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REVIEW

Avian interactions with renewable energy infrastructure: An update

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ABSTRACT

Energy infrastructure is widespread worldwide. Renewable energy technologies, which are expanding their footprint on the landscape and their contribution to energy availability, represent a different kind of infrastructure from extractive energy technologies. Although renewable energy sources may offer a 'greener alternative' to traditional extractive energy sources, mounting evidence suggests that renewable energy infrastructure, and the transmission lines needed to convey energy from renewable energy facilities to users, may impact birds. Peer-reviewed literature historically has focused on the direct effects of electrocution and, to a lesser extent, collisions with overhead power systems, and on avian collisions at wind energy facilities, with less consideration of indirect effects or other energy sectors. Here, we review studies that have examined direct and indirect effects on birds at utility-scale onshore wind- and solar-energy facilities, including their associated transmission lines. Although both direct and indirect effects appear site-, species-, and infrastructure-specific, generalities across energy sectors are apparent. For example, large-bodied species with high wing loading and relatively low maneuverability appear to be especially susceptible to direct effects of tall structures, and the risk of collision is likely greater when structures are placed perpendicular to flight paths or in areas of high use. Given that all infrastructure types result in direct loss or fragmentation of habitat and may affect the distribution of predators, indirect effects mediated by these mechanisms may be pervasive across energy facilities. When considered together, the direct and indirect effects of renewable energy facilities, and the transmission lines serving these facilities, are likely cumulative. Ultimately, cross-facility and cross-taxon meta-analyses will be necessary to fully understand the cumulative impacts of energy infrastructure on birds. Siting these facilities in a way that minimizes avian impacts will require an expanded understanding of how birds perceive facilities and the mechanisms underlying direct and indirect effects.

Keywords: avian, direct effects, indirect effects, mitigation, power line, solar, wind

Actualización de las interacciones entre aves y las estructuras de energía renovable

RESUMEN

La infraestructura energética está ampliamente distribuida en todo el mundo. Las tecnologías de energía renovable están expandiendo su huella en el paisaje y su contribución a la disponibilidad de energía, y representan un tipo diferente de infraestructura a la de las tecnologías extractivas de energía. Aunque las fuentes de energía renovable ofrecen una "alternativa más verde" en comparación con las fuentes tradicionales de extracción de energía, existe bastante evidencia que sugiere que la infraestructura de energía renovable y las líneas de transmisión necesarias para transportar la energía hacia los usuarios podrían afectar a las aves. La literatura científica tradicionalmente se ha enfocado en los efectos directos de la electrocución y, en menor medida, en las colisiones con los sistemas aéreos de energía y con las estructuras de energía eólica. En cambio, ha habido escasa consideración de sus efectos indirectos y de otros sectores energéticos. En este trabajo revisamos estudios que investigaron los efectos directos e indirectos sobre las aves a la escala de instalaciones terrestres de energía eólica y solar, incluyendo sus líneas de transmisión. Aunque los efectos directos e indirectos parecen ser específicos para cada sitio, especie y tipo de energía, existen generalidades evidentes entre diferentes sectores energéticos. Por ejemplo, las especies de mayor tamaño, con alta carga alar y maniobrabilidad relativamente baja parecen ser especialmente susceptibles a los efectos directos de las estructuras altas, y el riesgo de colisión probablemente es mayor cuando las estructuras se ubican perpendiculares al sentido del vuelo o en áreas con alto uso. Dado que todos los tipos de infraestructura resultan en la pérdida directa del hábitat o en su fragmentación y podrían afectar la distribución de los depredadores, los efectos indirectos mediados por estos mecanismos pueden ser comunes entre diferentes instalaciones energéticas. Cuando se consideran en conjunto, los efectos directos e indirectos en las instalaciones de energía renovable y en las líneas de transmisión asociadas probablemente son acumulativos. Finalmente, será necesario hacer meta análisis a través de varios tipos de instalaciones y taxones para entender completamente los impactos acumulativos de la infraestructura energética sobre las aves. La localización de estas instalaciones de forma que minimice el impacto sobre las aves requerirá un mayor entendimiento acerca de cómo las aves perciben las instalaciones y de los mecanismos que subyacen a los efectos directos e indirectos.

Palabras clave: aves, efectos directos, efectos indirectos, eólico, líneas de energía, mitigación, solar

Concerns regarding the depletion of fossil fuels, global climate change, and energy security have triggered rapid growth in the use of renewable energy technologies. For example, in the United States (U.S.), wind energy capacity increased by ~140% from 25,000 megawatts (MW) in 2008 to >61,000 MW in 2013 (American Wind Energy Association 2014). Collectively, ~13% of U.S. electricity generated in 2014 was derived from renewable energy sources (e.g., biomass [1.7%], geothermal [0.4%], hydroelectric [6.0%], solar [0.4%], and wind [4.4%]; U.S. Energy Information Administration 2015a). Continued growth of the wind energy sector is predicted to meet the U.S.'s wind energy target of 20% of all energy used by 2030 (U.S. Department of Energy 2008). Although government targets are centered on wind energy, the expansion of other renewable energy sectors also is expected (U.S. Energy Information Administration 2015b). In particular, projections suggest that the solar energy sector could meet 14% of electricity demands in the contiguous U.S. by 2030 and 27% by 2050 (U.S. Department of Energy 2012).

Renewable energy as a 'greener alternative' to the combustion of fossil fuels offers important environmental benefits over traditional energy sources, such as reductions in greenhouse gas emissions (Panwar et al. 2011). Yet, increasing evidence of direct and indirect effects has raised concerns regarding the potential impacts of renewable energy infrastructure on birds. Avian collisions with wind turbines (i.e. direct effects) are well documented and have received the most attention to date (e.g., Smallwood and Thelander 2008, Loss et al. 2013, Morinha et al. 2014). In comparison, studies of the direct effects of other types of renewable energy infrastructure on birds have been limited (but see McCrary et al. 1986, Lovich and Ennen 2011). Further, relatively few studies have considered the potential for indirect effects on avian behavior, spatial ecology, or demographics resulting from increased disturbance, changes in trophic interactions, or changes in habitat availability and connectivity (reviewed by Drewitt and Langston 2006, Zwart et al. 2016a). Renewable energy infrastructure often is accompanied by the construction of new transmission lines to connect renewable energy facilities to the existing power line network. Thus, the direct and indirect effects of multiple infrastructure types at renewable energy facilities need to be considered to identify the cumulative effects of a national (and global) transition from extractive to renewable energy production.

Of the studies that have assessed interactions between renewable energy infrastructure and birds, many have primarily targeted specific management crises, often focusing on species of conservation concern (e.g., Greater Sage-Grouse [*Centrocercus urophasianus*]: LeBeau et al. 2014; Greater Prairie-Chicken [*Tympanuchus cupido*]: Smith et al. 2016) in areas targeted for development (e.g., the Great Plains of North America; Harrison 2015, Whalen 2015, Winder et al. 2015). Thus, studies have been necessarily limited and inconsistent in the focal species addressed, experimental design, and study site. As a consequence, developing general siting guidelines and mitigation strategies for new facilities remains challenging. Given the projected increase in renewable energy infrastructure throughout the U.S. (U.S. Department of Energy 2008, U.S. Energy Information Administration 2015b), it is critical that we develop a more comprehensive understanding of the effects of renewable energy infrastructure on birds so that informed siting guidelines can be developed and implemented.

Here, we review recent studies of the direct and indirect effects on birds from utility-scale onshore wind- and solar-energy facilities and their accompanying transmission lines. We focused on these energy sectors because of their projected increase in the U.S. (U.S. Department of Energy 2008, U.S. Energy Information Administration 2015b). Our goals were to: (1) provide an up-to-date and consolidated summary of direct and indirect impacts of utility-scale onshore wind- and solar-energy infrastructure and associated power lines on birds based on peer-reviewed literature; (2) use our findings to inform siting guidelines; and (3) highlight important knowledge gaps and areas for future research.

KNOWN IMPACTS OF UTILITY-SCALE ONSHORE WIND- AND SOLAR-ENERGY INFRASTRUCTURE ON BIRDS

To summarize the impacts of utility-scale renewable energy infrastructure, we conducted a literature review to identify studies that empirically tested the effects of energy infrastructure on birds (i.e. not commentaries or predictive studies). We did so by using combinations of the following search terms in Web of Science (formerly ISI Web of Knowledge; Thomson Reuters, Philadelphia, Pennsylvania, USA): avian, bird, collision, conservation, electrocution, photovoltaic cell, renewable energy infrastructure, solar energy, transmission power line, wind energy, wind farm, and wind resource area.

Onshore Wind Energy

Direct effects. The direct effects of wind energy development on birds have received considerable attention (e.g., Smallwood and Thelander 2008, Loss et al. 2013, Erickson et al. 2014). Collisions between birds and onshore wind turbines result in impact trauma, which can result directly in death or render birds more susceptible to predation. Collisions have been documented for a wide range of taxa, including ducks (Johnson et al. 2002), grouse (Zeiler and Grünschachner-Berger 2009), raptors (De Lucas et al. 2008), and songbirds (Morinha et al. 2014). Of specific concern are fatalities of species of conservation concern (e.g., Western Burrowing Owl [*Athene cunicularia hypugaea*]; Smallwood et al. 2007) and species with small populations, delayed maturity, long lifespans, and low reproductive rates, for which even a few mortalities can have population-level effects (e.g., Golden Eagle [*Aquila chrysaetos*]: Lovich 2015; White-tailed Eagle [*Haliaeetus albicilla*]: Dahl et al. 2012). While the number of birds affected is uncertain (Pagel et al. 2013), estimates adjusted for searcher detection and scavenger removal suggest that between 140,000 and 328,000 birds are killed annually by collisions with turbines at wind energy facilities in the contiguous U.S. (Loss et al. 2013). For songbirds in particular, fatalities at wind energy facilities in the U.S. and Canada are estimated to be between 134,000 and 230,000 annually (Erickson et al. 2014). Avian collisions with turbines also have been documented outside the U.S. (e.g., Australia: Hull et al. 2013; Canada: Zimmerling et al. 2013; Japan: Kitano and Shiraki 2013; South Africa: Doty and Martin 2013; Western Europe: Everaert and Stienen 2007, De Lucas et al. 2012, Morinha et al. 2014), suggesting that the direct effects of wind energy facilities are of concern globally.

Intuitively, mortality rates at wind energy facilities should be related to avian abundance (Carrete et al. 2012), but a more complex suite of site-specific factors may be important (De Lucas et al. 2008, Marques et al. 2014). For example, habitats or prey that promote foraging at wind energy facilities are likely to increase collision rates (Barrios and Rodríguez 2004, Smallwood et al. 2007). Collisions may also increase when turbines are sited on landscape features, including cliffs and steep slopes, that are regularly used by hunting or migrating birds (e.g., Black Kite [*Milvus migrans*]; Kitano and Shiraki 2013). Weather may further increase collision risk when visibility around turbines is reduced (Kerlinger et al. 2010). For species that exploit thermals, the risk of collision may increase during weather that forces birds to gain lift from topographical features near wind turbines (Barrios and Rodríguez 2004, De Lucas et al. 2008). Collisions during migration may be particularly important because they have the potential to indirectly affect breeding populations far beyond the wind energy facility. Because most conservation efforts in North America are focused on breeding habitat, migration mortality can be a cryptic and often unrecognized effect of wind turbines.

Collision rates can additionally be affected by the design features of wind turbines. For example, collision rates between Western Burrowing Owls and wind turbines were highest at vertical axis towers, lower at tubular towers, and lowest at lattice towers, corresponding with a decline in the ability to see through the infrastructure type (Smallwood et al. 2007). Conversely, mortality rates of Eurasian Kestrels (*Falco tinnunculus*) and Eurasian Griffons (*Gyps fulvus*) were equivalent between tubular and lattice towers at a wind energy facility in the Straits of Gibraltar (Barrios and Rodríguez 2004). As turbine height increases, species that rely on lift for flight may become more susceptible to collisions (e.g., Eurasian Griffons; De Lucas et al. 2008), as may species that typically fly at higher altitudes (Loss et al. 2013). Turbine rotor diameter may also increase mortality rates through increasing the area within which birds are at risk (Loss et al. 2013; but see Barclay et al. 2007). For species attracted to artificial light sources (e.g., nocturnal migrants; Gauthreaux and Belser 2006), the use of steady-burning lights at facilities may increase mortality rates (Kerlinger et al. 2010). However, the use of flashing red lights at wind energy facilities, as recommended by the Federal Aviation Association, does not appear to influence collision rates between infrastructure and nocturnal migrants (Kerlinger et al. 2010). Fatalities may also increase when turbines are positioned perpendicularly to regular flight paths of birds; 90–95% of tern (*Sterna* spp.) fatalities at a wind energy facility in Belgium resulted from collisions with turbines positioned in a line perpendicular to their flight path between the breeding colony and feeding grounds (Everaert and Stienen 2007). Similarly, wind energy facilities sited along migration pathways may result in more migrant birds being killed than resident birds (Johnson et al. 2002).

Direct mortality also varies by species. Species that forage on the ground are less likely to collide with turbines compared with species that use aerial foraging (Hull et al. 2013). Similarly, aerial foragers that forage within rotor-swept areas and that appear to focus more on prey than on turbine blades are more susceptible to direct mortality than those that exercise caution around turbines (e.g., American Kestrel [*Falco sparverius*] vs. Northern Harrier [*Circus cyaneus*]; Smallwood et al. 2009). Also at risk are species that frequently engage with conspecifics during aerial territorial conflicts (e.g., Golden Eagle; Smallwood and Thelander 2008, Smallwood et al. 2009). Collision risk may be further elevated for species with visual fields that may prohibit them from detecting structures (e.g., wind turbines) directly ahead of them (e.g., vultures in the genus *Gyps*; Martin 2011, Martin et al. 2012), or for large species with weak-powered flight and high wing loading that rely on thermals for lift and thus have relatively low maneuverability in flight (e.g., Eurasian Griffon; De Lucas et al. 2008). Vulnerability to turbine collisions may also vary within species for which sex-specific behaviors result in one sex spending more time within rotor-swept areas. For example, heightened foraging activity of male terns during egg-laying and incubation at a wind energy facility in Belgium resulted in male-biased mortality (Stienen et al. 2008). Similarly, song flights performed by male Sky Larks (*Alauda arvensis*) during the breeding season at a wind energy facility in Portugal increased collision risk, resulting in male-biased mortality (Morinha et al. 2014).

Indirect effects. To date, most studies of indirect effects have focused on the displacement of birds from wind energy facilities. Displacement, typically measured via telemetry or point counts, has been documented for a wide range of taxa including geese (Larsen and Madsen 2000), ducks (Loesch et al. 2013), raptors (Pearce-Higgins et al. 2009, Garvin et al. 2011), grouse (Pearce-Higgins et al. 2012), shorebirds (Pearce-Higgins et al. 2009, 2012, Niemuth et al. 2013), and songbirds (Pearce-Higgins et al. 2009, Stevens et al. 2013). While the mechanisms driving displacement are poorly understood, loss or degradation of habitat may be important, especially for habitat specialists (e.g., Le Conte's Sparrow [*Ammodramus leconteii*]; Stevens et al. 2013), and may be compounded for species that are sensitive to turbine noise, construction noise, or tall structures (e.g., geese: Larsen and Madsen 2000; raptors: Garvin et al. 2011, Johnston et al. 2014). The latter may be especially relevant in open areas (e.g., grasslands), where species may be sensitive to tall structures, including wind turbines and power poles (e.g., prairie grouse; Hovick et al. 2014). While some species appear sensitive to wind energy development, evidence for the displacement of other species is either minimal or site-specific (e.g., Sky Lark: Devereux et al. 2008; Savannah Sparrow [*Passerculus sandwichensis*]: Stevens et al. 2013; Montagu's Harrier [*Circus pygargus*]: Hernández-Pliego et al. 2015; Eastern Meadowlark [*Sturnella magna*]: Hale et al. 2014), and some species may even be attracted to wind energy facilities (e.g., Killdeer [*Charadrius vociferus*]; Shaffer and Buhl 2016). Moreover, sensitivity to wind energy development may not always be reflected through changes in spatial ecology, but instead through other behaviors (e.g., lekking; Smith et al. 2016). Birds that avoid wind energy facilities during and immediately following construction may fail to show avoidance behavior thereafter (Madsen and Boertmann 2008, Pearce-Higgins et al. 2012), perhaps minimizing long-term effects in those species. Alternatively, some species may exhibit a delayed response to wind energy facilities, tolerating disturbance immediately following construction, but avoiding the site thereafter (e.g., Grasshopper Sparrow [*Ammodramus savannarum*]; Shaffer and Buhl 2016).

Wind energy facilities may also indirectly affect breeding performance. For example, distance to a turbine negatively affected nest survival of Greater Sage-Grouse (LeBeau et al. 2014), but had little effect on nest survival of Red-winged Blackbirds (*Agelaius phoeniceus*; Gillespie and Dinsmore 2014), Greater Prairie-Chickens (McNew et al. 2014, Harrison 2015), and McCown's Longspurs (*Rhynchophanes mccownii*; Mahoney and Chalfoun 2016). In contrast, Scissor-tailed Flycatchers (*Tyrannus forficatus*) nesting in sites close to a 75-turbine wind energy facility in Texas had higher nest survival compared with their counterparts nesting in sites farther away (Rubenstahl et al. 2012). Similarly, Hatchett et al. (2013) documented higher nest success for Dickcissels (*Spiza americana*) nesting near, compared with far from, a wind energy facility in Texas. However, the authors stressed that habitat configuration across the study site, not proximity to turbines, may have underpinned their results.

Wind energy development may also influence adult survival, but, again, effects are likely to be site- and species-specific. For example, annual survival of female Greater Prairie-Chickens increased postconstruction compared with preconstruction of a wind energy facility in Kansas (Winder et al. 2014). In contrast, distance to a turbine did not affect the survival of female Greater Prairie-Chickens breeding along a 25-km gradient at a wind energy facility in Nebraska (J. A. Smith personal observation). Similarly, the survival of female Greater Sage-Grouse breeding in the vicinity of a wind energy facility in Wyoming was unaffected by distance to a turbine (LeBeau et al. 2014).

Despite continuing efforts to assess the indirect effects of wind energy development on birds, the underlying mechanisms are seldom evaluated. For species targeted by brood parasites, a reduction in parasitism rates at wind energy facilities may increase nest success; Blue-gray Gnatcatchers (*Polioptila caerulea*) nesting close to a wind energy facility in Texas had a lower probability of nest parasitism by Brown-headed Cowbirds (*Molothrus ater*) and, subsequently, higher nest success than birds farther away. While it remains unclear why parasitism rates were lower at the wind energy facility, disturbance at the site may have impeded the ability of Brown-headed Cowbirds to detect nests (Bennett et al. 2014).

Changes in predator abundance may be key to understanding the indirect effects of wind energy development on measures of breeding success and adult survival (Rubenstahl et al. 2012, LeBeau et al. 2014, Winder et al. 2014). For example, avoidance of wind energy facilities by raptors (Pearce-Higgins et al. 2009, Garvin et al. 2011), or by mammalian predators due to increased disturbance associated with human activity (Gese et al. 1989, Gehrt et al. 2009), may reduce predation risk at sites close to wind energy facilities, consequently increasing survival. Alternatively, the presence of carcasses under wind turbines due to collision-induced mortalities may attract mammalian predators (Smallwood et al. 2010, Rogers et al. 2014), whose presence will, in turn, decrease survival. Despite these expectations, to our knowledge only one study has evaluated predation risk as a possible mechanism underlying survival by simultaneously assessing occupancy of predators and survival of Greater Prairie-Chickens. Site occupancy of avian predators in the vicinity of a wind energy facility in Nebraska was significantly lower within, compared with 2 km beyond, the wind energy facility (J. A. Smith personal observation). In contrast, mammalian predator site occupancy was unaffected. Although no effect was found on the survival of Greater Prairie-Chickens, the study provides evidence of an ecological mechanism that could have important implications for a wide range of species at risk from wind energy development.

The mechanisms underlying displacement or changes in the spatial ecology of birds at wind energy facilities are often discussed, but rarely evaluated. Given that prey species may avoid areas of high predation risk (reviewed by Lima 1998), changes in predator abundance at wind energy facilities (e.g., abundance of raptors; Pearce-Higgins et al. 2009) may be important for elucidating displacement behavior. Similarly, the presence of tall structures (i.e. wind turbines, power poles) at wind energy facilities that provide perches for avian predators may increase perceived predation risk, resulting in avoidance of those sites by potential prey species (e.g., Stevens et al. 2013). Alternatively, species associated with disturbed ground or gravel substrates may be attracted to wind energy facilities through increased opportunities for foraging or nesting (e.g., Killdeer; Shaffer and Buhl 2016), as has been observed at disturbance sites with relatively small footprints associated with other energy sectors (e.g., oil and natural gas developments; Gilbert and Chalfoun 2011, Ludlow et al. 2015). Wind turbines may also create barriers, causing birds to alter their flight patterns to avoid those areas (Drewitt and Langston 2006).

Increasing evidence suggests that birds may be sensitive to anthropogenic noise, and that noise from traffic, roads, aircraft, and energy infrastructure could disrupt acoustic communication through masking (Ortega 2012). In response to anthropogenic noise, birds may alter the characteristics of their vocalizations to compensate for masking (e.g., Hu and Cardoso 2010, Francis et al. 2012), or they may show behavioral avoidance (Bayne et al. 2008, Blickley et al. 2012, McClure et al. 2013). Recent research suggests that low-frequency noise produced by wind turbines may disrupt acoustic communication, causing birds to modify their vocalization characteristics (Whalen 2015, Zwart et al. 2016b). These results suggest that noise associated with wind energy development may disturb birds and could act as a mechanism driving indirect effects (e.g., lekking behavior; Smith et al. 2016). However, the likelihood of noise as an intermediary mechanism is likely to be species-specific, depending on the extent of masking (Rheindt 2003).

Solar Energy

Direct effects. Because solar energy development can occur in areas of high endemism (e.g., the deserts of the southwestern U.S.), the potential impacts on bird populations are substantial (Lovich and Ennen 2011). Yet, to our knowledge, only 1 peer-reviewed study of direct impacts exists: McCrary et al. (1986) concluded that the risk of collision with infrastructure at a solar energy facility in the Mojave Desert, California, was low after documenting 70 mortalities of 26 bird species over a 40-week period. The facility consisted of mirrors (heliostats) that concentrated solar energy onto a centrally located tower where liquid was converted to steam to generate electricity (hereafter 'solar tower'). More recent preliminary evaluations across 3 different solar energy facilities in southern California suggest that direct impacts are greater than previously thought (Kagan et al. 2014), and that installation design also affects risk. Kagan et al. (2014) considered 3 quite different installations: solar towers; photovoltaic cells that convert solar energy directly into electricity; and parabolic troughs consisting of mirrors that reflect solar energy onto a receiver tube within the trough which transports heated fluid to generate electricity. Opportunistic collection of carcasses at the 3 facilities suggested that mortality rates were higher at solar towers compared with parabolic troughs or photovoltaic cells. However, given the lack of information regarding fatalities at solar energy facilities, conclusive estimates of mortalities associated with solar energy facilities cannot be established (Loss et al. 2015).

Two main causes of death have been identified across solar energy facilities: impact trauma and exposure to concentrated solar energy (heat) at solar tower facilities (hereafter, 'solar flux'; Kagan et al. 2014). In common with other anthropogenic structures, all types of solar energy facilities may result in deaths of birds through impact trauma; solar flux trauma is unique to solar tower facilities. By damaging feathers (sometimes severely) when birds fly through areas of concentrated heat near the tower, solar flux can hinder a bird's ability to fly, induce shock, and damage soft tissue (Kagan et al. 2014). By impairing flight, solar flux trauma may increase the risk of direct collision with infrastructure or the ground, or may reduce a bird's ability to forage or evade predators.

Carcasses from a wide range of taxa have been identified at solar energy facilities (e.g., ducks, wading birds, raptors, rails, shorebirds, and songbirds; McCrary et al. 1986, Kagan et al. 2014). The mortality of an individual of the federally endangered subspecies of Ridgway's Rail (*Rallus obsoletus yumanensis*) suggests that solar energy facilities may have important consequences for species of conservation concern. While it appears that many species may be at risk, relatively high numbers of waterbird carcasses at photovoltaic cell facilities suggest that waterbirds may be particularly at risk where infrastructure (i.e. photovoltaic cells) reflects polarized light, giving the impression of water (Horváth et al. 2009, 2010). The water retention ponds needed at solar tower facilities may exacerbate risk by attracting birds to solar energy facilities, especially in arid landscapes (McCrary et al. 1986, Kagan et al. 2014). Insects that are apparently attracted to solar tower facilities may underlie the large number of aerial insectivores affected by solar flux (Hováth et al. 2010, Kagan et al. 2014), emphasizing the complex ecological processes that may contribute to risks to birds. While the mechanisms underlying mortality events are sometimes unclear, evidence indicating that solar energy facilities could be ecological traps (Schlaepfer et al. 2002) has begun to accrue.

Indirect effects. To our knowledge, only 1 peer-reviewed study has evaluated the indirect effects of solar energy development on birds. DeVault et al. (2014) demonstrated that solar photovoltaic facilities could potentially alter bird communities: In 5 locations across the U.S., species diversity was lower at photovoltaic array sites than in adjacent grasslands (37 vs. 46 species, respectively). In contrast, bird densities at the same photovoltaic array sites were more than twice those of adjacent grasslands. Observations during the study suggested that shade and the provision of perches increased bird use of the photovoltaic array sites. However, the results were species specific, with some small songbird species (e.g., American Robin [*Turdus migratorius*]) more abundant at photovoltaic facilities compared with adjacent grasslands used for habitat comparisons, but corvids and raptors less abundant. Similarly, raptor abundance was higher preconstruction compared with postconstruction of a utility-scale solar energy facility in south-central California, suggesting avoidance of the facility. In comparison, ravens and icterids increased in abundance during construction, possibly as a result of increased foraging opportunities at disturbed sites (J. Smith personal communication).

Similarly to the effects of wind energy development and other onshore energy development (e.g., oil and natural gas development; Kalyn Bogard and Davis 2014, Bayne et al. 2016), the potential indirect effects of solar energy facilities on birds are likely site-specific. For example, given that the footprint and configuration of solar energy facilities vary with the technology used (e.g., photovoltaic facilities are typically larger than solar tower sites; Hernandez et al. 2014a), indirect effects mediated through habitat loss or barrier effects are likely dependent on site-specific infrastructure (Hernandez et al. 2014b). Solar energy facilities may also disrupt local hydrology through groundwater extraction or channelization, which could reduce both food and habitat availability for birds (Grippo et al. 2015). Such effects are likely amplified at sites where footprints are large and at facilities that consume large volumes of groundwater (e.g., parabolic troughs and solar towers; Hernandez et al. 2014b, Grippo et al. 2015). The potential for contaminant runoff to indirectly affect birds also may be elevated at sites with large footprints (Grippo et al. 2015). Variation in other disturbances (e.g., vehicular traffic, construction noise, and operations) among sites could also contribute to site-specific variation in indirect effects (Lovich and Ennen 2011); we encourage further exploration of these factors.

Power Lines

Renewable energy facilities often require the construction of new transmission lines to deliver the energy produced at the facility to the existing power line network. These permanent connections may include many kilometers of lines supported by towers 30–35 m tall, and can traverse habitats beyond the line of sight from either the renewable energy facility or from a center of energy consumption. This is particularly true after ideal siting locations close to existing lines have been developed; subsequently constructed renewable energy facilities can be increasingly distant from the existing transmission line network, requiring increasingly longer connections. Transmission lines are associated with collision mortalities of flying birds (Rogers et al. 2014, Lobermeier et al. 2015; but see Luzenski et al. 2016), but renewable energy connections can be overlooked when investigating direct and indirect effects of renewable energy facilities.

Direct effects. Avian interactions with transmission lines appear to affect populations primarily through direct mortality, although indirect effects of habitat fragmentation have been hypothesized. Direct collision mortality is an ongoing concern in many areas of the U.S. (Yee 2008, Sporer et al. 2013, Luzenski et al. 2016). Collisions are most often associated with aquatic habitats, where species with high wing loading, high flight speeds, and poor maneuverability are common (Shaw et al. 2010, Quinn et al. 2011, Barrientos et al. 2012). Large, heavy-bodied species such as swans, pelicans, herons, and cranes are generally thought to be more susceptible to transmission line collisions than smaller, more maneuverable species (APLIC 2012). Nocturnal migrants have not been well studied, but also may be susceptible, particularly within migration corridors (Rogers et al. 2014), and especially in light of their susceptibility to collision with other types of tall anthropogenic structures (Drewitt and Langston 2008, Kerlinger et al. 2010, Gehring et al. 2011). Relatively small duck and grouse species are also vulnerable to collision because of their high flight speed, low altitude, and flocking flight, in which the view of upcoming obstacles is obscured by leading birds (APLIC 1994, Bevanger and Brøseth 2004). Transmission lines bisecting daily movement corridors, such as those located between roosting and foraging sites, have been most associated with avian collisions (Bevanger and Brøseth 2004, Stehn and Wassenich 2008, APLIC 2012), with risk exacerbated during low light, fog, and other inclement weather conditions (Savereno et al. 1996, APLIC 2012, Hüppop and Hilgerloh 2012). Transmission lines are typically constructed with relatively thin overhead shield wires at the top, and thicker energized conductors below. Birds appear to see energized conductors and adjust flight altitudes upward to avoid them, subsequently colliding with smaller, less visible overhead shield wires (Murphy et al. 2009, Ventana Wildlife Society 2009, Martin and Shaw 2010). Collision risk may be further exacerbated for species with narrower fields of view (Martin and Shaw 2010), but this remains an important research gap because to date it has been thoroughly studied only in Kori Bustards (*Ardeotis kori*), Blue Cranes (*Grus paradisea*), and White Storks (*Ciconia ciconia*), which are large, collision-prone species. Collision risk may be mitigated in migrating raptors, which tend to fly diurnally during good weather (Ligouri 2005) and appear to detect and avoid transmission lines, even those located in major migration corridors (Luzenski et al. 2016).

Indirect effects. The indirect effects of transmission lines are not well studied. Of the existing studies that have addressed indirect effects, most have considered grouse (Lammers et al. 2007, Coates et al. 2008, Coates and Delehanty 2010) or desert tortoises (*Gopherus agassizii*; Boarman 2003, Berry et al. 2013), species of conservation concern potentially preyed upon by corvids and raptors using utility structures as hunting perches. As power lines have proliferated, at least some corvid species appear to have expanded their breeding ranges (Jerzak 2001, Marzluff and Neatherlin 2006, Dwyer et al. 2013a) or increased their breeding densities (Coates et al. 2014) through utilizing power poles for nesting (Fleischer et al. 2008, Howe et al. 2014, Dwyer et al. 2015), possibly leading to indirect effects on their prey. Recent research suggests that avoidance by reindeer (*Rangifer tarandus*) may be linked to their ability to detect ultraviolet (UV) light emitted by transmission lines (Tyler et al. 2014). At least some birds also see in the UV spectrum (Lind et al. 2014), but the potential implications of this for indirect effects have not been thoroughly investigated.

SYNTHESIS AND SITING GUIDELINES

Our review summarizes existing studies of direct and indirect effects of energy infrastructure associated with 2 expanding energy sectors (onshore wind and solar), and indicates ongoing concern about the transmission lines connecting these facilities to existing electric transmission lines. This overview demonstrates that both the magnitude and the mechanisms of direct and indirect effects of renewable energy infrastructure and the associated power lines on birds are site- and species-specific (e.g., Villegas-Patraca et al. 2012, DeVault et al. 2014, Bayne et al. 2016). However, while we have provided comprehensive coverage of existing peer-reviewed literature, we stress that existing gray literature, much of which is held by private energy companies, would likely shed additional light on the direct and indirect effects of renewable energy infrastructures. Thus, increased public availability of privately funded data is urgently needed (Loss 2016).

Despite highlighting the prevalence of both site- and species-specific effects, some generalities can be drawn from our review. Large-bodied species with weakly powered flight, high wing loading, and relatively low maneuverability appear to be especially susceptible to the direct effects of tall structures at energy facilities (e.g., wind turbines and power poles). This is of concern, given that the sensitivity of such species at the population level is likely high because of delayed maturity and low reproductive rates (Dahl et al. 2012, Lovich 2015, Loss 2016). The effects of placement appear to be important across all energy infrastructure types considered in this review; infrastructure that bisects regular daily or migratory flight paths (e.g., turbine lines, transmission lines) may disproportionately affect birds compared with structures sited outside regular flight paths. The placement of infrastructure in habitat with few natural tall perches (deserts, grasslands, sagebrush steppe) may be more disruptive to the overall ecology of an area than the placement of infrastructure in habitat previously characterized by natural tall structures (forests), but further research is needed to explore these expectations. Given that all infrastructure results in direct habitat loss, indirect effects that act through the loss or fragmentation of habitat are likely to occur across all energy sectors. Similarly, given the potential for energy infrastructure and power lines to affect the distribution of predators, predation may be an important mechanism underlying indirect effects across energy facilities.

When considered together, the direct and indirect effects at renewable energy facilities and the transmission lines serving those facilities are likely cumulative and could be synergistic, especially when facilities are poorly sited (e.g., in areas of high bird abundance, in regular flight paths, or where facilities could act as ecological traps). However, the magnitude of direct effects is likely far less for energy facilities compared with other anthropogenic mortality sources in the U.S. (e.g., cats, buildings, communication towers, and automobiles; Loss et al. 2015), and the indirect effects of wind energy facilities may be less than those of traditional energy infrastructure

(Hovick et al. 2014). Nevertheless, the potential for additional effects of other infrastructure at energy facilities could further increase direct and indirect effects within an energy facility's footprint (e.g., roads: Benítez-López et al. 2010; maintenance buildings: Loss et al. 2014).

A critical end-goal for research in this field is to integrate research findings into mitigation strategies and to inform siting guidelines. Given the site- and species-specific nature of the effects of the energy infrastructure reviewed here, siting guidelines should be carefully developed in the context of vulnerable species within a particular geographic area. However, some key generalities have emerged that should be considered during siting decisions. We suggest the following: (1) Avoiding areas of high bird use (e.g., regularly used flight paths, migration corridors, and aggregation areas); (2) Avoiding areas inhabited by sensitive species or those of conservation concern; (3) Avoiding topographical features that promote foraging or that are used by migrating birds for uplift (e.g., the tops of slopes; Kitano and Shiraki 2013); (4) Avoiding areas of high biodiversity, endemism, and ecological sensitivity; (5) Developing conservation buffers for vulnerable species based on thresholds determined through empirical research; (6) Carefully selecting or modifying infrastructure to minimize collision risk or indirect effects (e.g., by the use of flashing red lights and ground devices, or by employing efficient technology that uses less space; Kerlinger et al. 2010, Martin 2012); and (7) Curtailing turbine operation under certain conditions (e.g., fog in the presence of sensitive species).

We also encourage the use of predictive models to gauge likely impacts at sites (e.g., Shaw et al. 2010, Dwyer et al. 2013b), and encourage the development and use of spatially explicit sensitivity maps that incorporate the distribution of bird populations, key flight paths, habitats, and risk factors (e.g., Bright et al. 2008, Dwyer et al. 2016, Pearse et al. 2016).

CONSIDERATIONS FOR FUTURE RESEARCH

The expected trajectory of the renewable energy sector (both in size and in technological advances) will expand the geographic area and, thus, habitats impacted by development. Much research to date has focused on wind energy development in grassland habitats in the Great Plains (e.g., LeBeau et al. 2014, Harrison 2015, Winder et al. 2015) and, to a lesser extent, solar energy development in the deserts of the southwestern U.S. (McCrary et al. 1986, Kagan et al. 2014). However, interactions between renewable energy infrastructure and birds are likely different among habitats (e.g., grasslands vs. woodlands), and thus continued habitat-specific research is needed. Because the effects of energy infrastructure on birds may vary with stage of operation (e.g., during construction, immediately following construction, and >1 yr postconstruction; Madsen and Boertmann 2008, Pearce-Higgins et al. 2012, Shaffer and Buhl 2016), such studies should be conducted over an extended period (e.g., 5, 10, or 15 yr). Studies that enable researchers to separate the effects of different infrastructure at facilities (e.g., roads, buildings, and wind turbines) are also encouraged. Given that wind energy infrastructure is also associated with bat collisions (e.g., Doty and Martin 2013), future research should seek to integrate avian and bat monitoring to identify cumulative effects.

Understanding the mechanisms that underlie the indirect effects of energy infrastructure on birds is essential if we are to establish conservation strategies that minimize potential impacts. While efforts have been made to address these concerns (Whalen 2015, J. A. Smith personal observation), the mechanistic drivers of effects are likely to vary with infrastructure type and across sites. Therefore, we encourage researchers to adopt mechanistic approaches in future studies of indirect effects by designing studies to reveal important mechanisms. Mechanisms could include, but are not limited to, changes in predation risk, food availability, and habitat availability, and avoidance of physical structures, lights, and UV light. Given that anthropogenic noise may disturb birds (Slabbekoorn and Ripmeester 2007, Blickley et al. 2012), we suggest that studies of energy development and avian interactions consider the role that infrastructure noise plays in driving indirect effects. Studies of solar facilities should explore the mechanisms resulting in avian concentrations at photovoltaic arrays (e.g., polarized light; Hováth et al. 2009).

Given that siting guidelines are often concerned with threshold distances (i.e. the distances from energy facilities at which effects on target species become negligible), we stress the relevance of using a gradient approach in studies of avian and energy infrastructure interactions. For example, by evaluating impacts on target populations at various distances from energy facilities, threshold distances can be identified and used to develop biologically meaningful conservation buffers. Such approaches have proven valuable in studies of disturbance associated with roads, urban areas, and oil and gas development (e.g., Reijnen et al. 1997, Laurance 2004, Palomino et al. 2007), and should be integrated into studies of renewable energy infrastructure (e.g., Winder et al. 2014, Harrison 2015, Whalen 2015). By centering buffers on sensitive habitat patches or populations, areas where development should be avoided can be delineated. However, we note that the effects of energy infrastructure may not always be detected via a gradient approach. Instead, the intensity of development (e.g., density of wind turbines) may be more informative (Mahoney and Chalfoun 2016). When possible, we also encourage implementation of a Before-After-

Control-Impact (BACI) study design that allows comparison of preconstruction, postconstruction, and control data, or, better still, an Impact-Gradient-Design (IGD) study design that incorporates the properties of both a gradient approach and a BACI study design. When preconstruction data is not available, control sites away from the focal energy facility should be considered. Researchers should also consider the specific biology (e.g., spatial ecology, life-history strategy) of the focal species, or focal populations, to sample suitable control sites.

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