centre for sustainable energy

Common concerns about wind power (2nd edn)

Chapter 11
What effect do wind turbines have on wildlife?

This is one of a series of chapters of evidence-based analysis drawing on peer-reviewed academic research and publicly funded studies.

For other chapters, see
www.cse.org.uk/concerns-wind-power-2017

Centre for Sustainable Energy, June 2017

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The first edition of Common Concerns about Wind Power was published in 2011 to provide factual information about wind energy, in part to counter the many myths and misconceptions surrounding this technology.

Since 2011, much has changed in the legal and economic sphere, and a second edition became necessary. Research has been carried out for this edition since 2014. Therefore, this edition is formatted as a series of individual chapters available for download at
www.cse.org.uk/concerns-wind-power-2017

All chapters written and researched by Iain Cox.

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Written and researched: 2016

The Centre for Sustainable Energy is a national charity committed to ending the misery of cold homes and fighting climate change.

We share our knowledge and practical experience to empower people to change the way they think and act about energy.

We are based in Bristol although most of our work has relevance and impact across the UK. Our clients and funders include national, regional and local government agencies, energy companies and charitable sources.

Chapter 11

What effect do wind turbines have on wildlife?

Summary

Reports of excessive avian mortality present in some of the first large-scale wind farms built in the 1980s, which particularly affected some protected and endangered bird of prey species, have cemented a long-standing misconception that most wind turbines will inevitably cause disproportionate harm to bird populations in the vicinity. In fact, wind turbines kill far fewer birds than other human activities. Birds colliding with building windows and the predations of domestic and feral cats are the leading causes of avian mortality due to human activity, and both far exceed anything caused by wind turbines. In terms of emissions and pollutants and the wider impacts these can have on wildlife, wind is also a significantly more benign source of electricity when compared to conventional forms of power generation.

Of more concern is the issue of bat fatalities, which may have a proportionally larger and more damaging effect due to the slow rate at which bats reproduce. The foraging and migratory patterns of bats are not well understood, although more data is being amassed across sites in Europe and America. Although it is thought that the unexpectedly high mortality at some sites may be accounted for by altered behaviour during seasonal migrations, there is the possibility that bats may be affected when following normal foraging patterns too. Thus, the matter is still subject to a significant degree of uncertainty, and there is an urgent need to acquire more data and incorporate what existing – albeit limited – knowledge of bat movements there is into the decision process when siting wind farms and placing individual turbines. There have been encouraging signs that some mitigation methods may be able to significantly reduce bat mortality rates, but these are so far unproven on a large scale.

Very little is known about the effects of wind turbines on non-volant animals (i.e. animals that do not fly), with only a limited number of studies on certain terrestrial species. Most evidence suggests that wind turbines have no discernable effect on the behaviour and population levels of the animals studied, which includes elk, reindeer, ground squirrels and tortoises. Although not as apparently pressing an issue as is the case for bats, there is clearly much scope for research to be done on terrestrial species as the number of operational wind farms continues to increase. In addition, it has been noted that many wind farm operators remain reluctant to openly share data on wildlife mortality, which harms research and may ultimately lead to flawed policy planning.

What is this based on?

Avian mortality due to all sorts of human activity (anthropogenic causes) has been well-documented for many decades, and is an ongoing area of research.[1–8] Some of the first large-scale wind farms built in the 1980s had a number of attributes that, it was soon realised, were causing a worryingly high number of avian fatalities due to birds colliding with operating turbines.[9] As well as some design features, the placement of these wind farms across habitats used by ecologically sensitive bird of prey (raptor) populations compounded the problem, resulting in particularly deleterious effect on some protected populations of rare species.[10] These instructive incidents took place in major wind developments built in several regions of Spain and in the US state of California.

Since the 1980s, changes in turbine design, size and siting procedures have reduced the extent of damage to avian wildlife by wind farms built subsequently, but the mistakes of earlier projects have created a deeply rooted misconception that most wind farms will inevitably cause disproportionate harm to bird populations in the vicinity. In fact, this is demonstrably not the case, with data suggesting that wind turbines kill far fewer birds than other human activities.[11] However, the impact on avian mortality should not be trivialised. As will be discussed subsequently, impacts can be disproportionate for certain species, and there are limitations to the existing data. Hence, ongoing concerns are not entirely unjustified.

The significant impact wind turbines can have on bat populations was first appreciated when reports emerged from the USA of a small number of wind farms in the Appalachian Mountains where surprisingly large numbers of bat carcasses had been found.[12,13] Although these particular instances seemed out of the ordinary, since other wind farms in the USA had reported much lower levels of bat mortality, the fact that bat population growth is relatively slow means they have a limited ability to recover from excess deaths.[14] This concern prompted more research into bat deaths at wind farm sites, and similar problems were also found at sites across Europe.[15] Deaths occur between many different species of bat, some populations of which are more sensitive to population decline than others.

Unlike the case of avian deaths, there is as yet no clear link between the general characteristics of wind farm sites, e.g. topography, and bat mortality caused by wind turbines. Why some species are affected at one site and different species are affected at another site is also not clear, although migratory patterns are likely to play an important role.[14,16] The evolution of wind turbine design and siting has not had the same effect of reducing mortality for bats as it has for birds.[17] The relative lack of data on bat behaviour also means that mitigation methods are not yet proven, although there are promising results from a few trials.

Not surprisingly, *volant* species (animals able to fly or glide) have been the focus of research with regards to the effect wind turbines have on wildlife. Comparably, the published research on the impact of wind turbines on *non-volant* species (animals that cannot fly) is sparse.[18] Pilot studies on terrestrial species, such as reindeer and caribou, suggest wind turbines do not have any meaningful impact on these populations. As discussed later on in this chapter, there is some limited evidence that wind turbine installations may affect prey–predator relationships both on land and in the sea, although in several cases the impact may have a beneficial effect on some species.

Limitations of existing data

Although several large-scale studies appear to be converging on roughly comparable estimates for avian deaths attributable to wind turbines[1,3] there remains a great deal of uncertainty within each data set, which often contain biases or wide-ranging estimates as a result.[1,2] Inconsistencies are evident when different data sets are compared, which is compounded by a lack of clarity in the way avian deaths at wind farm sites are often reported by the industry.[2,3] There are issues with the way areas are searched for evidence of bird fatalities, such as monitoring periods that are too short or fail to account for seasonal variability, difficulties inherent in finding carcasses in the first place, inappropriate intervals between routine carcass searches, and search radii that are too small.[2,1,19,20] We can ‘unpack’ some of these limitations, which helps illustrate the complexities inherent in assessing environmental impacts.

Not accounting for seasonal variability is an important consideration when monitoring wildlife impacts, especially for avian or bat species that are migratory. Monitoring periods are often too short (sometimes just six to eight weeks in a year) to account for interannual changes in population number. Although the timing of these monitoring periods are usually based on seasonal periods predicted to have high mortality, these short windows can have the effect of underestimating year-round mortality. Not only are significant fatalities missed in outside periods, but shorter search period means that fewer carcasses are found, which skews data when extrapolated.[2] To more effectively estimate year-round mortality, data should be collected in all seasons. For migratory populations, data should be collected throughout the whole migration period, rather than transecting the study population at one point during the migratory period.[19]

One ubiquitous limitation is low searcher-detection rate, which is a constant problem for any environmental impact study that relies on monitoring carcasses (bird, bat or otherwise), although there are statistical models to account for this; these models, however, require the application of appropriate search intervals.[2,20] For instance, a carcass missed by a searcher on a first pass may very likely be taken by scavengers within three days, so too long an interval between passes during any particular monitoring period will underestimate fatalities. Carcasses that have been dismembered by contact with turbine blades are harder to detect, as are carcasses that have been missed on the first pass and subsequently decomposed (if not taken by a scavenger already). A one-day interval between searcher passes may introduce a very slight positive bias into fatality rates, because, for example, dead birds killed by something other than the wind turbines are also more likely to be detected and may be included in the total for turbine-related fatalities.

Conversely, search intervals of seven days or more introduce a strong negative bias as many carcasses will be missed due to decomposition and removal by scavengers.[2] As mentioned already, these effects can be modelled to some degree, but search intervals must be appropriate and be consistently applied and clearly reported.[1,3,20] All of this also underlines the need to increase the chance of finding a carcass in the first place as much as possible. This can be accomplished, for example, by ensuring intervals between searches are not too long, or improving detection probability through the use of dogs, a method that has seen notable success when applied to studies of bat mortality at wind farms.[2,20,21]

Another example of the limitations of existing data for wind farms is that the search radius as a factor of turbine height may be routinely underestimated. For example, initial monitoring of problem sites in California typically used a maximum search radius of 50 metres when recording avian fatalities due to collisions with turbines, but subsequent research suggests this radius could be set as high as 125 metres.[2] That said, whilst there is general agreement that search radii being too small introduces a negative bias in reported mortality rates, it is also the case that background mortality (i.e., bird carcasses found in the search area that were not killed by the turbines) introduces a positive bias – this positive bias will increase as the search radius gets bigger, leading to an overestimate of avian deaths being attributed to wind turbines.[1]

Other errors arise due to lack of pre-impact population data, biases in extrapolated results that can positively or negatively skew estimates, and insufficient data to properly extrapolate site-specific figures to obtain meaningful estimates of the population impact on a regional, national and continent-wide scale.[11,19] These limitations apply equally, if not more so, to data obtained for bat fatalities. It is essential to understand that these limitations in the data exist, but it is also important to note that such limitations exist for all types of environmental impact assessments of this kind. As will be pointed out several times throughout this chapter, turbine-related mortality data for birds and bats is comparatively well-documented when measured against other human structures, such as conventional power plants, residential and commercial buildings, or road networks. Thus, whilst rates of avian and bat mortality are not to be dismissed, it is increasingly clear that wind power poses much less of a threat to wildlife than many existing human activities, even before taking into account any benefits of climate change mitigation.

What is the current evidence?

Impact on bird populations

At one of Spain's oldest wind farm developments in the Navarre region, the mortality rate for griffon vultures, a vulnerable species, was found to be exceptionally high; and in southern Spain similar results were seen for griffon vultures at several wind farm facilities in the mountains of the Campo de Gibraltar region.[4,10] The particular arrangement of turbines along ridges used by migrating raptors to gain height in the absence of thermals was thought to contribute to the high rate of fatalities, as little difference was seen between turbines of older and newer designs. Although relatively small in terms of generating capacity, several other European wind farms were also found to be responsible for excess mortality in sensitive breeding populations of seabirds (Zeebrugge, Belgium) and white-tailed eagles (Smøla, Norway).[4,22]

In the Altamont Pass Wind Resource Area (APWRA) in California, the first wind farm developments had turbines sited with very little consideration for the indigenous raptor populations, causing an excessive rate of mortality in six raptor species.[9] This effect is not observed to such a degree in similar wind farms sited elsewhere in the USA leading to the conclusion that poor planning and outmoded turbine design is largely responsible.[23] This is supported by evidence from APWRA sites that have been 'repowered', i.e. a smaller number of larger, modern monopole turbines have replaced older designs, which subsequently saw a significant decline in mortality rate.[24]

Whilst research is still ongoing, there is already a great deal of data available on the overall effects of wind turbines on bird populations. As with data on anthropogenic causes of avian mortality in general, much of this information collected is site-specific and requires a great deal of assimilation to enable an ecosystem-wide view of the effects of wind power on birds. There are also limitations due to inter-annual variability – mortality studies typically take place for short periods (a few months) based on seasonal periods predicted to have high mortality, but this has the effect of underestimating year-round mortality. It is possible that significant fatalities are missed in outside periods, and shorter search periods means fewer carcasses are found, which skews data when extrapolated.[2] The effects from these spatially restricted studies are often extrapolated to effects on regional populations and thence to national populations, even though the uncertainties are considerable when attempting to match up population trends across so many different scales.[19]

Similarly, studies rarely (if ever) incorporate mortality estimates specifically into the local populations that are directly affected. Instead, local mortality rates are frequently compared with total national or continent-wide populations.[1] Even though low mortality compared to total population would indicate there is not a problem, this approach tends to underestimate other considerations, such as the carrying capacity of the area affected locally and how the impact of developments can adversely affect species richness and population density in that area.[19] For some species, obtaining species-specific data may be crucial for the effective implementation of measures designed to conserve rare or vulnerable populations.[25] It is important not to overlook these issues of geographical scale. The population of a species within a particular region needs to remain viable, because the gradual cumulative fragmentation of bird populations may eventually pose a significant threat to the more vulnerable or less adaptive species.[26,27]

As the phenomenon of bird collisions with wind turbines becomes more widespread, as is inevitable if more turbines are built, then extrapolating local observations and small data sets to national scales is complex and comes with many caveats. Effects are immediately apparent when a 'headline' species (e.g. the griffon vulture and white-tailed eagle) are relatively confined to a particular landscape or habitat, but when attempting to infer the impact of wind power on more widespread species (mostly songbirds and other small, perching birds, known collectively as passerines) it is important to account for estimates comparing different spatial scales. However, extrapolation of data is still necessary if we are to estimate the wider impact of human developments on species, and has long proved useful in many ecological impact studies.[11] It should also be noted that this principle applies to all infrastructure impact studies, of which wind turbines are just a small part. Indeed, many existing facilities, such as those involved with fuel extraction and conventional power generation, may end up being superseded by wind power, which is itself less harmful on the whole (see following).

Because avian mortality from various human activities, or anthropogenic sources, has been continually assessed for decades, it is worthwhile summarising the data (see Figure 11.1). This shows that the contribution made by wind turbines to avian mortality is negligible when compared to overall mortality from anthropogenic sources. Figures collected across Europe and North America consistently show that bird deaths caused by collisions with wind turbines are insignificant when compared to overall avian mortality due to human activity.

Collisions with built infrastructure other than wind turbines

It has long been known that buildings are one of the most significant causes of avian mortality, responsible for billions of bird deaths worldwide.[4,28] This is thought to be largely due to windows, which birds seem poorly equipped to detect, and so fatalities are a given wherever birds and windows are found in proximity.[29] Contrary to what is commonly supposed, large, high-rise buildings contribute very little to this death toll; instead, residential dwellings and small commercial buildings of just two or three storeys are responsible for almost all bird deaths involving building collisions.[8] Collisions with and electrocution by power transmission lines is another significant cause of bird deaths, as are collisions with road traffic.[4,28,30,31] Communication towers are a smaller, but still very significant, contributor to mortality, with some very tall towers seemingly responsible for incidents where large numbers of birds are killed at one time.[19,32]

Predation by cats

More recent studies that have monitored the behaviour of free-ranging domestic cats and how many small animals and birds are taken by both owned and stray cats roaming their territory. Because they are fed by their owners, numbers of cats can reach very high densities in some areas, far higher than a habitat could support for any naturally occurring predator.[5] Most studies of the predation rate of cats in countries where cat ownership is popular (e.g. the UK, Australia, New Zealand, Canada and the USA) suggest that for many species of birds, the predation level is likely to cause long-term population decline.[33,34] In urban areas, it is likely that the effects on local bird populations are underestimated because studies are unable to assess a bird species' true abundance due to the fact that these areas have already long been subject to cat predation.[33] Urban areas can act as a 'sink' for some species, drawing in birds from surrounding semi-rural areas to compensate for higher overall numbers lost to cats in the urban habitat.[35]

Efforts to better understand the level of avian mortality due to domestic cats has revealed a truly astonishing death toll.* Based on there being nine million cats in Britain, it is estimated around 25–29 million birds are killed each year by free-ranging cats (more recent estimates suggest Britain now has 10 million domestic cats).[33,36] Studies of avian mortality in North America have estimated around 135 million birds are killed each year by domestic cats in Canada, and a staggering 2,400 million (or 2.4 billion) are killed each year in the contiguous United States. Over two-thirds of this is caused by un-owned cats (i.e. feral or stray cats), but even so the median estimated mortality in Canada and the USA caused by owned domestic cats totals roughly 799 million birds each year.[6,30]

Collisions with wind turbines

Following concerns over the impact on important raptor species due to poorly sited wind farms in the Navarre and Altamont regions, there have been a relatively large amount of data generated on the estimated avian mortality caused by wind turbines. Analysis of these findings has increasingly taken into account some of the deficiencies known to be inherent in mortality estimation surveys (discussed above, see p4). Consequently, more recent mortality estimates for the contiguous United States has considered a mean projected estimate of 234,000 bird deaths each year due to collisions with wind turbines (estimates ranged from 140,000 to 328,000).[3]

This estimate, the authors noted, was higher than previous estimates of around 20,000–40,000 bird deaths,[28] but a similar study that applied more stringent criteria to likely underestimations suggested the number of bird deaths in the USA caused by wind turbines could be as high as 573,000.[2] Other studies have looked at the effect on different species, such as passerines. The median annual mortality rate of passerines due to wind turbine collisions across Canada and the USA is estimated to be between 134,000 and 230,000 birds,

* Note that the discussion here only addresses birds killed by cats. Domestic cats are also responsible for killing even greater numbers of small animals, including mammals, reptiles and amphibians.

which accounts for 63% of all types of bird killed by wind turbines. Diurnal raptors (birds of prey active during the daytime) and upland game birds were the next two major groups, accounting for another 8% of fatalities in each case (i.e. 16% in total).[1] The authors used these figures to give an estimate of 214,000–368,000 total fatalities each year for all bird species caused by collisions with wind turbines, which overlaps the higher-end estimate of 328,000 for the contiguous United States mentioned above.[1,3]

These estimates show that avian deaths caused by wind power contribute a fraction of one per cent to all bird deaths caused by human activity. Figure 11.1 shows different sets of data for annual mortality estimates due to various human activities from studies based on large, nationwide data sets in North America. The studies for wind power covered roughly 9%–15% of total wind farm installed capacity in the USA (between 2012 and 2013). Relative to other sectors of industry and types of infrastructure, the wind industry has been unusually closely-studied with regards to avian mortality and has comparatively reliable data as a result when considering extrapolating figures for wind energy nationwide.[1,2,7,32,37] This may have important ramifications when attempting to compare wind energy impacts with other infrastructure, as discussed further below.

Deaths caused by non-renewable energy production

Since wind farms are being introduced as a means to reduce carbon dioxide emissions, a more meaningful way to analyse avian mortality would be to compare wind power with non-renewable energy sources. The studies discussed above rarely present bird deaths in this way (if at all), although several may quote estimates of birds killed per turbine or per megawatt of installed capacity. Whilst simply comparing total deaths to other forms of infrastructure can be useful in terms of placing anthropogenic causes of bird deaths in context, making comparisons specifically between energy sources is necessary to more fully comprehend the true costs and benefits involved in producing electricity.[38] The peer-reviewed literature does not appear to contain any studies that set out to compare electricity sources and avian mortality on a watt-by-watt basis, except for Sovacool's preliminary study in 2009,[39] revised in 2012.[38] The author applies limited data from examples of coal, nuclear and wind power plants to estimate that existing fossil fuels cause 15 times the number of bird deaths for every gigawatt-hour (GWh) produced: 5.18 deaths/GWh for fossil fuels, 0.42/GWh for nuclear, and 0.27/GWh for wind power.

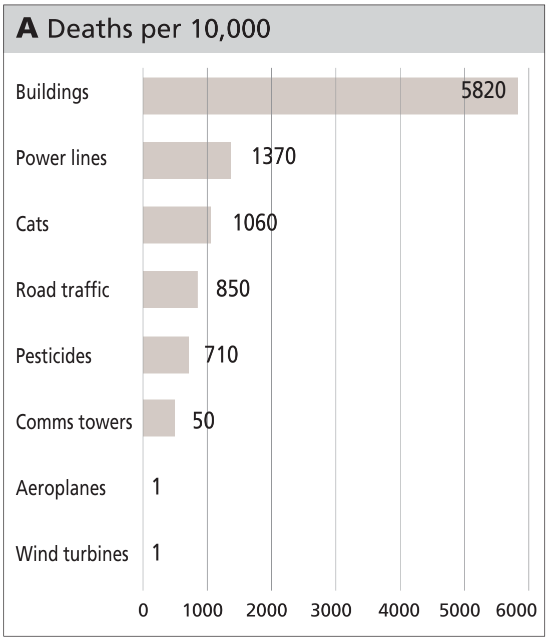
What can we make of these estimates? Of note, especially with regards to the preceding discussion of various mortality estimates, data on bird deaths used by Sovacool can be considered conservative, as it relies on older studies.[28,38] An approximate estimate of avian mortality per GWh might be obtained from more recent studies, on the basis of total installed capacity for the contiguous United States[†] combined with the average capacity factor of wind turbines (taken as 33% – see ref.11 in chapter 4). In these instances, high-end estimates of avian mortality per GWh are more than 10 times the number quoted by Sovacool (2.0–3.6 deaths/GWh versus 0.27/GWh quoted above), still lower than fossil fuels, but the gap has narrowed.[1,2] However, one must also bear in mind that systematic studies which attempt to gauge avian mortality due to conventional power generators are rare – nothing like the detailed analysis of bird deaths performed for wind farms has been done for conventional power plants. The simple fact is that wind farms have been subjected to far greater scrutiny. Whilst directly comparing collision rates between structures such as wind turbines and conventional power stations allows an easy comparison, it is much harder to account for the many *negative externalities* of conventional electricity generation – acid rain and its damage to fisheries and crops, water degradation and excessive consumption, particle pollution, radioactive waste and abandoned uranium mines and mills, and the cumulative environmental damage to ecosystems and biodiversity through species loss and habitat destruction.[40,41]

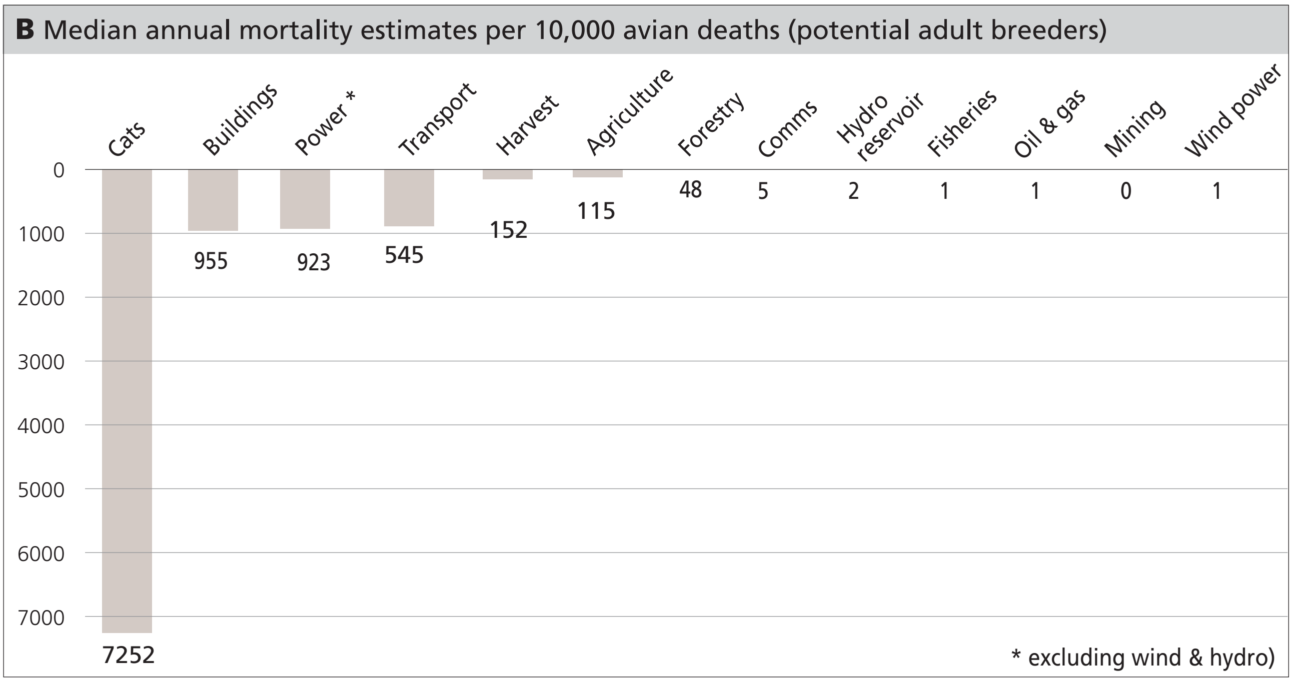
Studies frequently cite the average number of collisions per individual turbine. Data from many different regions of North America suggest a annual collision rate of nine birds/turbine.[1–3,37] Again, a rough inference can be made from this with regards to the UK. A high estimate of 20 GW installed onshore wind capacity is a feasible scenario set by the National Grid.[42] As of 2014, the average size of a turbine in the UK is 2.5 MW, although that is rapidly moving closer to 3.0 MW.43 Keeping the current average size, 20 GW of installed capacity is equivalent to 8,000 2.5 MW turbines, which would likely result in an estimated 71,000 birds killed due to collisions with operating turbines. Making a similar assumption as to annual electricity generation that was used above, this would be 1.23 bird deaths/GWh. The above figures are significant, although it is clear that even 71,000 bird deaths pales in comparison to the 25–29 million killed each year by domestic cats in the UK. What *can* be stated with certainty is that no form of electricity supply is completely benign.

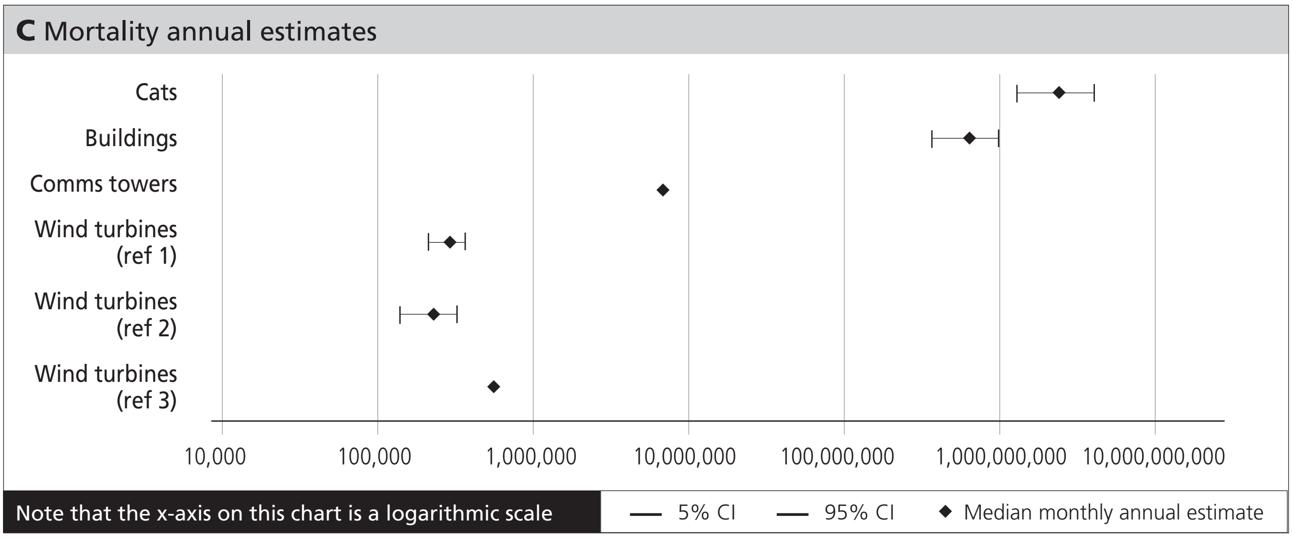
There are some concerns that habitat loss poses greater threat to bird species than collisions.[27] However, the footprint of wind turbines is comparatively small, allowing other activities, such as farming, to take place around wind farms, and being much smaller in area

† Erickson (ref.(1)) took total installed capacity to be 63 GW, Smallwood (ref.(2)) stated 52 GW.

Figure 11.1 Data from eight separate studies carried out over the past 12 years on estimated annual avian mortality due to human activity, based on data from North America. Panels A (data from ref.28, 2002) and B (data from ref.30, 2013) show bird deaths attributable to each cause per 10,000 fatalities that occur. While the 2002 study determined that collisions with buildings were the leading cause of bird deaths from human activity, the later study demonstrated predation by domestic cats to be a more significant factor. In both cases, wind power contributes ≤0.01% of total avian mortality. Panel C shows total median estimated annual avian mortality values from 6 different studies – note that the x-axis is a logarithmic scale. Values in C were taken from refs. 1–3 (which studied avian deaths caused by wind power) and 6–8 (which studied avian deaths from other causes), and, where values were stated in the study, confidence intervals are also shown. A similar trend can be seen across all data sets, showing wind turbines account for only a tiny fraction of total bird deaths. The two most recent studies (refs. 6 and 30 [both 2013]) reveal domestic cats are by far the single largest cause of birds killed due to human activity, contributing many thousands of times the number of bird deaths that are attributed to wind turbines.







than, say, national road networks.[37,44] Studies of large wind farms suggests the construction phase is the main driver of population decline, with populations returning or stabilising once turbines are operating.[45–47] Despite this, care should be taken that wind farms are not sited or laid out in such a way as to cause barriers to migratory species.[4,47]

Impact on bat populations

Bat fatalities were known at wind farms in the USA as part of earlier studies on bird mortality,[48] but the phenomenon received more attention from conservation researchers when a surge in bat deaths was recorded at several wind farms in the Appalachian Mountain region between 2002 and 2005.[23] In particular, a small installation in Tennessee and a much larger wind farm in West Virginia both reported a worryingly high fatality rate ranging between roughly 20 and 50 bats per turbine.[12,13] Although some of the US studies suggested no endangered bat species were being harmed,[13] and that other wind farms reported much lower numbers of bat deaths,[49] the few cases of large fatality rates being reported were alarming given that bats are long-lived and slow to reproduce, thus having a limited capacity to recover from any abrupt decline in population.[14]

The problem also quickly became apparent in Europe. Between 2003 and 2014, there were over 6,400 bat carcasses discovered at wind power facilities across Europe where mortality was attributed to the presence of wind turbines – this represents 27 affected bat species.[15] Some species on the European mainland are known to migrate notable distances, but data on UK migratory patterns is currently scarce.50 However, studies on bat deaths involving wind turbines across Europe have not revealed any clear difference between migratory and non-migratory bat species, which is in contrast to the findings in North America, where sites with unusually numbers of bat fatalities are associated with migratory populations.[51–53]

Although several nesting populations in the UK are showing positive growth trends,[54] this is likely to be due to bat conservation measures that have been introduced since the 1990s, and prior to this bat populations had steadily declined due to human activity. In addition, 13 of the 17 nesting species in the UK are known to be at the edge of their European ranges, which means the UK populations for these species tend to be rarer, smaller in number and exhibit negligible growth rates.[55,56] This can be problematic when assessing wind power schemes and similar infrastructure projects, because an impact assessment often relies on the assumption that wildlife losses can be mitigated to the degree that they do not affect the wider population; but, if bat populations in certain areas are already vulnerable, any significant reduction in numbers may have severe consequences.[57] The discovery that bat fatalities can occur in large numbers around some wind farms was initially surprising, since bats are known to be excellent at avoiding moving objects using their ability to navigate by echolocation. Researchers put forward many hypotheses to try and explain what might be contributing to these fatalities.[17,58] One factor that has quickly become apparent as multi-megawatt wind turbines become the norm is the speed at which a rotating blade tip moves. Speeds in excess of 160 mph are not uncommon, and this is simply too fast for bats in the proximity to detect and avoid in time.[53] As well as striking the turbines blades directly, there is increasing evidence that dramatic changes in air pressure around the moving blade edges induces barotrauma,[‡] which causes fatal internal haemorrhaging.[53,59]

There are likely other factors that contribute to the number of bats killed by wind turbines. Like similar data for birds, estimates of bat fatalities based on carcass discovery is subject to uncertainty. Even so, enough is known to see some patterns that set bat fatalities apart from bird fatalities: bat carcasses are typically found much closer to the base of wind turbines, bat fatalities are not observed next to non-rotating (i.e. non-operating) turbines, and bat mortality is negligible around other prominent structures.[49,58] The lack of bat deaths caused by other prominent structures is very different from recorded bird deaths caused by collisions, since, as discussed above, considerable avian mortality arises from birds colliding with structures such as buildings, communication towers, power lines, cooling towers and wire fences.[4,7,8,30] Thus, aside from random collisions being on account of the simple fact that bats are present at a wind farm site, data suggests there are additional factors that attract bats to rotating turbines in the first place, or that coincide with migratory and foraging behaviours, all of which combine to cause excess mortality.[14,17] These uncertainties mean predicting potential impacts during the planning phase can be challenging.

Mitigating avian and bat mortality

The reasons for birds colliding with wind turbines are now much better understood since the early days of wind power in California and northern Spain. For instance, vulnerable populations of raptors are known to follow ridgelines and steep slopes, which is why wind farms sited at Navarre and the APWRA have seen excessive mortality for species such as vultures and other

‡ Barotrauma results from the sudden increase in outside air pressure relative to the pressure within a bat's internal air spaces caused by the passing pressure wave at the turbine blade's leading edge. This difference in pressure can cause vulnerable tissues, such as the lungs, to rupture.

birds of prey.[22] Understanding how landscape features may cause birds to follow particular flight patterns is a key part in mitigating the impact of wind farms before they are even built. Knowledge of foraging areas for resident birds and flight paths of migratory species is also crucial. However, it is a fact that many preconstruction estimates of avian mortality have been found to be unreliable, typically due to planners failing to consider site-specific risks and variations between turbines within a single installation.[3]

Poorly sited wind farms across important topographical features and existing flight paths can cause long-term impacts. For instance, upgrading of turbines to larger, tubular designs in the APWRA has led to reduced avian mortality,[24] but the same pattern has not been observed in the Navarre region where similar ‘repowering’ has taken place. The experience in Navarre demonstrates that, in some cases, avian mortality does not necessarily correlate with turbine structure itself, merely the presence of wind turbines along a particular topographical bottleneck.[10] This can result in misleading predictions for mortality estimates when developments are first installed or upgraded.[60] Similarly, the expansion of wind power into novel environments also needs to be approached with care, since knowledge concerning the behaviour of resident avian species may be insufficient. For example, a recent study of gannet populations off the coast of Scotland that used 3D monitoring demonstrated foraging birds routinely flying at heights (up to 27m), which would bring them into conflict with the blades of offshore wind turbines.[61] This is contrary to previous radar data that suggested they flew no higher than 12 meters.

For bat mortality, this situation is more complicated. There is no clear link between topography and fatality rates between wind farms, although placement of individual turbines possibly has a significant effect given that some turbines are responsible for disproportionate levels of bat deaths. However, one key aspect is likely to be the identification of ‘movement corridors’ for bat species that move between sites for hibernation or breeding at certain times of the year.[14] Identifying potential impacts during the planning phase may be difficult when population movements are uncertain, unless there are clearly evident circumstances where impacts are likely to occur, e.g. near an important roost, or where it can be easily predicted that impacts will not occur, such as hostile, windy and cold sites where bats are unlikely to be found.[57]

Behavioural patterns are important, as we have seen with example of gannets off the Scottish coast. This applies to all avian species, including passerines, e.g. the behaviour of larks at certain times of the year may contribute to higher mortality rates due to male birds flying higher than normal (up to 250 m) whilst courtship singing.[1] Movements in flocks can also affect behaviour. There may be limitations to some collision prediction models, which do not take into account social interactions when birds fly in groups.[62] As well as seasons, common behaviours are intimately associated with the physical habitat – as one author noted, raptors ‘do not move over the area at random, but follow main wind currents, which are affected by topography’.[60] That said, it is known that some populations show avoidance behaviour, which results in a level of bird collisions that are not a cause for concern.[47] However, this phenomenon is species- and site-specific, and so requires good knowledge derived from careful monitoring of proposed sites using recognised experts in bat behaviour.

These factors are equally important for predicting the impact of wind farm developments on bat populations.[57] Foraging bats will routinely adhere to movement corridors in their local habitat. For example, wind turbines near wooded areas may involve the construction of access roads and the creation of clearings around the turbine bases. This can significantly affect the use of these areas by individual species of bats, which reduces the usefulness of preconstruction behavioural studies when applied to the landscape after a wind farm has been built.[63] The reasons for foraging bats straying near to, or being attracted to, wind turbines are known to vary between species, and there is currently little consensus on how common patterns of behaviour can be predicted.[14,57]

For avoiding unnecessary bird deaths, the best course of action at the planning stage is to take into account strategic needs across a wide area, so as to optimise the placement of wind turbines to meet energy needs and minimise new connective infrastructure at the same time as avoiding sensitive populations.[52,64] This can make use of existing detailed sensitivity mapping of habitats, populations and flight paths available for some regions, such as areas of Scotland[65], although these should not take the place of a local environmental impact assessment.[22] In the European Union all wind energy developments that are likely to have a significant impact on environment should be subjected to an environmental impact assessment (EIA).[§] As mentioned above, repowering of existing wind farms can reduce total bird deaths, although there may be some trade-off necessary to protect local bat populations.

Changes to the site characteristics and operation of individual wind farms and turbines are possible that can also mitigate bird deaths. It is known that the use of constant (steady-burn) lighting at wind farms and similar facilities (e.g. communication towers) can contribute to excessive bird fatalities, especially in areas prone to inclement weather.[7,32] Flashing lights, which are

§ Article 2 of Directive 85/337/EEC.

mandated by civil aviation authorities, do not appear to have the same effect. Individual turbines can also be limited at certain times of the day during sensitive periods, such as the known presence of migratory flocks, or returning foragers at certain times of day.[22] The area around the base of wind turbines can also be made less attractive to potential prey, such as rodent species that raptors typically hunt.[66] Finally, identifying individual turbines that cause the majority of fatalities can enable repositioning of the offending turbine or changes to its daily operation, which can be achieved quite easily through remote systems control.[22,66]

Mitigating excessive and potentially damaging levels of bat mortality may prove more challenging than for birds. There are possibly several confounding factors that lead to bat deaths at wind farm sites, since it is possible that as well as collisions, the incidence of barotrauma may mean some bat kills are missed because the animals have time to fly away before dying from their injury.[14] Of some concern is the finding that the increased height of modern turbines contributes to fatalities in migratory bat populations.[17] There are theories that this effect is caused by the habit of migrating bats to fly higher than their usual foraging routine, and that some bats may not use echolocation when following migration paths.[58] Although this may have implications for newer wind farms and the repowering of existing wind farms with larger turbines, it should be noted that migratory bats seem to be of particular concern in North America rather than Europe,[51,52] and the increase in generating capacity from larger turbines can greatly reduce the number of deaths per megawatt.[14]

A positive development is the finding that 'feathering' turbines, whereby the turbine's cut-in point is at a slightly higher wind speed, can significantly reduce bat fatalities.[67] Further evidence for slightly higher cut-in speeds is encouraging, especially for turbines that rotate at low wind speeds even though no power, or a negligible amount of power, is being generated.[14] Because bats do not forage in winds over a certain speed, the prevailing wind speed can be a strong predictor of bat activity, which makes feathering a useful mitigation method, and it results in only a few percentage points in lost electricity generation over the course of a year.[47,67]

However, reducing wind power output may not be feasible for older, existing wind farms, so alternative mitigation measures need to be found. Measures might include changing turbine colour to reduce insects congregating around turbines; using electromagnetic signals from small radar sets to reduce number of bats foraging around turbines (not migratory bats); and using ultrasound bursts to interfere with echolocation and discourage bats from feeding around turbines.[68,69] However, none of these methods have been tested at working wind farms to assess their effectiveness, and only feathering remains proven to be a successful mitigation measure.[14,57,70]

Impacts on non-volant wildlife

Most studies on non-volant wildlife in relation to wind farms have been prompted by known effects of oil and gas operations on terrestrial mammals in remote areas.[18] For wind farms, published research is relatively sparse, relating to populations of wild elk in North America and semi-domestic reindeer in Norway.[71,72] In a similar fashion to the development of avian monitoring on wind farms, studies of infrastructure impacts on terrestrial wildlife are carried out after construction, and there are few before-and-after impact studies.

Initial studies on the effect of wild elk in response to wind farms were prompted by evidence that oil wells built in Alaska caused changes to caribou foraging habits, and by evidence that roads and tourist facilities in Norway reduced local population density for caribou.[18,71] However, a study of Rocky Mountain elk in Oklahoma demonstrated that foraging and normal ranges were completely unaffected by wind farm development, either during or after construction.[71] Similarly, behaviour of semi-domestic reindeer was unaffected by the presence of wind turbines, with no behavioural aversion evident.[72]

Other preliminary studies suggest that, in some circumstances, the presence of wind farms can actually reduce predation, e.g. tortoise populations in California had a slight but significant increase in survival where a large wind farm had been developed.[18] Though seemingly a positive outcome, there is no evidence that the wind farm in question was planned with any regard for the local tortoise population. In the absence of further data, there is no guarantee that such an outcome would be seen at other wind farm sites with similar resident wildlife.[73] A study of ground squirrels in proximity to wind turbines within the APWRA showed that squirrels living in burrows close to wind turbines exhibited a greater degree of vigilance that was thought to compensate for the noise from the turbines. With respect to colony size and predator abundance, there appeared to be no difference between squirrel colonies close to or far away from the wind turbines.[18,52] Similarly, marine species have been seen to increasingly congregate or forage in proximity to offshore wind farms. This applies to species of fish that are avoiding predators or using turbine pilings as potential breeding spots, or to predator species themselves, such as seals navigating between turbines.[74–76] Other impacts on marine environments are discussed in chapter 6, 'Offshore wind turbines'.

Conclusion

Burgeoning utility-scale wind farms in the 1980s were often poorly sited, resulting in excessive fatalities for some important bird of prey species. Since then, the impact of wind farms on avian mortality has been the subject of a great deal of study, arguably to an extent not seen for any other form of infrastructure, many of these far more prevalent in modern societies. It is an accepted fact that wind turbines contribute to bird and bat deaths. In the context of all avian fatalities, however, the number of birds killed by collisions with wind turbines represents an insignificant fraction of the total number attributable human activity. It is no secret that wind turbines kill birds, and wind farms in the UK are subject to an Environmental Impact Assessment, which must take into account any sensitive bird populations, including migratory species. The planning regulations and advisory guidelines ensure bird populations in areas affected are studied to best predict the influence a proposed wind farm might have, and planning permission should be refused if the perceived detrimental effects are unacceptable or cannot be sufficiently mitigated.

Of more concern is the issue of bat fatalities, which may occur on a proportionally larger scale, and are potentially more damaging to some of the species involved. The foraging and migratory patterns of bats are not well understood, although more data is being amassed across sites in Europe and America. Although it is thought that the unexpectedly high mortality at some sites may be accounted for by altered behaviour during seasonal migrations, there is the possibility that bats may be affected when following normal foraging patterns too. One key difference between recorded bird and bat deaths is that bats appear to be particularly susceptible to wind turbines, as bats are not found to be killed as a result of contact with other structures, unlike the case for birds.

Co-ordinating the needs of both local and migratory bird and bat populations presents a challenge to the wind energy industry, and one that will have to be tackled on a site-by-site basis. The natural development of the commercial wind sector that has brought about turbines with taller, tubular designs that have slower rotating blades has mitigated bird fatalities to some extent, although there is a risk this may actually increase the threat to vulnerable bat populations. The accumulation of useful data since the 1980s, with regards to birds, has helped generate the information needed to correctly plan future sites for wind farms. It seems reasonable to assume that the impact of any wind farm can be significantly reduced through careful siting in response to data gathered on seasonal density in feeding and nesting areas, and on flight paths. Meticulous collection of information can aid flexibility when developing sites for wind energy, using 'micro-siting' so as not to disrupt flight paths.

Despite the positive developments with regards to reducing bird mortality, there is still a need for wind farm operators to perform more comprehensive monitoring, and ensure that more data is collected both before and after a wind farm is built. Routine monitoring of wind farms is often not rigorous enough in its approach, and many mortality studies rely on separate detection trials that themselves introduce forms of bias. Detection trials should be an integral part of routine monitoring – this would improve the raw data and carcass detection probabilities, which would reduce the need for post-hoc adjusting of data.

It is important that wind farms are developed with the possible threat to bat populations kept in mind, and where bat deaths are known to occur at existing wind farms mitigation measures need to be implemented as a precaution until such are effects are found to not have an impact on the viability of the population. Research has shown that curtailing wind turbine operation at lower wind speeds can significantly reduce bat deaths with minimal loss of power generation, but this remains to be tested on a large scale. The effectiveness of other mitigation methods is so far unproven. There is considerable variation in bat fatality rates between wind farms in different regions and continents, and it is also the case that individual turbines may be responsible for the majority of fatalities at a given wind farm, which suggests that it may be feasible to mitigate the impact on bats through micro-siting and making adjustments to the operating profile of specific turbines.

To date, little is known about the effect wind farms may have on other wildlife. The limited evidence suggests terrestrial animals are largely unaffected. There have been recent studies to suggest that patterns of foraging and predation by marine animals may be altered by the presence of offshore wind turbines, although there is evidence that such effects are not necessarily detrimental (see also chapter 6).

An assessment of current data shows that wind turbines kill few birds individually, but perhaps of greater importance is how estimates of total avian deaths due to wind energy compare to other sources of mortality. It has been clearly established that buildings – particularly residential and low-rise structures – communication towers, road traffic, transmission lines and agriculture result in far greater numbers of bird deaths each year, yet these latter causes of bird mortality have received comparatively little notice in the public sphere. Domestic cats, allowed to range freely, are by far the single largest cause of bird mortality, being responsible for many hundreds, if not thousands, of times more bird deaths than wind turbines. Comparing these data with that accumulated from wind farms suggests more consideration should be given to other anthropogenic sources of mortality that have to date received comparatively little attention from planners, regulatory authorities and (crucially) the media.

Wind farms are clearly delineated infrastructure developments that can be carefully planned to incorporate strategies for the avoidance, mitigation and offset of bird fatalities. Many other sources of avian mortality require much more complex approaches to governance. The issue is one of a tragedy of the commons. For instance, the difficulty with the bird–window collision issue are the building managers, housing developers and millions of homeowners who choose to build or retain regular windows with no regard for their impact on bird populations, despite it being shown, for example, that retrofitting UV-reflective film to offending windows can make them a visible barrier to birds but not to humans. The same goes for cat ownership, where there exists a profound disconnect between most cat owners' perception of the problem and the data that demonstrates cats are a persistent and serious threat to many avian populations. Each of these groups is responsible for a tiny slice of the cumulative problem. Solutions exist to help avoid these issues, but in the absence of public opprobrium or legislative pressure none of them are likely to be implemented. In this regard, the improvements made in the wind energy sector with regards to avian mortality shows that it can lead by example, by continuing to evolve its planning and operational methods in light of emerging data, thus delivering on its promise to be a clean and environmentally benign form of electricity.

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