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# Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity

Benjamin K. Sovacool *

*Energy Governance Program, Centre on Asia and Globalisation, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore 259772, Singapore*

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ABSTRACT

This article explores the threats that wind farms pose to birds and bats before briefly surveying the recent literature on avian mortality and summarizing some of the problems with it. Based on operating performance in the United States and Europe, this study offers an approximate calculation for the number of birds killed per kWh generated for wind electricity, fossil-fuel, and nuclear power systems. The study estimates that wind farms and nuclear power stations are responsible each for between 0.3 and 0.4 fatalities per gigawatt-hour (GWh) of electricity while fossil-fueled power stations are responsible for about 5.2 fatalities per GWh. While this paper should be respected as a preliminary assessment, the estimate means that wind farms killed approximately seven thousand birds in the United States in 2006 but nuclear plants killed about 327,000 and fossil-fueled power plants 14.5 million. The paper concludes that further study is needed, but also that fossil-fueled power stations appear to pose a much greater threat to avian wildlife than wind and nuclear power technologies.



## 1. Introduction

In early 2007, legislators introduced a bill into the United States House of Representatives trying to bar the approval of all new wind power projects absent extensive review undertaken by the US Fish & Wildlife Service. The effort was an attempt to minimize the threat that wind farms pose to birds, bats, and other avian species. While the bill failed to become law, some regulators within the country evidently take the issue of avian mortality serious enough to block wind electricity expansion entirely until the issue could be further studied. In Europe a few months later, concerned scientists assessed the mean avian mortality for 12 wind farms in Belgium, Netherlands, Spain, and the United Kingdom and concluded that "wind farms kill millions of birds yearly around the world" and that guidelines for wind farm citing must be changed (Kikuchi, 2008).

Both incidents demonstrate that for wind electricity, one of the most vociferous environmental concerns relates to the death of birds, bats, and other avian species that can fatally collide with turbine towers, blades, and power lines, an issue termed "avian mortality". Many ecologists, biologists, ornithologists, and environmentalists at large have spoken out against wind power on the grounds that it presents too great a risk to avian wildlife. Nonetheless, their concern, while justified, tells us little about the comparative risks that conventional and nuclear power plants pose to birds and other forms of avian wildlife. Moreover, it does not inform us, in assessing avian deaths per unit of electricity generated, how good or bad wind electricity is when compared to other sources of electricity supply.

This article begins by explaining the threats that wind farms pose to birds and bats before briefly surveying the recent literature on avian mortality and summarizing some of the problems with it. Based on operating performance in the United States and Europe, the paper then offers an indicative calculation for the number of birds killed per kilowatt-hour (kWh) generated for wind electricity, fossil-fuel, and nuclear power systems. The study estimates that wind farms and nuclear power stations are responsible each for between 0.3 and 0.4 fatalities per gigawatt-hour (GWh) of electricity while fossil-fueled power stations are responsible for about 5.2 fatalities per GWh. Within the uncertainties of the data used, the estimate means that wind farms killed approximately seven thousand birds in the United States in 2006 but nuclear plants killed about 327,000 and fossil-fueled power plants 14.5 million. The paper concludes that further study is needed, but also that fossil-fueled power stations appear to pose a much greater threat to birds and avian wildlife than wind farms and nuclear power plants.

## 2. Wind farms and avian mortality

A survey conducted by the author found more than 600 studies, articles, and reports investigating avian deaths and wind farms published from 1998 to 2008. Studies have generally noted

* Tel.: +65 6516 7501; fax: +65 6468 4186.
*E-mail address:* bsovacool@nus.edu.sg

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that onshore and offshore wind turbines present direct and indirect hazards to birds and other avian species. Birds can smash into a turbine blade when they are fixated on perching or hunting and pass through its rotor plane; they can strike support structures; they can hit parts of towers; or they can collide with associated transmission and distribution (T&D) lines. These risks are exacerbated when turbines are placed on ridges and upwind slopes, built close to migration routes, or operated during periods of poor visibility such as fog, rain, and at night. Some species, such as bats, face additional risks from the rapid reduction in air pressure near turbine blades, which can cause internal hemorrhaging through a process known as barotrauma (Baerwald et al., 2008). Indirectly, wind farms can positively and negatively physically alter natural habitats, the quantity and quality of prey, and the availability of nesting sites (Fielding et al., 2006; National Wind Energy Coordinating Committee, 1999).

Concern about avian mortality and wind electricity began to surface in the late 1980s and early 1990s, and it was mostly focused on the Altamont Pass Wind Resource Area (APWRA), a 165 $km^2$ wind farm near San Francisco, California. One 1992 assessment sponsored by the California Energy Commission estimated that more than 1766 bats and 4721 wild birds, including more than 40 species, some of them endangered, died every year while passing through the APWRA (Asmus, 2005). Recent follow-up studies have tended to confirm this trend: Thelander and Rugge (2000) and Smallwood and Thelander (2005) studied raptor mortality at the APWRA and estimated that as many as 835 were killed each year. Thelander (2004) projected that 881 to 1300 birds perished there per year. Smallwood and Thelander (2008) calculated that as many as 67 gold eagles are killed annually at APWRA.

Such fatalities are not limited to California. Another study examined 64 wind turbines in West Virginia and Pennsylvania and calculated that about 2000 bats were killed during a much shorter 6-week interval (US GAO, 2005). Several additional studies conducted in the Appalachian Mountains (focused on the region from Tennessee to Vermont), Rocky Mountains, Pacific Northwest, and the Midwest have found that large numbers of nocturnal migrants (including bats) are uniquely at risk of colliding with wind turbines (Boone et al., 2005; Johnson and Greg, 2004). Erickson et al. (2001) reviewed 31 studies of bird collusions at utility-scale wind farms in the United States and found that 78% of carcasses found at facilities were songbirds protected by the Migratory Bird Treaty Act.

In Europe, Barrios and Rodriguez (2004) projected that 36 common kestrels and 30 griffon vultures were killed per year by wind turbines in Tarifa, Southern Spain. Everaert and Stienen (2006) concluded that 165 terns of several species collided with 25 wind turbines in Zeebrugge, Belgium. Lowther and Stewart (1998) undertook a series of weekly checks at a much larger 256-turbine wind farm in Spain and documented 106 avian mortalities over the course of a year.

Those studying avian mortality often put their estimates into a commonly used metric known as avian deaths per turbine per year. Kunz et al. (2007) conducted a meta-analysis of five wind farms in Iowa, Minnesota, Tennessee, West Virginia, and Wyoming, and found average bat mortality ranged from 1.3 to 38.2 per turbine per year. Kuvlesky et al. (2007) did the same but broadened the scope to include bird fatalities in Europe and the United States from 1985 to 2005, and found a range of deaths from 0 to more than 30 per turbine per year. Winegrad (2004) produced a national survey of avian mortality rates and estimated that 2.2 birds died per turbine per year in California, 1.8 per turbine per year for most parts of the United States; and a much higher 7.5 per turbine per year at the Buffalo Mountain wind farm in Tennessee.

However, there has been a noticeable absence or low frequency of avian deaths at other wind farms. Kerlinger (1997) conducted a five-month survey at the Searsburg, Vermont Wind Energy Facility and found no fatalities. Lubbers (1988) surveyed eighteen 300 kW wind turbines in Oosterbierum, Denmark, and found only 3 fatalities over 75 days, or less than 0.8 per turbine per year. Marsh (2007) found a bird casualty rate of 0.22 birds per turbine year after monitoring 964 turbines across 26 wind farms in Northern Spain. Rigorous observation of a 22-turbine wind farm in Wales documented that it has killed *no* birds, and researchers found a shift in bird activity to a neighboring area (Lowther, 1998). Aerial surveys, radar monitoring, and video surveillance of offshore wind farms in Denmark revealed that the risk of a collision between a bird and a turbine was less than 1 out of 30,000 (Sovacool et al., 2008). Osborn et al. (2000) assessed bird fatalities at a 73-turbine wind farm near Buffalo Ridge, Minnesota, and found only 12 carcasses over the course of 20 months.

## 3. Problems with current research

The above studies, while useful and important, nonetheless suffer from three common problems: (1) they rarely compare their results with studies of other wind farms to contextualize their estimates; (2) most do not compare the possible avian deaths from wind electricity with other sources, and when they do, studies typically do not compare them to other *energy* sources; and (3) none attempted to calculate the number of avian deaths per kWh from energy sources so that more meaningful comparisons might be made between different forms of electricity supply.

### *3.1. Variation and small sample size*

A majority of studies examined focused on individual wind farms but did not attempt to compare results across many wind farms or larger geographic areas. There are some notable exceptions, many of which are cited in this study. Still, in an evaluation of 616 studies on wind electricity and avian mortality examined by the author, more than 510 (or 80% of the sample) focused only on one or two wind farms. The problem with such narrow sampling is that a great deal of variability in the amount of avian death associated with particular wind farms exists, ranging from 0 to almost 40 deaths per turbine per year (see Table 1).

What explains this great variability? The risk of avian death differs according to weather, layout of the wind farm, type of wind technology, specific bird migration routes, and topography, along with the particular bird species and number of birds found in the area (Kuvlesky et al., 2007). A bird's flight performance strongly determines the chances of collision with pylons and power lines. Janss (2000) found poor fliers such as ducks, heavy birds such as swans and cranes, and birds that concentrate in flocks are at greater risk. Kunz et al. (2007) noted that most mortality estimates had to be adjusted upwards or downwards as scavengers were known to remove bird and bat carcasses before

**Table 1**
Estimates of avian mortality at different wind farms.

| Source | Location | Avian mortality (fatalities/turbine/year) |
|---|---|---|
| Kunz et al. (2007) | United States | 1.3–38.2 |
| Kuvlesky et al. (2007) | Europe and the United States | 0–30 |
| Winegrad (2004) | United States | 1.8–7.5 |
| Osborn et al. (2000) | United States | 1.6 |
| Lubbers (1988) | Denmark | 0.8 |
| Marsh (2007) | Spain | 0.2 |
| Lowther and Stewart (1998) | United Kingdom | 0 |

researchers could discover them. Human error plays a role as well, as researchers miss carcasses, especially in agricultural landscapes and dense forest ridge tops.

Avian fatalities are also sensitive to time. Birds often learn to avoid wind farms after their first few years of operation. One of the most comprehensive studies ever undertaken, a $3\frac{1}{2}$-year study including fatality searches at 1536 turbines across Altamont Pass, concluded that a majority of fatalities were during the first few years of operation, and that birds became aware of operating wind turbines and took measures to avoid them (Smallwood and Thelander, 2005). Birds, in other words, are able to learn about new types of hazards, just as they learn that roads and other areas are dangerous.

Furthermore, the type of wind technology can significantly reduce bird fatalities. Altamont Pass, for example, is located near bird migration routes and has terrain, such as craggy landscapes and various canyons, making it ideal for birds of prey, and it is populated with mostly outdated turbine designs. It takes between 15 and 34 Altamont turbines to produce as much electricity as one modern turbine, and early turbines were mounted on towers at the same level as bird flight paths (60–80 feet in height).

Newer wind farms, however, can produce the same amount of electricity with fewer turbines, and turbines are mounted on towers that typically avoid birds at a height of 200–260 feet. Latest capacities are between 2.5 and 4 MW, the turbines tend to be spaced at a greater distance between each other, and many blades have slower rotational speeds. These turbines have gotten more efficient as their capacity factors have improved, and developers have gotten better at siting and installing them (Distefano, 2007). It is standard practice in the Pacific Northwest of the United States for all wind projects to involve habitat mapping, nest surveys, and general avian use surveys with a particular focus on threatened, engendered, or sensitive species. The standards are so strict they often cause developers to significantly modify the layout of wind farms and to abandon high-risk projects (Linehan and Andy, 2004).

Death rates of all flying animals have decreased in recent years as wind power entrepreneurs have installed larger turbine blades that turn more slowly, and have used advanced thermal monitoring and radar tracking to site turbines more carefully. Developers commonly avoid placing wind farms in areas of high nesting or seasonal density of birds, remove potential perches on lattice towers, and utilize micrositing and bird sensitivity mapping to position turbines in ways that minimize intersection with flight paths (Bright et al., 2008).

A study that focused only on one or two wind farms, therefore, could produce exceptionally high or low estimates of avian mortality as a result of the specific weather, type of wind farm, number of birds in the area, species of birds, quality of researchers collecting carcasses, terrain and siting, and form of wind technology that are not representative for all or even most wind turbines.

### 3.2. *Comparing avian deaths with non-energy-related fatalities*

Providing comparisons between the avian deaths from wind electricity and other causes is important, but comparisons thus far have only focused on avian fatalities from non-energy sources. Dozens of studies have noted that millions of birds die annually when they strike tall stationary communications towers, get run over by automobiles, or fall victim to stalking cats. After surveying wind development in California, Colorado, Iowa, Minnesota, New Mexico, Oklahoma, Oregon, Texas, Washington, and Wyoming (the 10 states with more than 90% of total installed wind power capacity), the US GAO (2005) calculated that building windows are by far the largest source of bird morality, accounting for 97–976 million deaths per year. Attacks from domestic and feral cats accounted for 110 million deaths; poisoning from pesticides 72 million; and collisions with communication towers 4–50 million (US GAO, 2005).

The Canadian Wind Energy Association estimated that more than 10,000 migratory birds die each year in the city of Toronto between 11p.m. and 5a.m. from collisions with brightly lit office towers (Marsh, 2007). A 29-year study of a single television tower in Florida found that it killed more than 44,000 birds of 186 species, and another 38-year study at a communication tower in Wisconsin found even greater deaths amounting to 121,560 birds of 123 species (Winegrad, 2004). Yet another study projected that glass windows kill 100–900 million birds per year; transmission lines to conventional power plants, 175 million; hunting, more than 100 million; house cats, 100 million; cars and trucks, 50–100 million; agriculture, 67 million (Pasqueletti, 2004). The National Academy of Sciences (2007) reported that less than 0.003% of anthropogenic bird deaths every year were attributed to wind turbines in four eastern states in the United States, and confirmed that collisions with buildings and communication towers pose a much greater risk.

However, since house cats and office windows do not yet produce electricity, the comparisons are less relevant than those that assess avian deaths from other sources of electricity generation.

### 3.3. *Failing to quantify avian deaths per unit of electricity generated*

Finally, not one of the studies examined produced an estimate of how many birds die from wind electricity correlated with the amount of electricity those wind turbines actually generated. This lack of a quantifiable figure allows opponents of wind power to perhaps unfairly portray it as a threat to birds when the evidence concerning the impacts from conventional sources is completely lacking. Strong advocates of wind power do the same thing, citing low absolute numbers of avian deaths but not admitting that those fatalities would grow significantly as the number of wind farms expanded. Metrics such as fatalities per turbine per year, in other words, do little to clarify or contextualize avian risks compared directly to other sources of energy supply, and make it difficult to properly assess the true threat that wind, conventional, and nuclear electricity technologies pose to birds and bats.

As a result, the situation is prone to rhetorical abuse on both sides. Wildlife campaigners in Europe, for instance, publicly noted that a wind farm obliterated an entire breeding population of an endangered species, provoking public outrage. What they did not tell people were that the fatalities involved only nine birds that died over the course of 10 months at a 68-turbine wind farm, where a family of white-tailed sea eagles perished. Since that family had all of the previous year's chicks with it, campaigners were able to claim it exterminated an entire breeding population, even if their statement was a bit hyperbolic (Marsh, 2007). On the other side, proponents of wind power have often argued that wind farms pose little to no threat to birds listed under the Migratory Bird Treaty Act, Bald and Golden Eagle Protection Act, and Endangered Species Act because of low fatality estimates per turbine, downplaying the fact that as the number of turbines increases so does the threat to avian wildlife.

## 4. Estimating and contextualizing avian mortality

In an attempt to address some of these shortcomings, the author assessed and compared the avian deaths per GWh from

**Table 2**
Assessment of avian mortality for wind energy.

| Wind farm | Details | Avian mortality (total number/year) | Avian mortality (fatalities per GWh) |
|---|---|---|---|
| Vansycle, Oregon | Thirty six 660 kW turbines | 10 | 0.146 |
| Klondike, Oregon | Sixteen 1.5 MW turbines | 8 | 0.115 |
| Foot Creek Rim, Wyoming | One hundred and thirty three 600 and 750 kW turbines | 35 | 0.135 |
| Mountaineer, West Virginia | Forty four 1.5 MW turbines | 118 | 0.524 |
| Nine Canyon, Washington | Thirty seven 1.3 MW turbines | 36 | 0.259 |
| Buffalo Ridge, Minnesota | Seventy three 300 kW turbines | 14 | 0.222 |
| Total/average | 339 turbines/274 MW | 221 | 0.279 |

three electricity systems: wind farms, fossil-fueled power plants (coal, natural gas, and oil generators), and nuclear power plants.

### 4.1. Wind electricity

Unlike fossil-fuel and nuclear power plants, which spread their avian-related impacts across an entire fuel cycle, most of a wind farm's impact occurs in one location. Wind moves but windy locations do not, meaning wind energy differs from coal, oil, gas, and uranium-based energy sources because fuel cannot be extracted and transported for use at a distant site (Pasqueletti, 2004). To determine an estimate of avian mortality representative of all wind farms, a broad enough area had to be assessed taking into account a variety of species of birds, locations, wind farm configurations, and types of wind technologies. The performance of wind farms is also important, since the amount of electricity a wind farm produces directly influences the amount of avian deaths per GWh.

The author began by determining the average load or capacity factor for a modern wind turbine—that is, the ratio of the actual output of a wind turbine over time compared to its output if it had operated at full capacity. The US Department of Energy (2008) conducted a comprehensive assessment of wind turbine performance across a sample of 170 wind projects built between 1983 and 2006 (totaling 91% of nationwide installed capacity in 2006, or 10,564 MW). The DOE found that despite great variations in windiness at each location, the average capacity factor for wind hovered around 22% in 1998 but jumped to 31% in 2003 and 35% in 2006 as turbine technology improved. Out of 58 projects installed between 2004 and 2006, more than one-quarter achieved capacity factors in the low to mid-forties, with average capacity factors for Hawaii reaching 45%, those in the Heartland averaging 40.8%, and those in California averaging 36.9%. Because *half* of the country's entire wind capacity was installed in the United States in 2007 and wind technology continues to improve, the author presumed that a capacity factor of 33% was an accurate indication of average wind turbine performance.

Next, the author assessed the real-world operating performance of six wind projects, each varying according to windiness, size, and location in the United States. Using data collected by Erickson and Wally (2004), avian mortality was quantified per GWh for 339 individual turbines constituting 274 MW of capacity (see Table 2). The thirty-six 660 kW wind turbines comprising the Vansycle Oregon wind farm averaged 10 avian fatalities per year. The sixteen 1.5 MW wind turbines in Klondike, Oregon, were responsible for 8 fatalities per year. The one-hundred-and-thirty-three 600 and 750 kW wind turbines at Foot Creek Rim, Wyoming, were responsible for 35 avian deaths per year. The forty-four 1.5 MW wind turbines at the Mountaineer wind farm in West Virginia were responsible for 118 fatalities per year. The thirty-seven 1.3 MW turbines at Nine Canyon, Washington, were responsible for 36 fatalities per year. Finally, the seventy-three 300 kW wind turbines in Buffalo Ridge, Minnesota, were responsible for 14 deaths per year. Averaged out over all six wind farms, and presuming a capacity factor of 33%, those 339 turbines were responsible for 0.279 avian deaths per GWh.

### 4.2. Coal, oil, and natural gas power plants

Coal-, oil-, and natural gas-fired power plants induce avian deaths at various points throughout their fuel cycle: upstream during coal mining, through collision and electrocution with operating plant equipment, and from poisoning and death caused by acid rain, mercury pollution, and climate change.

Starting with the upstream impacts, Winegrad (2004) estimated that mountaintop removal and valley fill operations in just four states—Kentucky, Tennessee, Virginia, and West Virginia—destroyed more than 387,000 acres of mature deciduous forests. Such a loss of forest resulted in approximately 191,722 deaths of the global population of Cerulean Warblers, and can be loosely calculated to amount to 0.02 Warbler deaths per GWh.[1]

Avian wildlife also frequently collides with or faces electrocution at power plant equipment. An observation of 500 m of power lines feeding a 400 MW conventional power plant in Spain estimated that it electrocuted 467 birds and killed an additional 52 in collisions with lines and towers over the course of two years (or about 260 per year) (Janss, 2000). Presuming a capacity factor of 85%, and that power plant was responsible for 0.09 deaths per GWh. Similarly, Anderson (1978) observed 300 waterfowl killed each year by colliding into Kincaid Power Plant near Lake Sangchris, Illinois. Presuming that the 1108 MW power station operated at 85% capacity factor, it was responsible for about 0.04 deaths per GWh. The mean for both facilities is 0.07 fatalities per GWh.

Acid rain occurs when sulfur and nitrogen compounds rise into the atmosphere and combine with water to then fall to the earth as rain, snow, mist, and fog. Ecologists, biologists, and ornithologists have shown that the acid rain partly formed from power plant pollution destroys nesting sites for birds, advances stages of forest dieback, thins forest canopies, lessens the amount of available food, alters habitat, and degrades soil. One study concluded that acid rain induced "great impacts on the reproduction and population size of piscivorous birds, forest birds, and insectivorous and granivorous birds" (Graveland 1998, p. 50). After taking into account and adjusting for soil and vegetation,

[1] Mountaintop removal produces about 10,000 t of coal per acre mined. Each acre mined kills approximately 0.49 Warblers. Each ton of coal produces about 2460 kWh of electricity. Putting all three together and the mountaintop removal ongoing in Appalachia is responsible for about 0.5 deaths per 24.6 GWh, or 0.02 deaths per GWh.

habitat alteration, population density, and vegetation cover, an extensive study conducted by the Cornell Laboratory of Ornithology estimated that acid rain annually reduced the population of wood thrushes in the United States by 2–5% (Hames et al., 2002).[2] The upper end of the estimate reflects wood thrushes living at higher elevations and thus subject to greater levels of acid rain found in the Adirondacks, Appalachian Mountains, Great Smokey Mountains, and the Allegheny Plateau. The results can be used to loosely quantify avian deaths of 0.05 fatalities per GWh.[3]

Acid rain pollution is not the only threat from fossil-fueled power plants. A string of scientific studies have confirmed that the emission of mercury, another byproduct of fossil-fuel combustion, can be lethal at even relatively low doses to avian fauna. Mercury exposure to albatross, falcons, mallards, terns, gulls and other seabirds, woodstorks, pheasants, and bald eagles has been proven in laboratory studies and biological monitoring of real birds to lead to fewer eggs, fewer produced young, and reduced survival rates.[4] Hallam et al. (1996) studied a colony of the endangered woodstork in the Everglades of Florida, at great risk because the birds spend most of their time in water, and observed that methyl mercury poisoning caused tameness, lack of muscle coordination, progressed to inability to fly, and death. They attributed 3–50% reductions in annual colony size to possible mercury poisoning. Burger and Gochfeld (1997) found high levels of mercury in the feathers and eggs of many species of birds, and concluded that they caused abnormalities and lowered reproductive success. Relying on the collection of feathers to determine mercury exposure, Burger and Gochfeld discovered that even low levels of mercury exposure (0.5–0.6 ppm wet weight in eggs) was sufficient to cause decreased egg weight, embryo malformations, lowered hatchability, neural shrinkage, and increased mortality. They also noted that mercury contamination was concentrated in the coastal areas of the United States, with mercury accumulating in the bottom of rivers, streams, lakes, and coastal lagoons that many birds rely on for drinking water. While efforts at quantification are highly uncertain, they extrapolated their results to posit that mercury poisoning and contamination was responsible for population declines ranging from 1% to 11% across 14 species of penguins, albatross, ducks, eagles, hawks, terns, gulls, and other birds. These numbers, as well, can be roughly quantified into 0.06 deaths per GWh.[5]

Finally, while perhaps the most difficult to quantify, climate change is already threatening the survival of millions of birds around the world. About 80% of the North American duck population, for example, breeds in the prairie potholes of the northern Great Plains. Climatologists expect that temperature increases of 1 °C could decimate duck populations by about 25% if rainfall remains constant (Serchuk, 2000). A more disturbing study conducted by Thomas et al. (2004) concluded that climate change was the single greatest long-term threat to birds and other avian wildlife. Looking at the mid-range scenarios in climate change expected by the Intergovernmental Panel on Climate Change, Thomas et al. projected that 15–37% of all species of birds will be committed to extinction by 2050. These numbers, too, can be quantified into 4.98 deaths per GWh.[6]

Adding the avian deaths from coal mining, plant operation, acid rain, mercury, and climate change together results in a total of 5.18 fatalities per GWh (see Table 3).

### 4.3. Nuclear power plants

The threat to avian wildlife from nuclear power plants can also be divided into upstream and downstream fatalities.

Uranium milling and mining can poison and kill hundreds of birds per facility per year. Indeed, in early 2008 the Cotter Corporation was fined $40,000 for the death of 40 geese and ducks at the Cañon City Uranium Mill in Colorado. The birds apparently ingested contaminated water at one of the settling ponds at the uranium mine (Uranium Watch, 2008). These deaths can be very roughly quantified into 0.006 deaths per GWh.[7] The US Fish and Wildlife Service (2008) have also noted that abandoned open pit uranium mines in Wyoming can form lakes hazardous to wildlife. Uranium-bearing formations are usually associated with strata containing high concentrations of selenium. It is not uncommon for these pits to kill 300 birds per year. Because those mines operated at about one-tenth the efficiency of Canon City, they would correlate to about 0.45 deaths per GWh. Taking the mean from both uranium mines gets us 0.228 fatalities per GWh.

Like fossil-fueled power stations and wind farms, avian fauna can also collide with nuclear power plants. Three thousand birds

[2] Utilizing data from National Atmospheric Deposition Project's National Trends Network, soil maps from the Natural Resources Conservation Service, and a comprehensive Breeding Bird Survey, the study determined that acid rain directly threatens avian wildlife. The researchers found that by causing the loss of needles and leaves, acid rain created a more open forest canopy and killed many species of trees. The thinning of the canopy resulted in lower abundance of preferred prey for birds, increased the amount of time birds spent scanning for predators, decreased time spent actively feeding, nesting, roosting, and foraging, and altered soil fauna. The researchers concluded that acidification leached much needed calcium from the soil needed for wood thrush breeding, altered the habitat by decreasing the availability of snails, pill bugs, millipedes, and earthworms, slowed the decomposition of leaf litter, and forced birds to consume more toxic aluminum, cadmium, and lead.

[3] The wood thrush population in the United States totals about 14 million (Roth et al., 1996; National Audubon Society, 2008), so a mean population reduction of 3.5% amounts to 490,000 deaths per year. Fossil-fueled electricity combustion is responsible for about one-third to one-fourth of all sulfur dioxide and nitrogen oxide emissions, the two primary precursors to acid rain, making it indirectly responsible for about 122,500–161,700 wood thrush deaths. Taking the mean, 142,100, and dividing it by the 2.87 million GWh coal, oil, and gas generators produced in 2006, one gets a fatality rate of 0.05 GWh.

[4] Boening (2000) found that mercury tended to concentrate in the liver, kidneys, feathers, and eggs of adult birds. Booth and Dirk (2005) found that mercury pollution was dangerous for seabirds feeding on fish. Mora et al. (2002) correlated mercury ingestion with low reproductive rates in peregrine falcons in Texas. Palma et al. (2005) concluded that mercury had deleterious effects on reproductive output of eagles in Portugal. Gochfeld (1980) discovered that the widespread presence of mercury in seabirds significantly contributed to premature death and morbidity. Ikemoto et al. (2005) found that mercury was responsible for birth defects and death among species of albatross in Japan. Koster et al. (1996) concluded that mercury threatened herring gull colonies in the Great Lakes with reduced hatchability of eggs and lowered survival rates.

[5] The National Audubon Society (2007) has placed more than 6.7 million albatross, ducks, hawks, terns, and gulls in the US on their Watch List of threatened species. While these numbers are indeed a small fraction of the overall population, attributing a mean population reduction of 6% correlates with 402,000 mercury-induced deaths. Fossil-fueled power plants are responsible for about 40% of the country's mercury emissions. Taking 40% of 402,000 one gets 160,800, and dividing it by the 2.87 million GWh generated by fossil-fueled power stations results in 0.06 deaths per GWh.

[6] While there are more than 9800 species and an estimated global population of 100 billion to one trillion individual wild birds in the world, only 5.6 billion birds live in United States during the summer (Hughes et al., 1997; Elliott, 2003; Hassan et al., 2005). Taking the mean in climate change induced avian deaths expected by Thomas et al. (26%), one gets 1.5 billion birds spread across 41 years for the United States, or an average of 36.6 million dead birds per year. Attributing 39% of these deaths to power plants (responsible for 39% of the country's carbon dioxide emissions), one gets 14.3 million birds for 2.87 million GWh per year, or 4.98 deaths per GWh. Carbon dioxide emissions were selected for analysis because Hanson and Sato (2004) report that they are responsible for 90% of the climate-forcing effects of greenhouse gases (with nitrous oxide accounting for 5%, methane at 4%, and other trace gases 1%).

[7] While the Cañon City Uranium Mill operates intermittently (it is idle most of the time), it can produce 1200 t of raw uranium per day during peak production. Presuming it was operating on the day the 40 waterfowl were killed, 1200 t of raw uranium can be processed to about 8.4 t of enriched fuel. Each ton of enriched fuel produces about 792 GWh, implying that the mine was responsible for 40 avian deaths to produce 6652 GWh, or 0.006 fatalities per GWh.

**Table 3**
Assessment of avian mortality for fossil fuel power plants.

| Component of fuel cycle | Explanation | Avian mortality (fatalities per GWh) |
|---|---|---|
| Coal mining | Bird fatalities from mountaintop removal and destruction of forests from coal mining | 0.02 |
| Plant operation | Bird collisions with coal power plant smokestacks, buildings, and cooling towers | 0.07 |
| Acid rain | Bird fatalities from acidification of soil and destruction of forests | 0.05 |
| Mercury | Bird fatalities from ingesting toxic mercury | 0.06 |
| Climate change | Bird fatalities from rapidly accelerating climate change | 4.98 |
| Total | | 5.18 |

**Table 4**
Assessment of avian mortality for nuclear power plants.

| Component of fuel cycle | Explanation | Avian mortality (fatalities per GWh) |
|---|---|---|
| Uranium mining and milling | Bird fatalities from toxic waste ponds and mill and mine sites | 0.228 |
| Plant operation | Bird collisions with nuclear cooling towers and equipment | 0.188 |
| Total | | 0.416 |

died in two successive nights in 1982 from collisions with smokestacks and cooling towers at Florida Power Corporation's Crystal River Generating Facility (Maehr et al., 1983). Given that the power plant now hosts an 838 MW nuclear reactor, and presuming it operated with a capacity factor of 90% and that the 3000 deaths were the only ones throughout the year, the facility was responsible for 0.454 avian deaths per GWh. Ornithologists observed 274 fatal bird collisions with an elevated cooling tower at the Limerick nuclear power plant in Pennsylvania from 1979 to 1980 (Veltri and Daniel, 2005). Since the Limerick plant has a 1200 MW reactor, and also assuming it operated at a 90% capacity factor, it was responsible for 0.261 deaths per GWh. At the Susquehanna plant in eastern Pennsylvania, 1500 dead birds were collected between 1978 and 1986 for an average of 187 fatalities per year (Biewald, 2005). Assuming that the 2200 MW plant operated at 90% capacity factor, it was responsible for 0.01 deaths per GWh. Extensive surveys for dead birds were also conducted at the Davis–Bess nuclear plant near Lake Erie in Northern Ohio. Ornithologists recorded a total of 1554 bird fatalities or an average of 196 per year from 1972 to 1979 (Biewald, 2005). Given that the power plant hosts an 873 MW reactor, and assuming it operated with a 90% capacity factor, and the plant was responsible for 0.0285 fatalities per GWh. Taking the mean for each of the four power plants results in 0.188 deaths per GWh.

Table 4 calculates that the total avian deaths per GWh for nuclear power plants at about 0.416.

## 5. Conclusions

The issue of avian mortality and electricity generation is certainly complex. Avian wildlife can perish by striking wind turbines, nuclear power plant cooling structures, transmission and distribution lines, and smokestacks at fossil fuel-fired power stations. Birds can starve to death in forests ravaged by acid rain, ingest hazardous and fatal doses of mercury, drink contaminated water at uranium mines and mills, or die in large numbers as climate change wreaks havoc on migration routes and degrades habitats. Power plants directly and indirectly kill many different types of species, different members of the same species, at different times and in different ways.

For wind turbines, the risk appears to be greatest to birds striking towers or turbine blades and for bats suffering barotrauma. For fossil-fueled power stations, the most significant fatalities come from climate change, which is altering weather patterns and destroying habitats that birds depend on. For nuclear power plants, the risk is almost equally spread across hazardous pollution at uranium mine sites and collisions with draft cooling structures. Yet, taken together, fossil-fueled facilities are about 17 times more dangerous to birds on a per GWh basis than wind and nuclear power stations. In absolute terms, wind turbines may have killed about 7000 birds in 2006 but fossil-fueled stations killed 14.5 million and nuclear power plants 327,000 (see Table 5 and Fig. 1).

Three conclusions, however, must be stated when observing the estimates provided by Table 5 and Fig. 1. First, far more detailed, rigorous, and sophisticated analysis is called for that takes into account the complexities of the wind, fossil-fueled, and nuclear energy fuel cycles. The shortcomings of this preliminary study are as obvious as they are numerous: a focus on bird deaths but not bird births[8]; a small sample size for wind, coal, and nuclear facilities that may not be representative; a focus on individual species such as the wood thrush or waterfowl to produce overall estimates of avian mortality that are definitely not representative (and undoubtedly conservative); a presumption that coal was only mined using mountaintop removal (thereby excluding the impacts from other types of coal mining); fatalities that happened on particular days and weeks that were then presumed to be the only ones throughout the year (also resulting in conservative estimates); an assumption that only carbon dioxide emissions from power plants contribute to climate change (again conservative for excluding other greenhouse gases); highly uncertain deaths attributed to climate change that may be

[8] Wind, fossil-fuel, and nuclear energy systems can also affect bird births. Wind farms can have beneficial effects on bird habitat when planned properly and coal and uranium mining can destroy and damage potential breeding sites.

**Table 5**
Comparative assessment of avian mortality for fossil fuel, nuclear, and wind power plants in the United States.

| Fuel source | Assumptions | Avian mortality (total per year) | Avian mortality (fatalities per GWh) |
|---|---|---|---|
| Wind energy | Based on real-world operating experience of 339 wind turbines comprising six wind farms constituting 274 MW of installed capacity. Total avian mortality per year taken by applying 0.269 fatalities per GWh multiplied by the 25,781 GWh of wind electricity generated in 2006 | 7193 | 0.269 |
| Fossil fuels | Based on real-world operating experience for two coal facilities as well as the indirect damages from mountain top removal coal mining in Appalachia, acid rain pollution on wood thrushes, mercury pollution, and anticipated impacts of climate change. Total avian mortality taken by applying the 5.18 fatalities per GWh multiplied by the 2.8 million GWh of electricity produced by the country's fleet of coal-, natural gas-, and oil-fired power stations in 2006 | 14.5 million | 5.18 |
| Nuclear power | Based on real-world operating experience at four nuclear power plants and two uranium mines/mills. Total avian mortality taken by applying the 0.416 fatalities per GWh multiplied by the 77,219 GWh of electricity produced by the country's nuclear plants in 2006 | 327,483 | 0.416 |

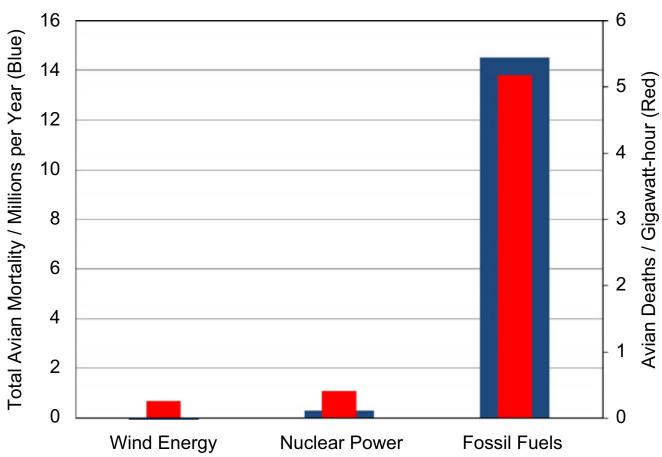


**Fig. 1.** Estimated avian mortality for wind, fossil-fuel, and nuclear energy per year. (Readers are invited to view the online version of the article to decipher the references to color.)

prevented if future greenhouse gas emissions are significantly reduced.

While the rudimentary numbers presented here are intended to provoke further research and discussion, they nonetheless still emphasize the importance of providing estimates of avian mortality per unit of electricity generated. Metrics such as fatalities per turbine, transmission line, or power plant structure per year, as well as estimates of the absolute number of avian deaths attributed to agriculture, communication towers, cats, and automobiles, tell us nothing about the avian fatalities involved with producing a GWh of electricity. Such metrics do not enable meaningful comparison among electricity sources, and are open to abuse from many strong opponents and proponents of wind energy. More than anything else, this study is a call for equal and careful study and observation of the avian mortality associated with other electricity sources besides wind power so that the issue can be properly balanced and contextualized.

Second, while the avian deaths attributed to fossil-fuel, wind, and nuclear power plants do vary, they also imply that there is no form of electricity supply completely benign to birds. The best strategy for preserving avian wildlife, therefore, would be to encourage the more efficient use of energy before any type of new power plant or wind farm is constructed.

Third, and perhaps more important, for it applies to many types of assessment beyond the electricity sector, is the lesson that the most visible impacts from a given technology are not always the most egregious. Wind turbines seem to present a significant threat to birds because all of their negative externalities are concentrated in one place, while those from conventional and nuclear fuel cycles are spread across space and time. Avian mortality and wind energy has consequently received far more attention and research than the avian deaths associated with coal, oil, natural gas, and nuclear power systems, even though this study suggests that wind energy may be the least harmful to birds. The first-order estimates of avian mortality per GWh offered here imply that fossil fuels may be more dangerous to avian wildlife (and nuclear power plants slightly more dangerous) than wind farms, and they remind us that what can sometimes be considered the most obvious consequence of a particular energy system may not always be the most meaningful or important.

## References

Anderson, William L., 1978. Waterfowl collisions with power lines at a coal-fired power plant. Wildlife Society Bulletin 6 (2), 77–83.

Asmus, Peter, 2005. Wind and wings: the environmental impact of windpower. Electric Perspectives 30 (3), 68–80 (May/June, 2005).

Baerwald, Erin F., D' Amours, Gen, Klug, Brandon, Barclay, Robert, 2008. Barotrauma is a significant cause of bat fatalities at wind turbines. Current Biology 18 (16), 695–696.

Barrios, L., Rodriguez, A., 2004. Behavioral and environmental correlates of soaring bird mortality at onshore wind turbines. Journal of Applied Ecology 41, 72–81.

Biewald, Bruce., 2005. Environmental impacts and economic costs of nuclear power and alternatives. Testimony Before the Atomic Safety and Licensing Board (April 5), 18pp.

Boening, Dean W., 2000. Ecological effects, transport, and fate of mercury: a general review. Chemosphere 40, 1335–1351.

Boone, D. Daniel et al., 2005. Landscape classification system: addressing environmental issues associated with utility-scale wind energy development in Virginia (The Environmental Working Group of the Virginia Wind Energy Collaborative, 2005).

Booth, Shawn, Zeller, Dirk, 2005. Mercury, food webs, and marine mammals: implications of diet and climate change for human health. Environmental Health Perspectives 113 (5), 521–528.

Bright, Jenny, Langston, Rowena, Bullman, Rhys, Evans, Richard, Gardner, Sam, Pearce-Higgens, James, 2008. Map of bird sensitivities to wind farms in Scotland: a tool to aid planning and conservation. Biological Conservation 141, 2342–2356.

Burger, Joanna, Gochfeld, Michael, 1997. Risk, mercury levels, and birds: relating adverse laboratory effects to field biomonitoring. Environmental Research 75, 160–172.

Distefano, Michael, 2007. The truth about wind turbines and avian mortality. Sustainable Development Law & Policy (Fall, 2007), 10–11.

Elliott, J., 2003. World Bird Populations (Chicago, IL: Argonne National Laboratory), available at 〈http://www.newton.dep.anl.gov/askasci/zoo00/zoo00443.htm〉.
Erickson, W.P., Johnson, G.D., Strickland, M.D., Young, D. P., et al., 2001. Avian collisions with wind turbines: a summary of existing studies and comparisons to other sources of avian collision mortality in the United States, Report to the National Wind Coordinating Committee (Cheyenne, Wyoming: NWCC).
Erickson, Wally. 2004. Bird fatality and risk at new generation wind projects. In : Susan Schwartz (Ed.), Proceedings of the Wind Energy and Birds/Bats Workshop: Understanding and Resolving Bird and Bat Impacts. Resolve, Washington, DC, September, 2004, pp. 12–19.
Everaert, J., Stienen, W., 2006. Impact of wind turbines on birds in Zeebrugge (Belgium): significant effect on breeding tern colony due to collisions. Biodiversity and Conservation 16 (12), 3345–3359.
Fielding, Alan H., Whitfield, D., McLeod, D., 2006. Spatial association as an indicator of the potential for future interactions between wind energy development and Golden Eagles in Scotland. Biological Conservation 131, 359–369.
Gochfeld, Michael, 1980. Mercury levels in some seabirds of the Humboldt Current Peru. Environmental Pollution 22, 197–205.
Graveland, Jaap, 1998. Effects of acid rain on bird populations. Environmental Reviews 6, 41–54.
Hallam, Thomas G., Trawick, Tamara, Wolff, Wilfried, 1996. Modeling effects of chemicals on a population: application to a wading bird nesting colony. Ecological Modeling 92, 155–178.
Hames, Ralph S, Rosenberg, Kenneth, Lowe, James, Barker, Sara, Dhondt, Andre, 2002. Adverse effects of acid rain on the distribution of the wood thrush *Hylocichla mustelina* in North America. Proceedings of the National Academy of Science 99 (17), 11,235–11,240.
Hanson, James, Sato, Makiko, 2004. Greenhouse gas growth rates. Proceedings of the National Academies of Science 101, 16,109–16,111.
Hassan, Rashid, Scholes, Robert, Ash, Neville, 2005. Ecosystems and Human Well-being: Current State and Trends. Island Press, New York.
Hughes, Jennifer B., Dailey, Gretchen, Ehrlich, Paul, 1997. Population diversity: its extent and extinction. Science 278, 689–692.
Ikemoto, Tokutaka, Kunito, T., Tanabe, S., et al., 2005. Non-destructive monitoring of trace element levels in short-tailed albatrosses and black footed albatrosses. Marine Pollution Bulletin 51, 889–895.
Janss, Guyonne F.E., 2000. Avian mortality from power lines: a morphologic approach of a species-specific mortality. Biological Conservation 95, 353–359.
Johnson, Greg. 2004. A review of bat impacts at wind farms in the US. In: Susan Schwartz (Ed.), Proceedings of the Wind Energy and Birds/Bats Workshop: Understanding and Resolving Bird and Bat Impacts. Resolve, Washington, DC. September, 2004, pp. 46–50.
Kerlinger, P., 1997. A study of avian fatalities at the Green Mountain Power Corporation's Searsburg, Vermont, wind power facility (Burlington, VT: Vermont Department of Public Service).
Kikuchi, Ryunosuke, 2008. Adverse impacts of wind power generation on collision behavior of birds and anti-predator behavior of squirrels. Journal for Nature Conservation 16, 44–55.
Koster, M.D., Ryckman, D., Weseloh, D., Struger, J., 1996. Mercury levels in great lakes herring gull eggs, 1972–1992. Environmental Pollution 93 (3), 261–270.
Kuvlesky, William P., Brennan, Leonard, Morrison, Michael, Boydston, Kathy, et al., 2007. Wind energy development and wildlife conservation: challenges and opportunities. Journal of Wildlife Management 71 (8), 2487–2498.
Kunz, Thomas H., Arnett, Edward, Cooper, Brian, Erickson, Wallace, et al., 2007. Assessing impacts of wind-energy development on nocturnally active birds and bats: a guidance document. The Journal of Wildlife Management 71 (8), 2449–2483.
Linehan, Andy, 2004. State of the Industry in the Pacific Northwest. In: Susan Schwartz (Ed.), Proceedings of the Wind Energy and Birds/Bats Workshop: Understanding and Resolving Bird and Bat Impacts. Resolve, Washington, DC, September, 2004, pp. 12–19.
Lowther, Stewart. 1998. The European perspective: some lessons from case studies, Proceedings of the National Avian Wind Power Planning Meeting III, San Diego, California, May, 1998 (King City, Ontario: LGL Limited, June, 2000), pp. 115–123.
Lubbers, F., 1988. Research program concerning the social and environmental aspects related to the windfarm project of Sep. Journal of Wind Engineering and Industrial Aerodynamics 27, 439–453.
Maehr, David, et al., 1983. Bird casualties at a central Florida power plant. Florida Field Naturalist, 45–68.
Marsh, George, 2007. WTS: the avian dilemma. Renewable Energy Focus, 42–45 (July/August).
Mora, M., Skiles, R., McKinney, B., Paredes, M., et al., 2002. Environmental contaminants in prey and tissues of the Peregrine falcon in the Big Bend region, Texas. Environmental Pollution 116, 169–176.
National Academy of Sciences. 2007. Environmental impacts of wind-energy projects (Washington, DC: National Research Council).
National Audubon Society. 2007. Audubon's WatchList 2002–2006 in taxonomic order by geographic region.
National Audubon Society, 2008. Wood Thrush Hylocichla mustelina. Bird Conservation Watch List, available at 〈http://www.audubon2.org/watchlist/viewSpecies.jsp?id=222〉.
National Wind Energy Coordinating Committee, Studying wind/bird interactions: a guidance document (Washington, DC: National Wind Coordinating Committee, December, 1999).
Osborn, Robert G., Higgins, Kenneth, Usgaard, Robert, Dieter, Charles, Neiger, Reff, 2000. Bird mortality associated with wind turbines at the Buffalo Ridge Wind Resource Area, Minnesota. American Midland Naturalist 143 (1), 41–52.
Palma, Luis, Beja, Pedro, Tavares, Paula, Monterio, Luis, 2005. Spatial variation of mercury levels in nesting Bonelli's eagles from Southwest Portugal. Environmental Pollution 134, 549–557.
Pasqueletti, Martin J., 2004. Wind power: obstacles and opportunities. Environment 46 (7), 22–31.
Roth, R. R., Johnson, M. S., and Underwood, T. J., 1996. Wood Thrush (Hylocichla mustelina), In: A. Poole, F. Gill, (Eds.), The Birds of North America, No. 246. The Academy of Natural Sciences, Philadelphia, PA, and The American Ornithologists' Union, Washington, D. C.
Serchuk, Adam, 2000. The Environmental Imperative for Renewable Energy. Crest, Washington, DC.
Smallwood, K.S., Thelander, C.G., 2005. Bird mortality in the Altamont Pass Wind Resource Area (Golden, Colorado: NREL/SR-500-36973, August, 2005).
Smallwood, K.S., Thelander, C.G., 2008. Bird mortality in the Altamont Pass. Journal of Wildlife Management 72, 215–223.
Sovacool, Benjamin K., Lindboe, Hans Henrik, Odgaard, Ole, 2008. Is the Danish wind energy model replicable for other countries? Electricity Journal 21 (2), 27–38.
Thelander, C. G., Rugge, L., 2000. Avian risk behavior and fatalities at the Altamont Wind Resource Area, March 1998–February 1999. National Renewable Energy Laboratory NREL/SR-500-27545, Golden, Colorado, USA.
Thelander, C. G., 2004. Bird fatalities in the Altamont Pass Wind Resource Area: a case study, part 1. Pages 25–28 In: S. Savitt Schwartz, (Ed.), Proceedings of the Wind Energy and Birds/Bats Workshop: Understanding And Resolving Bird And Bat Impacts, 18–19 May 2004. RESOLVE, Washington, D.C., USA.
Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, J.J., et al., 2004. Extinction risks from climate change. Nature 427, 145–148.
Uranium Watch. 2008. Cotter Corporation Fined $15,000 for death of migrating birds by solvent spill at Cañon City uranium mill (March 13), available at 〈http://uraniumwatch.org/newsarchive.htm〉.
US Department of Energy, 2008. Energy Efficiency and Renewable Energy Program. Annual Report on US Wind Power Installation, Cost, and Performance Trends: 2007. Washington, DC, US DOE, May 2008.
US Fish and Wildlife Service, 2008. Region six environmental contaminants—Pit Lakes. Available at 〈http://www.fws.gov/mountain-prairie/contaminants/contaminants8.html〉
US Government Accountability Office, Wind power: impacts on wildlife and government responsibilities for regulating development and protecting wildlife (Washington, DC: US GAO, September, 2005, GAO-05-906).
Veltri, Carl J., Klem, Daniel, 2005. Comparison of fatal bird injuries from collisions with towers and windows. Journal of Field Ornithology 76 (2), 127–133.
Winegrad, G., 2004. Wind turbines and birds. In: Susan Schwartz (Ed.), Proceedings of the Wind Energy and Birds/Bats Workshop: Understanding and Resolving Bird and Bat Impacts (Washington, DC: Resolve, September, 2004), pp. 22–28.