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RESEARCH ARTICLE

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Relative energy production determines effect of repowering on wildlife mortality at wind energy facilities

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Abstract

1. Reduction in wildlife mortality is often cited as a potential advantage to repowering wind facilities, that is, replacing smaller, lower capacity, closely spaced turbines, with larger, higher capacity ones, more widely spaced. Wildlife mortality rates, however, are affected by more than just size and spacing of turbines, varying with turbine operation, seasonal and daily weather and habitat, all of which can confound our ability to accurately measure the effect of repowering on wildlife mortality rates.
2. We investigated the effect of repowering on wildlife mortality rates in a study conducted near Palm Springs, CA. We controlled for confounding effects of weather and habitat by measuring turbine-caused wildlife mortality rates over a range of turbine sizes and spacing, all within the same time period, habitat and local weather conditions. We controlled for differences in turbine operation by standardizing mortality rate per unit energy produced.
3. We found that avian and bat mortality rate was constant per unit of energy produced, across all sizes and spacings of turbines.
4. *Synthesis and applications*. In the context of repowering a wind facility, our results suggest that the relative amount of energy produced, rather than simply the size, spacing or nameplate capacity of the replacement turbines, determines the relative rate of mortality prior to and after repowering. Consequently, in a given location, newer turbines would be expected to be less harmful to wildlife only if they produced less energy than the older models they replace. The implications are far-reaching as 18% of US and 8% of world-wide wind power capacity will likely be considered for repowering within ~5 years.

KEYWORDS

confounding, energy production, GWh, mortality rate per unit energy, Palm Springs, repowering, wildlife mortality, wind farm

1 | INTRODUCTION

Wind power is currently the source for >7% of US electricity produced (U.S. Energy Information Administration, 2019). Turbine size and, consequently, energy-generating capacity, has increased dramatically since 1990, from machines with nameplate capacities of 25 kW, to current models with capacities of ≥2,500 kW (European Wind Energy Association, 2009; U.S. Department of Energy, 2019). Concurrent with the rise in capacity has been a shift from lattice towers to monopoles, a >6-fold increase in rotor diameter from <20 to >120 m, and an increase in hub height from ~20 to >120 m (European Wind Energy Association, 2009; U.S. Department of Energy, 2019). Although rotations per minute (RPM) has decreased, the rotor-swept area (RSA) of turbines has increased approximately 40-fold, and blade-tip speed has increased approximately 50%, from ~200 to >300 kph. As capacity and size of turbines have grown, so has the number of turbines globally and concern regarding the population-level effects of fatalities of birds and bats caused by collisions with rotating turbine blades (Frick et al. 2017; Katzner et al. 2019; May et al. 2019).

Reported per-turbine mortality rates of birds and bats vary not only seasonally (Marques et al. 2014), among facilities (deLucas et al. 2012) and within a facility (Rydell et al. 2010), but also with turbine height (Barclay et al. 2007; Loss et al. 2013), wildlife species (Allison et al. 2019) and geographic region (Arnett et al. 2008). One of the factors most commonly thought to influence mortality rates is turbine size, variably reported as hub height, blade length, RSA or nameplate capacity. It is possible that longer blades with faster tip speeds, sweeping a larger area will cause greater mortality per turbine than smaller, slower ones. However, because larger turbines are installed at lower densities with blades higher above the ground, it is unclear what impacts to expect on mortality rates of birds and bats from planned installation of new turbines as the industry expands its capacity.

This question has become particularly important as older wind facilities are being 'repowered'. Repowering involves replacement of smaller, lower capacity, tightly spaced turbines with larger, higher capacity turbines installed at lower densities, most often with the intent to generate similar or greater quantities of electrical energy within the same area (Brown, 2017; Martino, 2014; Roth, 2018). Currently, ~18%

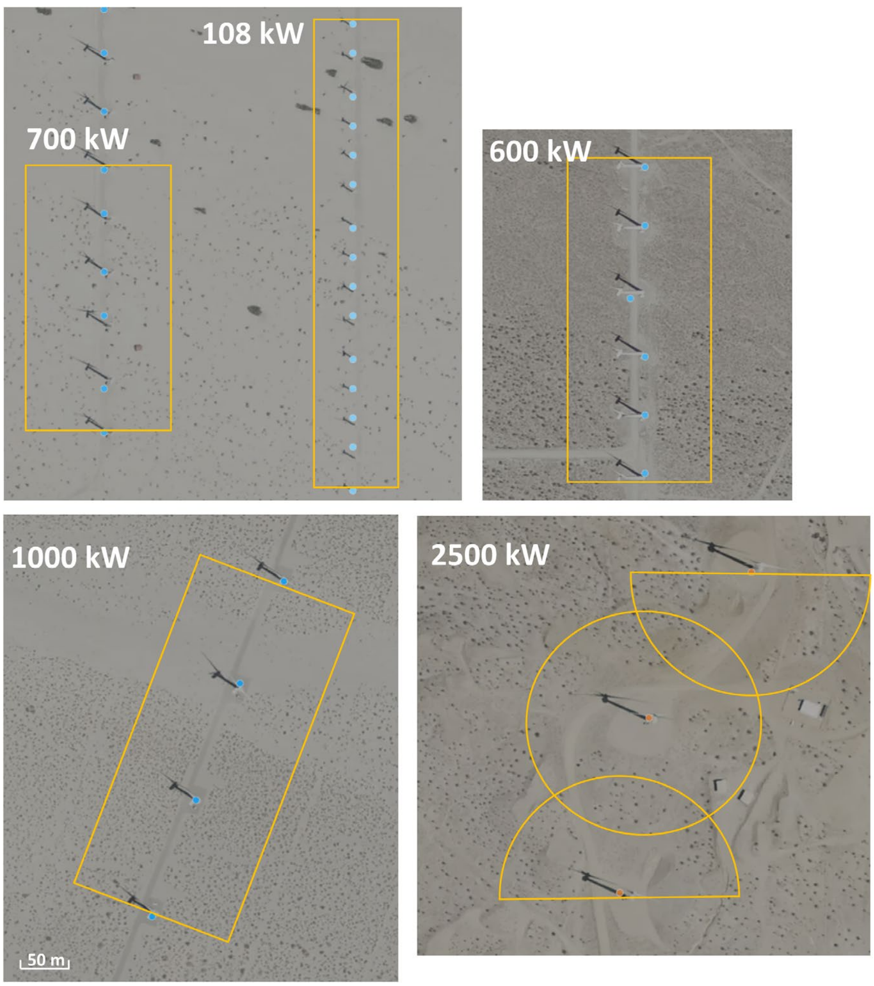

FIGURE 1 San Gorgonio Pass Wind Resource Area located near Palm Springs, CA, USA. Sites are expanded to show search areas that extended 1.25× maximum blade height around turbines. kW indicates nameplate capacity of individual turbines in the string

of existing turbines (~7.7 GW rated capacity) in the United States (Hoen et al. 2020) and ~8% world-wide are >15 years old and are likely to be considered for repowering within ~5 years. However, the effect of repowering on wildlife mortality has not been extensively studied. One study suggested that impacts to raptors may be reduced, in part, because modern tubular towers offer little perching opportunity relative to older lattice-style towers (Hunt, 2002). However, this conclusion was based on qualitative, not empirical, comparison of older 100 kW models on lattice-style towers with those rated at 700 kW on tubular towers. Another published study comparing only small-capacity turbines found no difference in annual mortality rates, when 126 25 kW vertical axis turbines were replaced with 31 66 kW horizontal-axis turbines (Smallwood & Karas, 2009). A third study concluded that repowering in the Altamont Pass Wind Resource Area in California would reduce the number of raptors killed per unit of energy produced, although energy production was not measured and the largest turbines monitored were 700 kW (ICF International, 2016). We are not aware of any carefully designed study of commonly used horizontal-axis turbines that compares mortality rates at older models with those at more modern models with ≥1,000 kW capacity.

Mortality rates of birds and bats can differ due to a suite of factors in addition to turbine size. These may include: (a) wind regime, maintenance regimes and operational agreements (including operational curtailment; (e.g. Baerwald et al. 2009; Arnett et al. 2011) that determine how fast and how often blades spin; (b) seasonal and daily weather patterns that affect when birds and bats are present and their behaviour (e.g. Cryan et al. 2013; Plonczkier & Simms, 2012) and (c) local habitat conditions that influence the density of birds and bats (e.g. deLucas et al. 2012). Unless held constant in an experimental context, these other factors can confound our ability to isolate the effects of turbine size on mortality rates of birds and bats.

We conducted our study at the San Gorgonio Pass Wind Resource Area (SGPWRA) north of Palm Springs in southern California, United States (Figure 1) because it includes turbines of a wide range of sizes in a confined area within which weather, wind and bird and bat movements are similar for all turbines. This allowed us to control for seasonal and daily weather patterns during the year and for microhabitat conditions. We knew, for each turbine, its model and nameplate capacity, and operators provided energy production data. We asked whether, after controlling for confounding factors, turbine-caused mortality rates of wildlife differed among turbines of different sizes.

2 | MATERIALS AND METHODS

2.1 | Study design

2.1.1 | Study area and site selection

The SGPWRA was established in the early 1980s as one of three primary wind resource areas in California. Wind turbines now cover an area from the top of the pass at ~850 to ~150 m ASL on the floor of the Coachella Valley. Vegetation in the area is desert scrub, dominated by creosote bush *Larrea tridentata*, bursage *Ambrosia dumosa* and associated species. Winds blow primarily west to east with average speed ~20 m/s.

Total energy production has increased at SGPWRA threefold since 1992 from ~500 to >1,500 GWh in 2017 (Roth, 2018). Energy production varies by season, from a low in January to highs in May and June (U.S. Energy Information Administration, 2018). Turbine nameplate capacity ranges from the smallest and oldest 60 kW models, to larger and newer 2,500 kW models. Repowering over the next few years is anticipated to reduce the number of wind turbines in the SGPWRA from >2,000 to ~600–700, with the objective of generating more energy than is currently produced but with larger turbines (Brown, 2017; Martino, 2014; Roth, 2018).

We selected strings of turbines (sites) within the SGPWRA along a gradient from older, smaller turbines, to newer, larger turbines, doing our best to adhere to certain criteria (see Supporting Information S1 for details). The selected sites (Figure 1) represented a gradient of energy production capacity that generally correlates well with many common measures of turbine size, for example, blade length, RSA, hub height, maximum blade height (Table 1). Individual turbine capacity at our sites varied almost 25-fold, from 108 to 2,500 kW capacity.

2.1.2 | Fatality monitoring and detection trials

We used dog-handler teams to search for carcasses in an area within 1.25× maximum blade height from turbines (Figure 1) every 3 days for 355 days (7 May 2018–26 April 2019). Concurrently, we conducted separate trials to estimate the proportion of animals killed that could be expected to persist to the next search (carcass persistence: CP) and the fraction of those that are found by searchers (searcher efficiency: SE; see Supporting Information S2 for design details). We

TABLE 1 Site and turbine data. Ht, maximum blade height (m); RSD, turbine rotor-swept diameter (m); RSA, turbine rotor-swept area (m^2); MW, rated capacity of turbine (MW); *n*, number of turbines searched; MWTot, total rated capacity of searched turbines (MW)

Site (kW)	Model	Ht	RSD	RSA	MW	*n*	MWTot
108	Micon-M108	42.0	18.9	281	0.108	14	1.512
600	Mitsubishi-MWT600	77.4	45	1,590	0.600	5	3.000
700[a]	NEG-Micon44	71.9	44	1,521	0.700	5	3.500
1,000	Mitsubishi-MWT62	90.8	61.4	2,961	1.000	3	3.000
2,500	Clipper-C93	126.0	93	6,793	2.500	2	5.000

[a]Turbines at this site had nameplate capacity of 750 kW but were operationally constrained to not surpass 700 kW.

placed 80–99 trial carcasses of three sizes (bats, small birds, large birds) within the search area at each site (trial unit) at random times and locations that were unknown to searchers (Table S1). Technicians not involved in searching monitored carcasses regularly for continued persistence. They noted which carcasses were removed by predators, and which were found by searchers and when they were found.

2.1.3 | Energy production

The companies operating the turbines at each site provided data on total MWh of energy produced by each monitored turbine during the 355-day study period. Due to change in ownership, energy production data were not available at the 2,500 kW site until 19 June 2018; we adjusted mortality rates estimates for this site accordingly (see Supporting Information S1 for details).

2.2 | Statistical analysis

We estimated bird and bat mortality rates and 95% confidence intervals at each site from estimated detection probabilities and observed carcass counts using tools in GenEst (Dalthorp et al. 2018) and Evidence of Absence. (see Supporting Information S2 for details on model selection). Mortality rate at each site was standardized per turbine, per nameplate capacity and per GWh energy produced. Standardized mortality was considered different among sites when the 95% confidence interval at any site failed to contain the average across sites.

3 | RESULTS

3.1 | Detection probability

The best CP model (Table S2) indicated that carcass persistence varied by trial unit and carcass size. The estimated proportion of carcasses persisting through to the next search (3d search interval) was never <50% (Table S3). Searcher efficiency varied by searchers and size class of carcass but did not differ among trial units (Table S4). The average proportion of carcasses that persisted and were found on the first search ranged from 40% to 90% (Table S5).

3.2 | Mortality rates

Bird and bat mortality rate per turbine generally increased with turbine size or MW capacity (Figure 2a,b; Table S6). Differences in

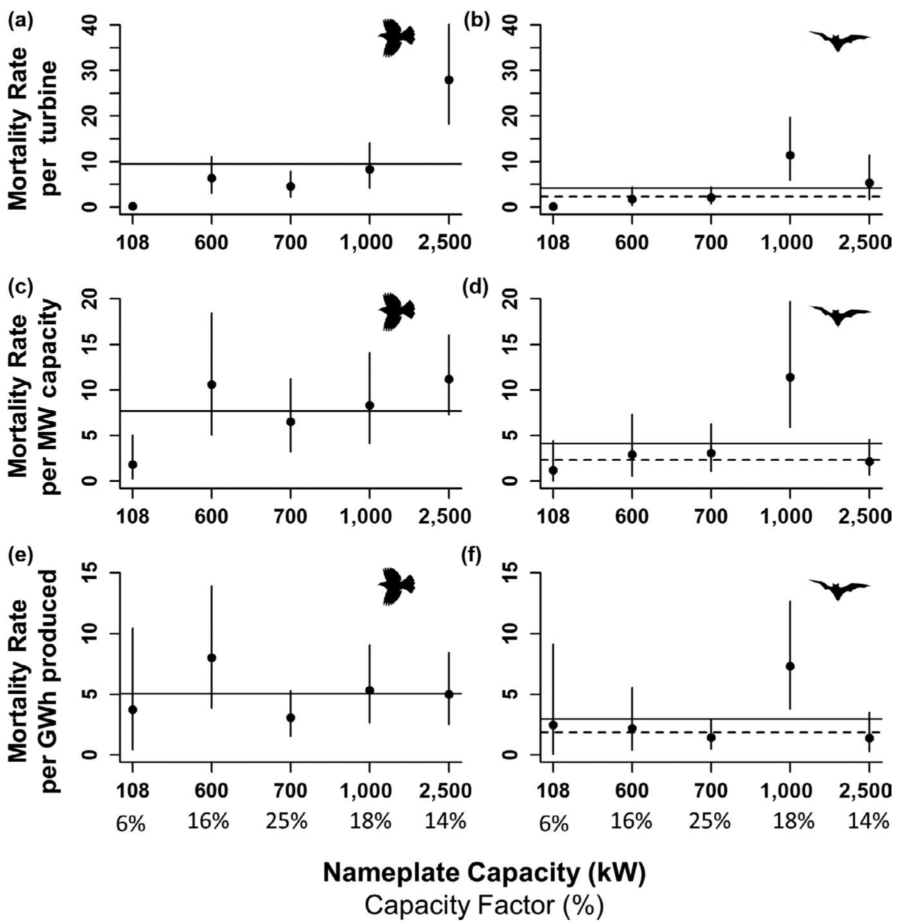

FIGURE 2 Estimated mean bird and bat mortality rate and 95% confidence limits at each site, labeled by nameplate capacity of the turbines (note change in *y*-axis range.) *X*-axis is ordinal. (a, b): Bird/Bat mortality per turbine. (c, d): Bird/bat mortality per MW nameplate capacity. (e, f): Bird/bat mortality rate per GWh produced. Capacity factor (total energy produced relative to theoretical maximum) for each string is shown beneath nameplate capacity labels in (e) and (f). Solid line = Average mortality across all turbine sizes. Dashed line = Average bat mortality across all turbine sizes excluding 1,000 kW turbines.

mortality rates among different sized turbines were reduced but not eliminated after standardizing by nameplate capacity (Figure 2c,d), a metric that loosely accounts for turbine size but ignores its operation time. Standardizing mortality rate by the amount of energy produced, a metric that accounts both for turbine size and operating time, resulted in estimates of mortality rates that were similar across all turbine sizes (Figure 2e,f). The one possible exception was bat mortality rate at the 1,000 kW turbines (Figure 2b,d,f), a special circumstance that we discuss below.

4 | DISCUSSION

Early studies suggested that mortality per turbine increases with turbine hub height (Loss et al. 2013) but that repowering with larger turbines at lower densities could result in lower mortality rates at the same facility (Smallwood & Karas, 2009). Some authors have suggested resolving this paradox by dividing per-turbine mortality by nameplate capacity of the turbine or by RSA (Johnson et al. 2016). However, each approach has its limitations because these measures are static and do not reflect operational differences among turbines. Standardizing mortality by any static measure implicitly assumes that all turbines are operating at equal capacity factor (the ratio of actual production to theoretical capacity.) In fact, over the course of a year, the amount of energy produced by a turbine is always less than, and often dramatically less than, its theoretical maximum capacity. As an example, within the United States in 2018 the capacity factor among facilities ranged from approximately 13%–52% (U.S. Department of Energy, 2020). As such, turbines with the same nameplate capacity or RSA, but at two neighbouring facilities or in two different years, may operate under very different schedules and thereby pose different risks to wildlife. As further example, in our study, the turbines we measured as 700 kW turbines, actually had rated capacity of 750 kW. Operational agreements constrained their output to not exceed 700 kW. This underscores a potential pitfall of simply standardizing mortality by a static measure and ignoring actual turbine operation.

In our study the oldest and smallest 108 kW turbines had the lowest capacity factor, but the greatest capacity factor was for the intermediate-aged 700 kW turbines, not at the newer 1,000 and 2,500 kW turbines (Figure 2). Energy produced by a turbine is an integrator of rated capacity (related to the size of the turbine) and operational patterns (how much and when the blades actually spin). Standardizing mortality rate by total energy production accounts for differences among turbines due to size as well as differences in operation. It is proportional to standardizing by capacity factor but is more easily interpreted.

The oldest and smallest turbines in our study generated the lowest mortality rate per turbine and the lowest mortality rate per rated capacity. However, these turbines were very near the end of their useful life and were slated for replacement in 2020. As a result, maintenance was minimal and they were often non-operational, producing energy at only 6% of their rated capacity. Other turbines operated with varying efficiency ranging from 14% to 25% of their capacity. After accounting for their variable operation time by standardizing mortality rate by amount of energy produced, the mortality rate at the 108 kW turbines was on a par with all the other turbines, even the largest ones with 25 times their capacity.

We found that wildlife mortality rates were relatively constant per unit energy produced by turbines under similar environmental conditions regardless of their size. Had we failed to hold potentially confounding factors constant in our design and to account for the actual operation of the turbines, we would have incorrectly interpreted the effects of repowering on wildlife mortality rates. While this does suggest that, at a given location, mortality rates per unit energy produced will be about the same for all turbine sizes, it does not suggest that mortality rate per unit energy produced will be the same in different locations. As environmental conditions change with location, mortality rates per unit energy produced will likely vary greatly among regions and among sites or even turbines with different bird and bat use of the airspace.

The high bat mortality rate of the 1,000 kW turbines in our study illustrates this point. The high mortality rate we detected at these turbines could be due simply to sampling variation, or, more likely, to characteristics of the site. These turbines were located within 650 m of the Whitewater Groundwater Replenishment Facility, a site known to attract insects, the primary prey for many bat species (Chatfield, 2018). The high bat mortality rate at this string, and the relatively constant rate among others, illustrates the potential importance of even small-scale turbine siting, rather than size, in determining mortality rates.

Facility and turbine location, and energy production, then, will likely be stronger determinants of mortality rates than will turbine size. Research to gauge the effects of turbines on wildlife, whether testing hypotheses regarding effectiveness of measures to reduce mortality or seeking to understand the relationship of mortality rates to the local environment, therefore will be improved if mortality rate is standardized per unit energy produced. Doing this implicitly accounts for variation in turbine size and explicitly accounts for variation in mortality due to varying turbine operation. Failure to account for energy production at some level may help explain why, to date, no relationship has been found between predicted risk and actual bird (deLucas et al. 2008; Ferrer et al. 2012) or bat (Lintott et al. 2016; Solick et al. 2020) mortality at wind farms.

5 | CONCLUSIONS

Concern for impacts of wind-power generation on wildlife has grown over the last 10–20 years and can be expected to increase as higher proportion of the power-generation portfolio is contributed by this energy source. Understanding impacts to wildlife caused by turbines is a central problem confronting both global expansion of wind energy and the increasingly prevalent process of repowering. Replacement of older and smaller wind turbines with newer, larger machines generating the same amount of energy will have little consequence for rates of wildlife mortality. To date, studies of this problem have been qualitative (Hunt, 2002), focused on atypical turbines (Smallwood & Karas, 2009), and failed to account for energy production (ICF International, 2016). Our study is the first to compare modern, horizontal-axis wind turbines of different ages in a study with high carcass detection rates, accurate accounting for energy production and a state-of-the-art analytical design.

Measuring the impacts of repowering is easily confounded by variability in space, time and operational constraints. Our study is the first to control for these features and it illustrates that benefits to wildlife of replacing older turbines with newer ones in the same location will depend largely on the relative amount of energy produced, not simply on the size or spacing of the replacement turbines. As wind technology continues to improve and modern turbines continue to increase in height, RSA and MW capacity, future research will be required to understand how this broader range of sizes and energy production might affect the impact of repowering on mortality rates of birds and bats.

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AUTHORS' CONTRIBUTIONS

A.F., T.K. and M.H. were involved in funding acquisition; M.H., T.K., A.F., T.C. and D.D. were involved in conceptualization; T.K., M.H., M.D. and H.S. were involved in supervision; M.H. and D.D. were involved in formal analysis; M.H. and T.K. were involved in writing (original draft); M.H., T.K., T.C., D.D., M.D. and A.F. were involved in writing (review and editing).

DATA AVAILABILITY STATEMENT

GenEst data are available at https://doi.org/10.5066/P9VV1Z3E (Huso et al. 2021).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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