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Environmentalists and environmental scientists have criticized wind energy in various forums for its negative impacts on wildlife, especially birds. This article highlights that nuclear power and fossil-fuelled power systems have a host of environmental and wildlife costs as well, particularly for birds. Therefore, as a low-emission, low-pollution energy source, the wider use of wind energy can save wildlife and birds as it displaces these more harmful sources of electricity. The paper provides two examples: one relates to a calculation of avian fatalities across wind electricity, fossil-fueled, and nuclear power systems in the entire United States. It estimates that wind farms are responsible for roughly 0.27 avian fatalities per gigawatt-hour (GWh) of electricity while nuclear power plants involve 0.6 fatalities per GWh and fossil-fueled power stations are responsible for about 9.4 fatalities per GWh. Within the uncertainties of the data used, the estimate means that wind farm-related avian fatalities equated to approximately 46,000 birds in the United States in 2009, but nuclear power plants killed about 460,000 and fossil-fueled power plants 24 million. A second example summarizes the wildlife benefits from a 580-MW wind farm at Altamont Pass in California, a facility that some have criticized for its impact on wildlife. The paper lastly highlights other social and environmental benefits to wind farms compared to other sources of electricity and energy.

Keywords: wind power; avian mortality; wind turbines

Introduction

Advocates of wind energy cherish its multitude of economic and energy security benefits compared to other sources of conventional electricity generation. Engineers and contractors can construct wind turbines more quickly than large-scale nuclear reactors and coal-fired power plants (Sovacool and Watts 2009). Use of wind turbines means less consumption and pollution of water resources – a real concern since about half of water use in the United States involves producing electricity in thermoelectric plants (US Geological Survey 2005). The deployment of wind farms diversifies the fuel mix of utility companies, thereby reducing the overall risk of fuel shortages, fuel cost hikes, and interruptions (Christensen et al. 2006). Wind energy tends to be more widely accepted by communities and can contribute to economic development through greater jobs and enhanced tax revenue than fossil-fueled

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infrastructures which primarily send money out of the local economy. (Slattery et al. 2011, 2012).

Wind energy, however, is not free from environmental costs, and it has become common practice for environmental scientists and environmental advocates to criticize wind turbines for their direct and indirect hazards to birds, bats, and natural habitats. Such authors have used the term 'avian mortality' to describe the process whereby birds are killed by colliding with wind energy infrastructure. Writing in a prominent biology journal, for example, Carrete et al. (2009) argue that wind farms 'have adverse effects on wildlife, particularly through collision with turbines' and that 'alarming numbers of Egyptian vultures [have been] found dead in the vicinity of wind-farms'. A follow up-study concludes that 'wind-farms have negative impacts on the environment, mainly through habitat destruction and bird mortality' (Carrete et al. 2012). Cryan and Brown (2007) note that 'wind turbines are killing bats in many areas of North America'. Dahl et al. (2012) write that despite producing 'clean' electricity, 'wind-farms do have impacts on the environment'. Other recently published articles have documented negative impacts from wind turbines on Griffon vultures in Spain (de Lucas et al. 2012), golden eagles in Scotland (Fielding et al. 2006), and 'sensitive birds' in the United Kingdom (Bright et al. 2008). Some have proposed 'no-go' zones for wind farms based on probable flight paths and habitats (Janss et al. 2010) and noted that wind farms can threaten non-avian species such as ground squirrels (Rabina et al. 2006).

Indeed, biology journals are not alone in drawing attention to the wildlife costs of wind energy. One of my earlier literature reviews of 616 studies on wind energy and avian mortality found that every single one drew a negative connection between wind energy and the natural environment (Sovacool 2009). A recent, cursory review undertaken by this author of articles published in the past 5 years in three scientific databases (Science Direct, BioOne, and EBSCO Host Environment Complete) – including prominent journals such as *Biological Conservation, Bioscience, Journal of Wildlife Management, Ornithological Science, Wildlife Biology*, and *Wildlife Society Bulletin* – identified 56 articles with 'wind energy' or 'wind turbine' in their title, abstract, or keywords. Every single one was negative in its treatment of wind energy. A meta-survey of dozens of other studies also concluded that 'associated infrastructure required to support an array of turbines—such as roads and transmission lines—represents an even larger potential threat to wildlife than the turbines themselves because such infrastructure can result in extensive habitat fragmentation and can provide avenues for invasion by exotic species' (Kuvlesky et al. 2007).

This evidence suggests that a consensus is emerging, or may already exist, within the wildlife community that wind turbines are environmentally calamitous or at least that such wind farms need better methods of construction, siting, and operational performance. This article, however, argues that conventional electricity systems, namely those combusting fossil fuels and fissioning atoms, present their own acute risks to wildlife and birds, risks that are far greater than those from wind energy. Consequently, wind energy brings with it advantages that make it an environmentally friendly source of electricity. Through a synthesis of previously published literature, the article notes that wind farms and nuclear power stations are responsible each for approximately 0.27 and 0.6 avian fatalities per gigawatt-hour (GWh) of electricity while fossil-fueled power stations are responsible for about 9.4 fatalities per GWh.

To make this argument about the costs of conventional electricity compared to the benefits of wind energy, the article proceeds as follows. It first compares avian fatalities from wind energy with other conventional forms of electricity generation at the national scale of the United States. It then compares avian-related mortality from wind turbines with nonenergy sources such as stationary towers and roads in addition to cats and automobiles and presents the Altamont Pass case study. It lastly summarizes some of the social and environmental benefits from wind energy, presents the study's caveats, and offers conclusions for those in the environmental sciences and energy policymaking communities.

In making this case, a number of salient limitations deserve mentioning. This study compares wind energy with nuclear power and fossil fuels but not other sources of electricity such as solar panels or hydroelectric dams. Many of the avian deaths from fossil fuels result indirectly from climate change, whereas those from wind energy and nuclear power are more direct from collisions with equipment (wind turbines and nuclear cooling towers) and contamination of land and water (uranium mines and enrichment facilities). The study focuses almost entirely on birds rather than bats and other types of wildlife. These shortcomings do mean that the study should be viewed as a first-order estimate to be (hopefully) reinforced by future research.

Avian mortality compared to other energy sources

Perhaps surprisingly, for some readers of this *Journal*, wind farms appear to have fewer avian deaths per GWh than fossil-fueled power plants (coal, natural gas, and oil generators) and nuclear power plants. For wind turbines and wind farms, fatalities arise from birds striking towers or turbine blades. 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 spreads across hazardous pollution at uranium mine sites and collisions with draft cooling structures. Yet, as this section of the paper demonstrates, taken together, fossil-fueled facilities are about 35 times more dangerous to birds on a per GWh basis than wind energy and nuclear power plants twice as hazardous. In absolute terms, Table 1 shows that, when climate change is included, avian fatalities from wind turbines include about 46,000 birds in 2009 but fossil-fueled stations were responsible for 24 million deaths and nuclear power plants 458,000 (See Table 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. Consider the real world operating performance of six wind farms, each varying according to windiness, size, and location, in the United States. Using data collected by Erickson (2004), though his numbers are uncorrected for searcher efficiency and scavenger losses (Willis et al. 2010; Sovacool 2010)[1], one can quantify avian fatalities per GWh, inclusive of transmission and distribution lines within each wind farm, for 339 individual turbines constituting 274 MW of capacity spread across six wind farms in Minnesota, Oregon, Washington, West Virginia, and Wyoming. Averaged out over all six wind farms and presuming a capacity factor of 33% reported by the

Table 1. Comparative assessment of avian mortality for fossil fuel, nuclear, and wind power plants in the United States, 2011.

Fuel source	Assumptions	Avian mortality (total per year, including climate change)	Avian mortality (fatalities per GWh, including climate change)	Avian mortality (total per year, excluding climate change)	Avian mortality (fatalities per GWh, excluding climate change)
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 171,422 GWh of wind electricity generated in 2011	46,113	0.269	46,113	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 9.36 fatalities per GWh multiplied by the 2.56 million GWh of electricity produced by the country's fleet of coal-, natural gas-, and oil-fired power stations in 2011	23.96 million	9.36	512,000	0.200

(*continued*)

Table 1. (*Continued*).

Fuel source	Assumptions	Avian mortality (total per year, including climate change)	Avian mortality (fatalities per GWh, including climate change)	Avian mortality (total per year, excluding climate change)	Avian mortality (fatalities per GWh, excluding climate change)
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 0.638 fatalities per GWh multiplied by the 718,388 GWh of electricity produced by the country's nuclear plants in 2011	458,331	0.638	458,331	0.638

Note: 2011 electricity generation statistics taken from US Energy Information Administration.

US Department of Energy (2008), those 339 turbines were responsible for 0.269 avian deaths per GWh.

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, onsite collision and electrocution with operating plant equipment, and downstream poisoning and death caused by acid rain, mercury pollution, and climate change.

Starting with the upstream part of their fuel cycle, Winegrad (2004) estimates that mountaintop removal and valley fill operations in four states – Kentucky, Tennessee, Virginia, and West Virginia – destroyed more than 387,000 acres of mature deciduous forests. Such a loss of forest will result in approximately 191,722 deaths of the global population of Cerulean Warblers. These deaths can be loosely calculated to amount to 0.02 Warbler deaths per GWh (Sovacool 2009).

Avian wildlife also frequently collides with or faces electrocution at thermoelectric power plant equipment. An observation of 500 m of distribution 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 2 years, creating about 260 deaths 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 precipitation and deposition 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. Studies have linked acid rain to bronchial constriction, elevated pulmonary resistance, and metabolism changes within a variety of avian species (Treissman et al. 2003). After taking into account and adjusting for soil, habitat alteration, population density, and vegetation cover, an extensive study from the Cornell Laboratory of Ornithology estimated that acid rain annually reduced the population of the wood thrushes in the United States by 2% to 5% (Hames et al. 2002). 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.[2]

Mercury, another hazardous pollutant with fossil-fueled electricity generation, can cause decreased bird egg weight, embryo malformations, lowered hatchability, neural shrinkage, and increased mortality. Mercury poisoning and contamination were responsible for population declines ranging from 1% to 11% across 14 species of penguins, albatross, ducks, eagles, hawks, terns, gulls, and other birds (Burger and Gochfeld 1997). These numbers, as well, can be roughly quantified into 0.06 deaths per GWh.[3]

Finally, while perhaps the most difficult to quantify, climate change is already threatening the survival of millions of birds around the world. 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, they projected that 15% to 37%

of all species of birds could be extinct by 2050. These numbers, too, can be tentatively quantified into 9.16 deaths per GWh from oil, natural gas, and coal-fired power stations.[4]

Adding the avian deaths from coal mining, plant operation, acid rain, mercury, and climate change together results in a total of 9.36 fatalities per GWh.

Nuclear power

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

Upstream, uranium milling and mining can poison and kill hundreds of birds per facility per year. Abandoned open pit uranium mines in Wyoming have formed lakes hazardous to wildlife. Uranium-bearing formations are usually associated with strata containing high concentrations of selenium. For example, one of these pits killed 300 birds during a single year (US Fish and Wildlife Service 2008). Presuming this rate stayed constant, deaths at this mine therefore correlate to about 0.45 deaths per GWh.

Like fossil-fueled power stations and wind farms, avian fauna can also collide with nuclear power plants. Three thousand birds died in two successive nights in 1982 from collisions with 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 Klem 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.

The total avian deaths per GWh for nuclear power plants are therefore about 0.638.

Limitations

At least three meaningful limitations concerning these estimates deserve to be mentioned. First, none of them account for avian species diversity. That is, they assume that 'a bird is a bird is a bird.' Biological differences between species is not accounted for, essentially meaning a dead raptor has the same significance as a dead sparrow or starling, even though the former is larger, longer-lived, and higher up the trophic level.

Second, for simplicity, the estimates apply to birds but not to bats – excluded in part because bats are mammals (Sovacool 2010), and also because the author was unaware of any reliable studies that looked specifically at the impact of coal, natural gas, oil, and nuclear power facilities on bats. Wind turbines do, however, have bat-related mortalities (Willis et al. 2010; Arnett et al. 2008; Kunz et al. 2007), and the author wholeheartedly encourages research comparing bat fatalities across various energy sources. Indeed, evidence from Barclay et al. (2007) compiled from 21 separate wind energy sites suggests that bat deaths may be as high as 1.46 per GWh.

Third, calculating the relationship between avian fatalities and climate change is admittedly simplistic. The role of climate change on bird extinctions, although indeed worrying, is not conclusive and as such should be approached with extreme caution. Studies looking at the expansion and contraction of ranges, shifts in migratory patterns, cumulative effects with other environmental threats, and predictions of 'winners' and 'losers' are only recently surfacing (see Møller et al. 2004; Crick 2004; Schwartz et al. 2006; Jetz et al. 2007; Sekercioglu et al. 2008; Gilman et al. 2010 for a sample). Moreover, the author has presumed that Thomas et al.'s (2004) estimate of bird *species* extinctions can be extrapolated to the number of *individuals* that will perish and that those deaths will occur at a constant rate year-to-year. Instead, the avian species most affected by climate change might be those with the smallest populations, and rates of decrease will probably vary, with most deaths occurring closer to 2050. The author is unaware of any reliable technique for how to account for these complexities within existing models.

Avian mortality compared to other non-energy sources

Moving away from avian fatalities per unit of energy produced to absolute numbers of avian deaths, millions of birds die annually when they strike high voltage transmission lines, collide with tall stationary communications towers, encounter moving automobiles, and fall victim to stalking cats.

High voltage transmission lines – which rarely serve wind farms, and instead interlink large-scale centralized baseload generators combusting fossil fuels or moderating the process of nuclear fission – can electrocute birds of prey, ravens, and thermal soarers and cause collision casualties with 'poor' fliers (Janss 2000). Martin and Shaw (2010) report that roughly 25% of juveniles and 6% of adult white storks in Europe die annually from power line collisions and that, in South Africa, 12% of blue cranes and 30% of Denham's bustards are killed annually by collisions with power lines.

Furthermore, Benítez-López et al. (2010) assessed the impact of road networks and other 'linear infrastructure' on wildlife and ecosystems and documented that they degrade bird habitats, isolate populations, increase human access, and induce road mortality. After reviewing 49 studies with 90 datasets and 2107 data points, they concluded that such infrastructure was responsible in a decline in species abundance of 28% to 36% for birds within 2.6 km and 25% to 38% for mammals within 17 km. Ecologist Paul Hawken (2010) has also calculated that the automobile-centered transport system in the United States requires a paved area equal to all arable land in Ohio, Indiana, and Pennsylvania to function and that it kills *millions* of wild animals each week (including domestic pets, deer, and birds). Aircraft pose another threat to avian wildlife, with one study documenting 44 species belonging to 37 genera at risk in Canada (Solman 1973), and officials at airports commonly using 'lethal control' to prevent birds from interfering with flight safety (Burt 2009).

Furthermore, windows exert a significant role in avian injury and death. Window fatalities are separated into two categories. The first type of window-associated avian death is from birds who fly unaware of clear windows believing they are flying through an unobstructed pathway. The second type results from male birds defending their territories against mirrored trespassers. Birds are at elevated risk – compared to insects and mammals – due to the amount of momentum they generate during flight (Klem, 1989; 1990a; 1990b).

The impacts of wind turbines are therefore negligible compared to these other sources of avian mortality. Upward of one-quarter of *all* bird species within the United States are documented striking anthropogenic structures. Estimates of annual avian deaths from collisions with buildings range from just under 100 million to greater than 1 billion casualties. Erickson et al. (2005) estimate 550 million building and structure related deaths – analyzed from surveys that took into account scavenging data and scavenger efficiency bias. After surveying wind development in California, Colorado, Iowa, Minnesota, New Mexico, Oklahoma, Oregon, Texas, Washington, and Wyoming (the 10 states with the most installed wind power capacity at the time), the US Government Accountability Office (2005) calculated that building windows are by far the largest source of bird morality, accounting for 97 million to 976 million deaths per year. Attacks from domestic and feral cats accounted for 110 million deaths; poisoning from pesticides 72 million deaths; and collisions with communication towers 4 to 50 million deaths. Yet another study projected that glass windows kill 100 to 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 to 100 million; and agriculture, 67 million (Pasqualetti 2004). Domestic and feral cats pose such a substantial risk to avian wildlife in Wisconsin, where they were projected to kill 39 to 40 million songbirds per year, that the state proposed allowing game hunters to shoot un-collared felines (Lane 2005).

Though perhaps less reliable due to their vested interest, the Canadian Wind Energy Association estimated that more than 10,000 migratory birds die each year in the city of Toronto between 11 pm and 5 am 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). The National Academy of Sciences (2007) attributed less than 0.003% of anthropogenic bird deaths every year to wind turbines in four eastern states in the United States. It also confirmed that collisions with buildings and communication towers pose a much greater risk. Put another way, the findings from the National Academy imply that it takes more than 30 wind turbines to reach a 'kill-rate' of one bird per year (Marris and Fairless 2007).

Altamont Pass: a revealing case study

Environmentalists and some media commentators have documented negative impacts on avian wildlife from the 580-MW wind farm at Altamont Pass. Yet closer examination reveals that it, too, appears to have net wildlife (and human health) benefits.

The Altamont Pass in California is an area known for high winds, straddling the borders between Alameda, Contra Costa, and San Joaquin counties about 48 km (30 miles) east of San Francisco. The site of the nation's first large wind farm and at one point the largest wind farm in the world, it had approximately 6700 wind turbines, some of them shown in Figure 1, representing $1 billion in capital investment and reached a capacity of 630 MW at the peak of its development in 1986 (Smith 1987). At one point in the 1980s, its production represented over half of the world's wind generation (McCubbin and Sovacool 2011a) – making it an ideal test case to explore what social and environmental benefits, if any, accrue to larger scale wind farms.

During the early 1990s, concern about avian mortality at Altamont Pass began to surface. A 1992 assessment sponsored by the California Energy Commission estimated than more than 1766 bats and 4721 wild birds, representing more than 40 species, some of them endangered, perished every year while passing through the Altamont Pass Wind Resource Area (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 Altamont Pass 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 golden eagles perished annually.

However, relying on pollution and mortality data from the Co-Benefits Risk Assessment Tool (COBRA) developed by the US Environmental Protection Agency, research undertaken with a colleague suggests that Altamont Pass might save more wildlife than it harms (McCubbin and Sovacool 2011a, 2011b). To make this claim, we examined and quantified the health and environmental benefits of wind power at Altamont Pass for two periods: 1987–2006, its first two decades of operation, and 2012 to 2031, 20 years of forecasted production for newer turbines installed within the resource area. Our study calculated human and wildlife health impacts from reduced ambient $PM_{2.5}$ levels, using well-established human health impact and valuation functions and some preliminary estimates and qualitative discussion of climate change.

We found, perhaps unexpectedly, that electricity production from Altamont Pass reduces emissions of SO_2, NO_x, $PM_{2.5}$, and greenhouse gases to the degree that it has a net beneficial impact on avian wildlife. Over the 40-year period under consideration, Altamont Pass reduced an estimated 164 tons of SO_2, 10,400 tons of NO_x, 1,570 tons of $PM_{2.5}$, and 39.4 million tons of CO_2. Put another way, the emissions saved during 20-years of operation at Altamont Pass amount to more than 10.4 million tons (23 billion pounds) of NO_x, SO_x, PM, and CO_2 – enough to cover the City of Oakland, California, in 114 m (373 ft) of pollution.

Figure 1. Panoramic view of the Altamont Pass wind farm in California.

In turn, the avoidance of these emissions reduces adverse effects to humans, wildlife, and ecosystems. By our estimation, the generation of Altamont Pass wind power saved approximately 168 fewer premature deaths and $1.4 billion in human health benefits. It avoided 128,700 avian deaths due to reduced $PM_{2.5}$ exposure and climate change – about 3217 birds per year, more than twice as many as the highest range of Thelander's (2004) estimate suggesting an annual death rate of 1300 birds (though, to be fair, the species of birds saved would likely be different than the species killed). Finally, we calculated the avoided damages of reducing greenhouse gas emissions at $2.21 billion measured in 2010 dollars. Table 2 summarizes these results.

What is striking about these findings is that (a) they are likely conservative and (b) they have been confirmed by follow-up studies. Our calculations underestimate the benefits from wind energy because they only compared it to a baseline of natural gas power plants rather than coal- or oil-fired facilities. Furthermore, we did not include upstream $PM_{2.5}$ emissions associated with energy production from fossil fuels, and we assumed that premature mortality occurred with a conservative 20-year lag, when work by Schwartz et al (2008) suggests that most deaths occur within the first 2 or 3 years. In addition, we did not include negative externalities associated with natural gas for vertebrate wildlife and fish, nor did we account for the adverse effects caused by ozone to human health, crops, and forests. Our own follow-up research has also found the same trend for wind farms – substantial environmental benefits exceeding costs in Idaho (McCubbin and Sovacool 2011b; 2011c).

In short, the evidence gathered here suggests that the negative environmental image of Altamont Pass, and perhaps other large-scale wind farms similar to it, may be undeserved, or at least in need of proper contextualization. Moreover, if these older and excessively less efficient wind farms have clear environmental advantages compared to other modern electricity sources, then newer and more efficient wind farms likely have even greater benefits.

The social and environmental advantages of wind energy

Although more complicated and difficult to calculate than species-specific avian fatalities, wind energy also displaces a broad number of social and environmental threats from other electricity sources. The National Research Council (2009) has noted that every kilowatt-watt hour (kWh) of conventional electricity generated produces a laundry list of damages, or 'negative externalities,' which include radioactive waste and abandoned uranium mines and mills, acid rain and its damage to fisheries and crops, water degradation and excessive consumption, particle pollution, and cumulative environmental damage to ecosystems and biodiversity through species loss and habitat destruction.

While the list of externalities from the National Research Council is incomplete, Thomas Sundqvist and Patrik Soderholm (2002) analyzed 38 electricity externality studies and 132 estimates for individual generators to determine the extent that positive and negative externalities were not reflected in electricity prices. They found that these costs, when averaged across studies, represented an additional 0.29 ¢/kWh for wind energy to 14.87 ¢/kWh for coal-fired electricity shown in Table 3. In this compilation of data across various energy sources, wind energy was by far the cleanest source.

Taking the mean values from Sundqvist and Soderholm (2002) and Sundqvist (2004) and adjusting them to 2010 dollars, one gets a rough picture for just how

Table 2. Summary of avoided impacts from Altamont Pass wind power generation.

Impact	Best estimate (low to high)* 1987–2006	2012–2031	Total
SO_2 emissions (tons avoided)	59 (44–74)	105 (76–134)	164 (121–208)
NO_x emissions (tons avoided)	6,050 (2,720–9,390)	4,300 (956–7,650)	10,400 (3,670–17,000)
$PM_{2.5}$ emissions (tons avoided)	617 (395–839)	956 (573–1,340)	1,570 (968–2,180)
CO_2-e emissions (mil. tons avoided)	14.6 (11–18.3)	24.8 (18.3–31.2)	39.4 (29.3–49.5)
Human mortality (deaths avoided; due to $PM_{2.5}$)	64 (12–116)	104 (17–191)	168 (29–307)
Total human health effects ($ million; due to $PM_{2.5}$)	$480 ($88–$870)	$920 ($150–$1,700)	$1,400 ($240–$2,500)
Avian deaths avoided ($PM_{2.5}$)	4,810 (1,220–8,410)	5,870 (1,280–10,500)	10,700 (2,500–18,900)
Avian deaths avoided (climate change extinctions)	40,800 (32,500–49,200)	77,400 (61,600–93,300)	118,000 (94,000–142,000)
Benefits of avoided CO_2-e emissions ($ million)	$571 ($188–$954)	$1,640 ($531–$2,760)	$2,210 ($719–$3,710)

*The best estimate is an average of the low and high impact scenario estimates, which are in parentheses. Note that numbers in this table are rounded to three significant digits, so a row may not sum to the total. Costs are in 2010 dollars.

Table 3. Negative externalities associated with electricity generation (cents/kWh in 1998 dollars).

Statistic	Coal	Oil	Gas	Nuclear	Hydro	Wind	Solar	Biomass
Min	0.06	0.03	0.003	0.0003	0.02	0	0	0
Max	72.42	39.93	13.22	64.45	26.26	0.80	1.69	22.09
Mean	14.87	13.57	5.02	8.63	3.84	0.29	0.69	5.20
Std. Dev.	16.89	12.51	4.73	18.62	8.40	0.20	0.57	6.11
N	29	15	24	16	11	14	7	16

Note: Source: Sundqvist (2004, Table 1). N = number of estimates included.

severe these externalities are for the United States.[5] Adding the likely damages from oil, natural gas, and coal equates to \$415.9 billion in negative externalities, which is \$129.8 billion more than the \$276.1 billion in revenue the electricity industry reported for 2009. In other words, fossil-fuel-fired electricity generation created \$415.9 billion of additional costs that neither producers nor consumers had to pay for in 2009, costs that were instead shifted to society at large in the form of premature deaths, debilitating illnesses, hospital admissions, and reduced productivity.

Here is the bad news. First, Sundqvist and Soderholm likely underestimate damages. In some cases, the studies they sampled relied on a 'willingness-to-pay' metric to assess damages, but many things such as clear skies or a dead child are difficult to impossible to quantify in dollars. Furthermore, virtually none of the studies accounted for the risk of irreversible environmental damages – such as tipping points that are crossed as the earth's climate changes, unknown ecological thresholds that are passed, and species extinctions – impossible to recover from once they happen. Most of the studies they surveyed modeled damages associated with a single power plant and not the combined or cumulative damages from a fleet of power plants or an entire utility system. Many of the studies they sampled assumed reference, rather than representative, technologies; that is, they assumed benchmark and state-of-the art technologies instead of those used by utilities in the real world where many power plants are more than 50 years old. Almost none of the studies they analyzed included the human health effects of exposure to electric and magnetic fields, which some researchers claim may contribute to childhood cancer. Lastly, and most importantly, when surveying externalities, Sundqvist and Soderholm did not include any value for CO_2 and climate change. They explain that their meta-survey found a range of damages so large (from 1.4 ¢/kWh to 700 ¢/kWh) that they decided to exclude climate change externalities. This specifically undervalues the benefits from wind energy, since a rigorous meta-survey from Jacobson (2009) concludes that wind energy had the lowest lifecycle greenhouse gas emissions *of any electricity source*, numbers shown in Table 4.

Second, other independent studies have corroborated the truly colossal negative externalities with fossil fuels such as coal. In one recent study, traditional coal-fired technology appeared to produce affordable power – under 5 ¢/kWh over the life of the equipment, which included capital, operating and maintenance costs, and fuel costs – while wind-turbine generators and biomass plants produced power that cost 7.4 ¢/kWh and 8.9 ¢/kWh, respectively, and tended to require larger amounts of land. However, when analysts factored in a host of externality costs, coal costs rose

Table 4. Lifecycle equivalent carbon dioxide emissions (grams of CO_2/kWh) for selected electricity sources.

Technology	Lifecycle	Opportunity costs	Risk of leakage, accident, and disruption	Total	Mean
Wind	2.8–7.4	0	0	2.8–7.4	5.1
Concentrated solar power	8.5–11.3	0	0	8.5–11.3	9.9
Geothermal	15.1–55	1–6	0	16.1–61	38.6
Solar PV	19–59	0	0	19–59	39
Hydroelectric	17–22	31–49	0	48–71	59.5
Nuclear	9–70	59–106	0–4.1	68–180	124
Clean coal with CCS	255–442	51–87	1.8–42	308–571	439

Note: Source: Jacobson 2009.

to almost 17 ¢/kWh, while biomass and wind plants yielded power costing much less (Roth and Ambs 2004). Another assessment calculated that if damages to the environment in the form of noxious emissions and impacts on human health resulting from combustion of coal, oil, and natural gas were included in electricity prices, coal would cost 261.8% more than it does (Norland and Ninassi 1998). Kammen and Pacca (2004) found that if they internalized the cost of mortality and asthma, just two items, into electricity rates, then the annual cost of operation for conventional coal power plants in Illinois, Massachusetts, and Washington was 50 ¢/kWh, almost eight times higher than the average 6.5 ¢/kWh paid by consumers at the time.

Many of the negative externalities from conventional energy systems specifically affect wildlife and ecosystems. For instance, one recent report for the New York State Energy Research and Development Authority (EBF 2009) qualitatively compared the risks to vertebrate wildlife from different power sources, including natural gas-fired plants and wind energy. After conducting a systematic review of the scientific literature, the study described the risks due to each of six lifecycle stages for each power source and then assigns a 'relative level of risk' to vertebrate wildlife ranging from lowest potential, lower potential, moderate potential, higher potential, to highest potential – see Tables 5 and 6. When looking at each lifecycle stage, it is clear that wind energy has the least potential to harm vertebrate wildlife in comparison to natural gas, coal, oil, nuclear, and hydroelectricity.

EBF's assessment that wind energy has a collection of environmental benefits – displaced resource extraction, fewer energy accidents, lower levels of noxious pollutants involved in manufacturing which all benefit various types of wildlife – or the inverse, that fossil-fueled facilities exert great damage on the environment, has been substantiated by numerous other studies (Ingelfinger and Anderson 2004; Naugle et al. 2006; Sawyer et al. 2006; Russell 2005; US Fish and Wildlife Service 2009; Pirie et al. 2009; Meng and Zhang 2002; Sovacool 2008b).

Conclusion

Whether looking at absolute avian fatalities or fatalities per unit of energy delivered, this article has demonstrated that nuclear power and fossil fuels are hazardous to

Table 5. Relative risk levels to wildlife by energy lifecycle stage.

Lifecycle stage	Wind	Natural gas	Coal	Oil	Nuclear	Hydro
Resource extraction	None	Higher	Highest	Higher	Highest	None
Fuel transportation	None	Moderate	Lower	Highest	Lowest	None
Facility construction	Lowest	Lowest	Lower	Lower	Lowest	Highest
Power generation	Moderate	Moderate	Highest	Higher	Moderate	Moderate
Transmission and delivery	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Facility decommissioning	Lowest	Lowest	Lower	Lowest	Lowest	Higher

Note: Source: Based on EBF (2009, Table 3-1).

Table 6. Effects on invertebrate wildlife by lifecycle category and relative level of risk.

Lifecycle stage	Effects of wind energy	Effects of natural gas-fired plants
Resource extraction	NA	Injury or death to wildlife and habitat degradation from oil spills and wastes in oil pits when natural gas is extracted from onshore crude oil pumping. Injury or death to wildlife and habitat degradation from accidental oil spills and discharge of drilling muds, cuttings, and production water as a result of simultaneous offshore oil and natural gas exploration and extraction. Injury and mortality to wildlife (e.g. birds and bats) from collision with offshore oil and gas platforms. Injury and mortality to wildlife (birds) from exposure to toxic emissions and fire from stacks of onshore and offshore oil and gas platforms.
Fuel transportation	NA	Habitat fragmentation along pipeline route, leading to invasion of edge species and displacement of interior species. Pipeline gas leaks (e.g. methane, a contributor to greenhouse gasses).
Facility construction	Habitat fragmentation from the construction of electric transmission facilities and roads.	Habitat fragmentation from the construction of electric transmission facilities and roads.
	Loss of habitat through land clearing for facilities.	Loss of habitat through land clearing for facilities.
	Temporary wildlife disturbance and displacement from construction noise and activity.	Wildlife disturbance and displacement from construction noise and activity.

(*continued*)

Table 6. (*Continued*).

Lifecycle stage	Effects of wind energy	Effects of natural gas-fired plants
Power generation	Injury and mortality to birds and bats from collision with wind turbines.	Injury and mortality to birds and bats from collision with vertical structures (e.g. stacks, cooling towers). Mortality, injury, and behavioral changes to wildlife caused by toxic air emissions. Injury and mortality to aquatic wildlife from cooling water intake systems. Injury, mortality, and behavioral changes in fish from thermal discharge from cooling systems. Aquatic habitat degradation from acidification of lakes and streams caused by air emissions (e.g. SO_2, NO_x) deposited as dry and wet acidic deposition. Upland and alpine habitat degradation from injury or death to vegetation caused by acidic deposition. Habitat loss from climate changes caused by greenhouse gas emission. Geographical range changes, abundance changes, change in timing of migration or emergence, change in timing of breeding activities, and change in food sources of wildlife from climate change caused by greenhouse gas emission.

(*continued*)

Table 6. (*Continued*).

Lifecycle stage	Effects of wind energy	Effects of natural gas-fired plants
Transmission and delivery	Injury and mortality to birds from collisions with transmission and distribution lines	Injury and mortality to birds from collisions with transmission and distribution lines.
	Mortality to birds caused by electrocutions from power lines and substations.	Mortality to birds caused by electrocutions from power lines and substations.
	Habitat fragmentation from maintenance of transmission facilities.	Habitat fragmentation from maintenance of transmission facilities.
Decommission	Wildlife disturbance and displacement from demolition process due to noise and activity.	Wildlife disturbance and displacement from demolition process due to noise and activity.
		Injury and mortality from contamination of aquatic systems caused by mobilizing electricity generation wastes.

Note: Source: Based on EBF.

birds and that, contrariwise, wind energy is far less harmful to wildlife. Even the 580-MW Altamont Pass wind farm has meaningful wildlife benefits. To recap, about 46,000 avian mortalities were associated with wind farms across the United States in 2009 but nuclear plants killed about 458,000 and fossil-fueled power plants almost 24 million, estimates illustrated by Figure 2. Figure 2 also reveals how the number of absolute birds killed by wind energy pales in comparison to other causes such as windows and cats. Regardless of where the wind turbines are located, by minimizing reliance on fossil fuels and nuclear power, they prevent the death and injury of wildlife that would otherwise occur across the world's coal mines, uranium tail ponds, oil refineries, natural gas facilities, uranium acidified forests, polluted lakes, and habitats soon to be threatened by climate change.

A few caveats, however, deserve mentioning when observing the estimates provided by Figure 2. More sophisticated analysis is called for that takes into account the complexities of the wind, fossil-fueled, and nuclear energy fuel cycles and also compares these three sources of electricity with other alternatives, including energy efficiency. The shortcomings of the assessment provided here are numerous: a focus on bird deaths but not bird births; treating all birds as 'the same' rather than accounting for species diversity; 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 very likely conservative); a presumption that coal was only mined using mountain top 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

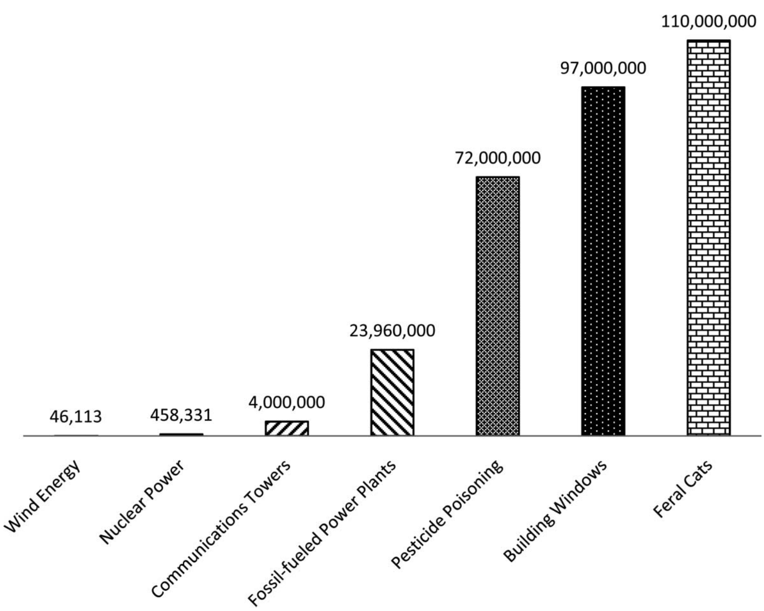

Figure 2. Avian deaths per year in the United States from various energy and non-energy sources, 2009. Note: When a range of estimates has been given, the figure presents only data for the lowest end of that range.

power plants contribute to climate change (again conservative for excluding other greenhouse gases); highly uncertain deaths attributed to climate change that may be prevented if future greenhouse gas emissions are significantly reduced.

Put another way, lumping estimates from different species, locations, and time periods do not capture temporal differences relating to migration patterns or spatial differences concerning migratory corridors. A study with a larger sample size that focused on a greater number of species across more locations, including migration routes and other important areas, over a longer period of time and encompassing the entire part of the fuel cycle for different electricity systems would be useful and expedient. Moreover, these findings are not a license for wind turbines to kill birds, for wind farms to be sited recklessly, or for research to cease on better designs that make wind energy less destructive to wildlife and its habitat. Although wind turbines have fewer fatalities per GWh than other sources, they still have negative externalities and are not completely benign.

Nonetheless, placing the issue of avian deaths in wider context is essential so that wildlife advocates, environmentalists, and even policymakers can better understand the true costs and benefits involved in producing electricity. Wind turbines do not exist in isolation; they are part of an electric utility system and compete with an entire portfolio of options including energy efficiency and distributed generation as well as nuclear reactors, natural gas turbines, and coal-fired power plants. Looking at the animal deaths and other social and environmental costs for wind turbines but not their benefits, and also ignoring the costs of fossil fueled and nuclear options, is (at best) incomplete and (at worst) misleading.

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Notes

1. Although Erickson professes to using ‘standardized fatality monitoring data’, Willis et al. point out that, when corrected for scavenger and efficiency losses, the number of birds killed by these six wind farms could be as high as 0.653 per GWh. However, I do not use the numbers from Willis et al. because the associated avian deaths for nuclear power and fossil fuels are not adjusted for scavenger and efficiency losses. I wanted a comparison between the three sources of energy to remain consistent, viewing ‘apples to apples’ as it were.
2. The wood thrush population in the United States totals about 14 million, 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 to 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.
3. The National Audubon Society has placed more than 6.7 million albatross, ducks, hawks, terns, and gulls in the United States 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.

4. There are more than 9800 species and an estimated global population of 100 billion to 1 trillion individual wild birds in the world (a mean estimate of 500 billion birds). The United States is presumed to have between 10% and 12% of this total, or roughly 55 billion birds, within its geographic borders in the summer. Taking the mean in climate change induced avian deaths expected by Thomas et al. (26%), one gets 14.3 billion bird deaths spread across 38 years for the United States or an average of 376 million dead birds per year. Attributing 7% of these deaths to fossil-fueled power plants (responsible for 39% of the country's carbon dioxide emissions, and US emissions are responsible for about 18% of the global total), one gets 26.3 million birds for 2.87 million GWh per year or 9.16 deaths per GWh. This estimate is a very crude approximation – for more see the section on 'Limitations'.
5. Taking the extra cost associated with scrubbed coal (19.79 ¢/kWh in 2010 dollars) – and multiplying it by coal's generation in 2009 (1756 billion kWh), amounts to $347.5 billion in damages. For oil generators, the number is $6.9 billion (17.97 ¢/kWh and 38,937 million kWh). For natural gas power plants, the number is $61.5 billion (6.68 ¢/kWh and 921 billion kWh).

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