-0

Verones F, Saner D, Pfister S, et al (2013) Effects of consumptive water use on biodiversity in wetlands of international importance. Environ Sci Technol 47:12248–57. doi: 10.1021/es403635j

Wade PR (1998) Calculating limits to the allowable human-caused mortality of Cetatceans and Pinnipeds. Mar Mammal Sci 14:1–37. doi: 10.1111/j.1748-7692.1998.tb00688.x

Wang S, Wang S, Smith P (2015) Ecological impacts of wind farms on birds: Questions, hypotheses, and research needs. Renew Sustain Energy Rev 44:599–607. doi: 10.1016/j.rser.2015.01.031

Warwick-Evans V, Atkinson PW, Walkington I, Green JA (2017) Predicting the impacts of windfarms on seabirds: an Individual Based Model. J Appl Ecol 1–13. doi: 10.1111/1365-2664.12996

Wessman CA (1992) Spatial scale and global change: Bridging the gap from plots to GCM grid cells. Annu Rev Ecol Syst 23:175–200.

Wilman H, Belmaker J, Simpson J, et al (2014) EltonTraits 1.0: Species-level foraging attributes of the world's birds and mammals. Ecology 95:2027. doi: 10.1890/13-1917.1

Winter Y (1999) Flight speed and body mass of nectar-feeding bats (Glossophaginae) during foraging. J Exp Biol 202:1917–1930.