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A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States

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ABSTRACT

Despite the benefits of reduced toxic and carbon emissions and a perpetual energy resource, there is potential for negative environmental impacts resulting from utility-scale solar energy (USSE) development. Although USSE development may represent an avian mortality source, there is little knowledge regarding the magnitude of these impacts in the context of other avian mortality sources. In this study we present a first assessment of avian mortality at USSE facilities through a synthesis of available avian monitoring and mortality information at existing USSE facilities. Using this information, we contextualize USSE avian mortality relative to other forms of avian mortality at 2 spatial scales: a regional scale (confined to southern California) and a national scale. Systematic avian mortality information was available for three USSE facilities in the southern California region. We estimated annual USSE-related avian mortality to be between 16,200 and 59,400 birds in the southern California region, which was extrapolated to between 37,800 and 138,600 birds for all USSE facilities across the United States that are either installed or under construction. We also discuss issues related to avian–solar interactions that should be addressed in future research and monitoring programs.

1. Introduction

Renewable energy development has been increasing as an alternative to fossil-fuel based technologies, in large part to reduce toxic air emissions and CO_2-induced effects on climate [1,2]. According to the U.S. Energy Information Association [3], electric generation from renewables in the United States has increased by over 50% since 2004 and renewable energy sources currently provide approximately 14% of the nation's electricity. Solar energy-based technologies represent a rapidly developing renewable energy sector that has seen exponential growth in recent years [4,5]. For example, since 2013 alone, cumulative installations of photovoltaic (PV) solar energy technologies, including residential, commercial, and utility-scale installations, have more than doubled in the United States [6].

Utility-scale solar energy (USSE) projects generate electricity for delivery via the electric transmission grid and sale in the utility market. This differs from distributed solar energy systems which are designed for electric generation and utilization at local scales. According to the Solar Energy Industries Association (SEIA) [7], there currently are approximately 800 USSE projects ($\geq$1 MW [MW]) in the United States that are either in operations or under construction, representing approximately 14 GW (GW) of electric capacity. Based on solar insolation models developed by the National Renewable Energy Laboratory [8], the greatest solar resource potential in the United States occurs in the southwest within the six following states: Colorado, New Mexico, Utah, Arizona, Nevada, and California (Fig. 1). Indeed, most of the installed or planned utility-scale solar facilities in the United States (based on electric capacity and includes projects that are operating, under construction, and under development) are located within these six southwestern states (Fig. 2) [7].

There are two basic types of solar energy technologies employed at USSE installations in the United States [9]: photovoltaic (PV) and concentrating solar power (CSP). Photovoltaic systems use cells to convert sunlight to electric current, whereas CSP systems use reflective surfaces to concentrate sunlight to heat a receiver. That heat is subsequently converted to electricity using a thermoelectric power cycle. CSP systems typically include power tower systems

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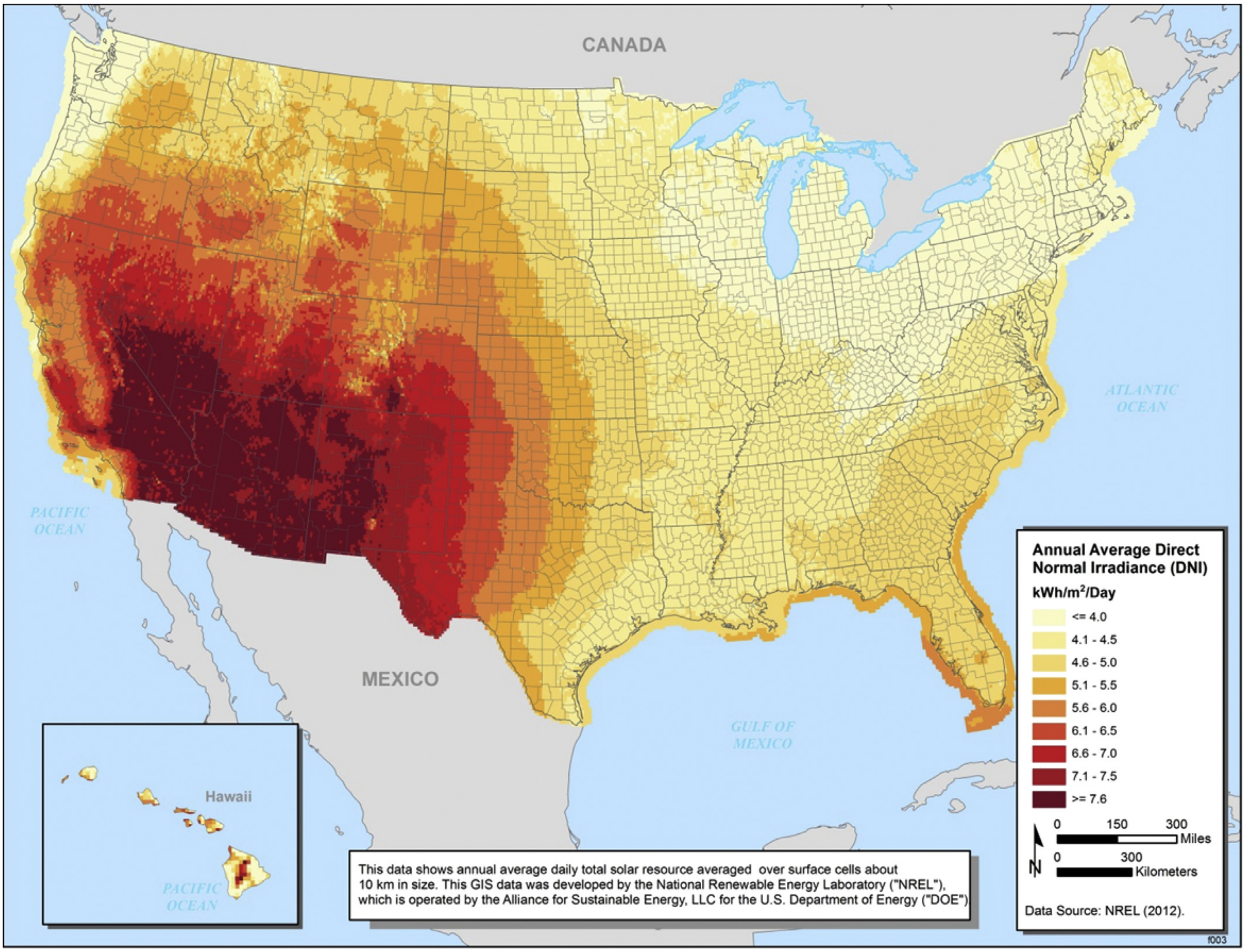

Fig. 1. Solar energy potential in the United States [8].

with heliostats (angled mirrors) and parabolic trough systems (parabolic mirrors). In the United States, most of the electricity produced by utility-scale solar energy projects through 2015 was generated using PV technologies [6].

Despite the benefits of reduced toxic and carbon emissions from a perpetual energy resource, there is potential for negative environmental impacts resulting from utility-scale solar development [9,10]. Utility-scale solar energy facilities in the United States require large spatial footprints (between 1.4 and 6.2 ha of land per MW of electric production) and are projected to require a total of 370,000–1,100,000 ha of land by 2030, mostly in the arid regions of the southwestern states [11]. These large scale developments and land-cover change associated with them may result in a variety of environmental impacts. Among the potential environmental impacts are ecological impacts to wildlife species and their habitats. Recent studies have suggested that utility-scale solar developments may represent a source of mortality for wildlife such as birds [12]. There are currently 2 known types of direct solar energy-related bird mortality [9,12,13]:

1. Collision-related mortality – mortality resulting from the direct contact of the bird with a solar project structure(s). This type of mortality has been documented at solar projects of all technology types.
2. Solar flux-related mortality – mortality resulting from the burning/singeing effects of exposure to concentrated sunlight. Mortality may result in several ways: (a) direct mortality; (b) singeing of flight feathers that cause loss of flight ability, leading to impact with other objects; or (c) impairment of flight capability to reduce the ability to forage or avoid predators, resulting in starvation or predation of the individual [12]. Solar flux-related mortality has been observed only at facilities employing power tower technologies.

The nature and magnitude of impacts to bird populations and communities is generally related to the following three primary project-specific factors [10,14]: location, size, and technology. Bird abundance and activity at local and regional scales varies by the distribution of habitat and other landscape features (e.g., elevation) in the environment [15–19]. Therefore, the location of a solar energy project relative to bird habitats, such as migration flyways, wetlands, and riparian vegetation, could influence avian mortality risk. The footprint size of the solar project is a direct measure of the amount of surface disturbance and human activity. Projects with larger footprints, therefore, may result in more avian fatalities than projects with smaller footprints. Lastly, different solar technologies and project designs may influence avian mortality risk. For example, project designs that utilize constructed cooling ponds, or

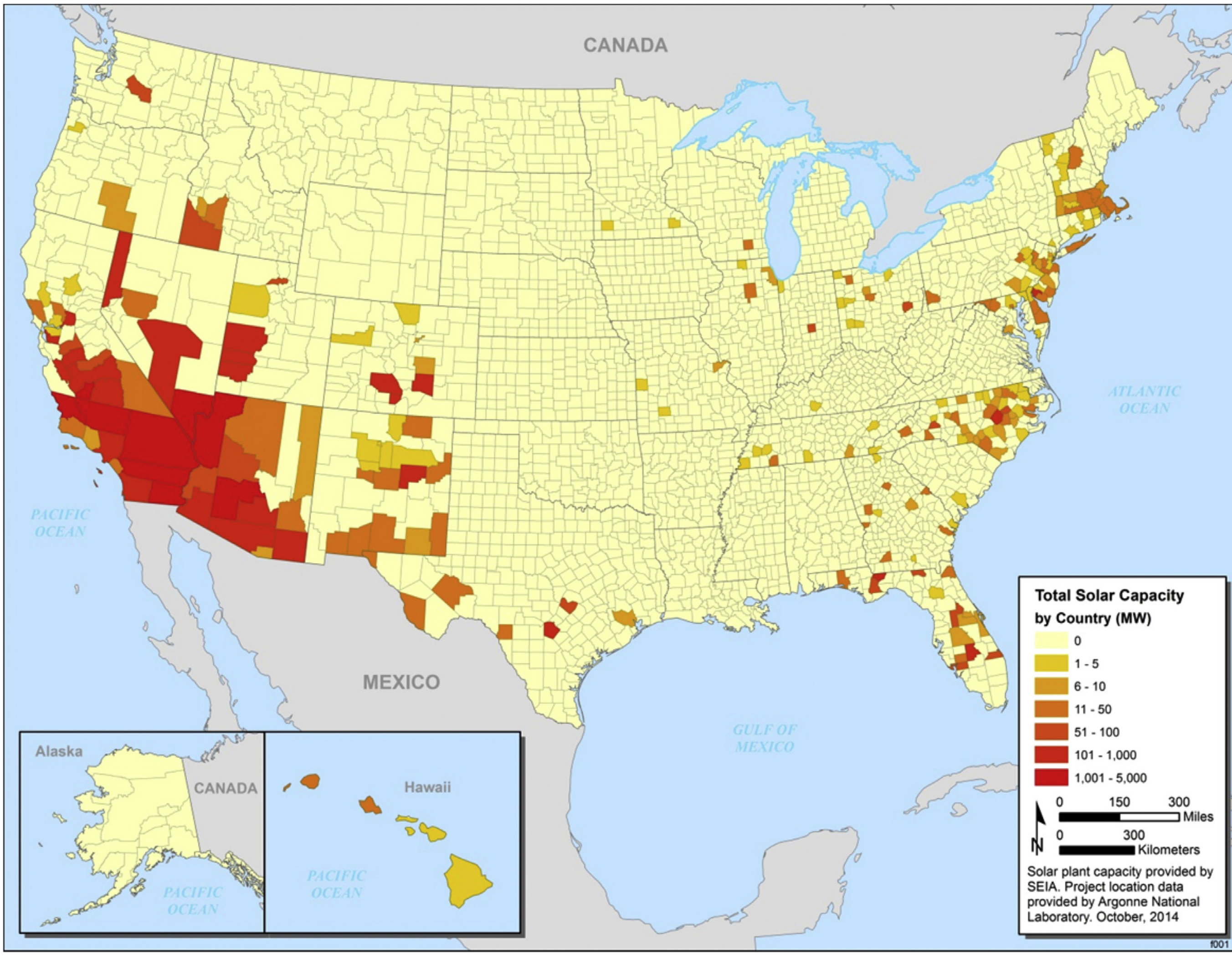

Fig. 2. Total solar energy production capacity (MW) by County [7].

solar collectors that reflect polarized sunlight in such a way so as to be perceived as waterbodies, may attract birds and their prey (e.g., insects), thereby increasing the risk of bird collisions with project structures [10,12,14,20]. To date, however, no empirical research has been conducted to evaluate the attraction of utility-scale solar facilities to migrating or foraging birds. Although collision-related impacts may occur at all types of solar energy technologies, the effects of solar flux on birds to date have been observed only at facilities employing power tower technologies [9,12,13].

One approach to understanding the impacts of utility-scale solar energy development on birds is through understanding mortality risk from solar energy development in the context of other industrial developments. Techniques to estimate avian mortality based on systematic monitoring methods have been previously employed for other sources of avian mortality (e.g., [21–24]). Despite the potential for avian mortality from solar energy development, however, there is currently little empirical data on avian mortality at solar facilities (but see McCrary et al. [13]). However, as more data resulting from avian monitoring at solar energy facilities become available, a systematic assessment of available data can provide a better understanding of avian fatality risk at utility-scale solar energy developments.

The objectives of this study were to 1) synthesize currently-available information regarding avian mortality at utility-scale solar facilities; 2) contextualize avian mortality at utility-scale solar facilities relative to other human sources of avian mortality; and 3) discuss issues related to avian–solar interactions that need to be addressed in future research and monitoring designs.

2. Methods

2.1. Study area

Despite efforts to collect avian–solar data at USSE facilities throughout the United States (see RESULTS), our comprehensive search for available avian fatality information at USSE facilities revealed that information was primarily only available within the region of southern California. For this reason, we defined our study area as the area that encompassed approximately 148,000 km^2 within the 10 southern-most counties of California (Fig. 3). This region was chosen for the amount of current and planned utility-scale solar energy development and availability of project-specific information on avian fatalities. Nearly 50% of utility-scale solar developments either under construction or in operation in the

Fig. 3. Utility-scale solar facilities with available avian fatality data and major wind projects within the Southern California study area.

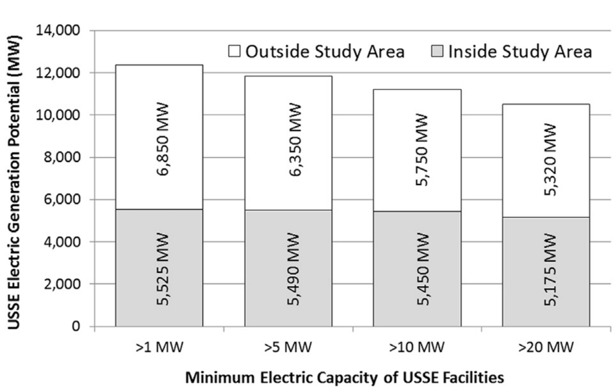

Fig. 4. Utility-Scale Solar Energy (USSE) electric generation potential in the Southern California Study Area and within the United States by minimum name plate electric capacity category.

United States are located in this region (Figs. 2 and 4) [7]. In addition, all currently-available information on avian mortality at U.S. utility-scale solar energy facilities are associated with only those projects occurring in this region (see Results).

2.2. Literature review

We conducted a review of available information on avian monitoring and mortality at utility-scale solar energy facilities by obtaining project-specific information from publicly-available online sources, such as the California Energy Commission (CEC; http://www.energy.ca.gov/). We conducted a comprehensive online search of the open literature on Web of Science (https://webofknowledge.com/) and Google Scholar (http://scholar.google.com/) using search terms “solar energy” and a combination of “bird”, “deaths”, “fatality”, “mortality”, “monitoring”, “avian mortality”, and “avian monitoring”. We also contacted and requested avian mortality information from solar energy developers and industry representatives operating in the United States and internationally.

Only studies at solar facilities in which avian fatalities were recorded from systematic surveys were considered in this study. Systematic data include fatalities observed during the course of survey efforts designed to characterize avian mortality at the project. Other fatality observations, such as incidental fatality data, were not part of focused systematic searches for carcasses and therefore could not be used to estimate project-specific mortality rates.

2.3. Mortality rate estimation

A standard metric commonly used for assessing avian mortality at energy production facilities is the mortality rate estimated as the total number of bird deaths per unit of energy production (e.g., bird deaths per MW per year) [24,25]. Our primary focus was to standardize avian mortality rates to the name plate capacity of utility energy developments to enable more direct comparison to other energy-related mortality sources such as wind energy. However, we also calculated mortality rates by the amount of electricity produced at each facility assuming a 30% capacity factor (the approximate capacity factor observed during the first year of operations at the Ivanpah Solar Electric Generating System). Using these metrics, a regional avian mortality rate was estimated for utility-scale solar projects in the study area (Fig. 3).

It is important that mortality estimates be adjusted to account for biases in scavenging and ability of searchers to detect carcasses [28–30]. Searcher efficiency is a metric to quantify the ability of searchers to detect carcasses. It typically refers to the percentage of carcasses observed by searchers relative to a known number of carcasses. Factors such as bird size and the presence of obstructions such as vegetation and structures may influence searcher efficiency [28,30]. The carcass persistence rate is a metric to quantify the amount of time (usually days) that a carcass is available to be observed before it is scavenged by predators. Factors such as bird size and local predator densities may influence carcass persistence estimates [28–30]. We ensured that all studies used in avian mortality rate estimates included mathematical approaches to account for predation and searcher efficiency biases (e.g., [30,31]. For those studies that did not consider predation and searcher efficiency biases in mortality rate estimation, we applied adjustments for those biases based on average predation and searcher efficiency rates observed at nearby solar and wind energy projects in the region (see supplemental information).

Avian mortality at some USSE facilities was recorded as separate mortality rates for fatalities known to be attributable to the facility (e.g., observable collision trauma or singed feathers) and unknown fatalities in which carcasses found on the project site showed no observable project-associated cause of death. The total avian mortality rate was calculated as a range representing the minimum (based on carcasses with a known cause of death attributable to the facility) and the maximum (based on the sum of birds with known and unknown causes of death). It is important to identify and distinguish between these two types of mortality estimates because birds with an unknown cause of death may have died due to natural causes (i.e., predation or disease) and may not be attributed to the solar facility. Following this, we used information provided by SEIA [7] to determine the total name plate electric capacity of all current and planned USSE facilities in the study region. We multiplied total USSE electric capacity with estimated USSE mortality rates to calculate total annual USSE-related avian mortality. We also used the regional USSE mortality rate to estimate USSE-related avian mortality across all USSE facilities that were in operations or under construction in the United States [7]. We used the regional USSE mortality rate to extrapolate USSE-related mortalities at a national scale because USSE developments in the southern California study region represented nearly 50% of all USSE developments in the United States (Fig. 4).

2.4. Contextualizing solar avian mortality

To our knowledge, this study is the first systematic synthesis of avian mortality at USSE facilities. There are no previous efforts to systematically contextualize solar–avian mortalities to other avian mortality sources. There have been several efforts to assess avian mortality associated with other renewable energy developments such as wind energy [23,24] and non-energy sources such as road mortality [32], collisions with buildings and other structures such as communication towers [21,32–34], and cat predation [35]. We reviewed these avian monitoring and mortality studies to estimate mortality rates from energy and non-energy sources that could be comparable to USSE-related mortalities. The mortality sources chosen for comparison include (1) wind energy development, (2) fossil fuel energy development, (3) collisions with communication towers, (4) road mortality, and (5) building collisions. We used mortality rate estimates from these sources to contextualize avian mortality at two geographic scales: within the southern California study region and across the United States.

2.4.1. Wind energy development

Recent assessments of avian mortality at wind energy facilities across the United States have been reported by Loss et al. [36] and Smallwood et al. [23]. To assess avian mortality associated with wind energy developments in the southern California study region, the locations of wind energy facilities and associated electric generation capacity within the study region were obtained using turbine locations mapped by the U.S. Geological Survey (USGS) through July 2013 [37]. We searched available literature for systematic avian monitoring and mortality studies that provided statistically-based adjusted mortality estimates at these wind energy facilities in the region. Using these studies, we calculated a capacity-weighted average mortality rate (number of birds/MW/year) across the wind energy projects in the region and determined the total electric energy production of the mapped wind energy facilities in the region to estimate total annual avian mortality associated with wind energy developments in the southern California region. We used estimates provided by Loss et al. [36] and Smallwood [23] to estimate avian mortalities at wind facilities across the United States.

2.4.2. Fossil fuel energy development

Sovacool [25] estimated avian mortality from fossil fuel power plants across the United States as a result of collision with infrastructure, electrocutions, pollution and contamination, and climate change. In addition, Sovacool [25] estimated climate change-induced avian mortality (in terms of habitat loss and changes in migration) predicted to be the result of fossil fuel power plant operations. We obtained data on the number and electric capacity of fossil fuel power plants in the southern California region from the California Energy Commission Almanac of Power Plants (http://energyalmanac.ca.gov/powerplants/). We applied the fossil fuel mortality estimate from Sovacool [25] to calculate a regional annual mortality estimate resulting from fossil fuel power plants. We also used the mortalities calculated by Sovacool [25] as an estimate of avian mortalities associated with fossil fuel power plants across the United States.

2.4.3. Collisions with communication towers

Longcore et al. [33] conducted a systematic review of avian mortality at communication towers in an effort to estimate avian mortality resulting from collisions with communication towers and associated structures (e.g., guy wires) across North America. Mortality estimates were calculated within Bird Conservation Regions (BCR) and aggregated to represent an overall mortality estimate across North America. Longcore et al. [33] estimated over 6 million bird mortalities resulting from collisions with communication towers across North America. To estimate annual avian mortality associated with collisions with communication towers in the study region, we applied the mortality estimates within the BCRs reported by Longcore et al. [33] proportional to the distribution of BCRs in this study's region.

2.4.4. Road mortality

The avian impacts of roadways, including direct collision mortality and indirect effects such as habitat fragmentation, have been a concern among scientists for many years [32,38,39]. Knowledge about avian fatality estimates associated with roadways in the United States comes from the works of Banks [40] and Erickson et al. [32]. In a synthesis of existing fatality information, Banks [40] found that avian mortality along roadways in the United States ranged from 2.7 to 96.2 bird deaths per mile of roadway (4.3–153.9 bird deaths per km). Based on an analysis of all roadways in the United States, Erickson et al. [32] estimated total avian mortality associated with vehicle traffic along roadways in the United States between 89 million and 340 million birds per year. In a more recent study in Canada, Bishop and Brogan [41], found that, after accounting for scavenging, total estimated road mortality was 21.6 bird deaths per mile of roadway (34.6 bird deaths per km). We obtained roadway GIS data from the U.S. Census Bureau [42] to estimate the amount of paved roadways in the study region. We used this estimate to calculate avian road mortality within the range of mortality rates reported by Banks [40] and Bishop and Brogan [41].

2.4.5. Building collisions

Loss et al. [34] provided a systematic review and estimate of avian mortality associated with building collisions in the United States. Reviewing published literature and unpublished data, Loss et al. [34] estimated avian mortality at buildings of three different classes: residential structures, low-rise buildings (1–3 stories high), and high-rise buildings (≥4 stories tall). Estimated mortality in each building class was calculated by multiplying data-derived mortality probabilities by the estimated number of buildings in the United States. Based on this approach, Loss et al. [34] calculated annual bird mortality at building structures across the United States to be between 365 million and 988 million birds. For purposes of establishing context in this study, avian mortality at buildings was only calculated for residences in the study region because information on residential structures were readily available from the U.S. Census Bureau housing unit statistics [43] and information provided by individual county assessor's offices. The calculation of avian mortalities resulting from collisions with residential structures, therefore, represents a minimum building collision mortality estimate for the region and is used solely for contextualization purposes. Loss et al. [34] calculated the 95% CI of annual bird mortality at residences to be between 1.3 and 3.1 birds per residence across the United States (median: 2.1 birds). We obtained data on the number of residential structures within the southern California region from the U.S. Census Bureau American Housing Survey [43] and individual county assessor's offices and applied the building collision-related mortality estimates provided by Loss et al. [34] to calculate a regional annual mortality estimate resulting from bird collisions with residential structures.

3. Results

3.1. Avian mortality at USSE facilities

A summary of all USSE facilities in the United States with available avian monitoring and mortality information is provided in the Supplemental Information. We identified 3 USSE facilities in the United States at which avian fatality data have been systematically collected and suitable for mortality rate estimation (Table 1). These three USSE facilities occur in the southern California study region: California Solar One (CSO), California Valley Solar Ranch (CVSR), and Ivanpah Solar Electric Generating System (ISEGS) (Fig. 3). The CSO facility was a CSP power tower project with a name plate electrical capacity of 10 MW that was decommissioned in 1987. Systematic surveys on CSO's 7.3 ha (18 acre) project area were conducted over the course of one year between 1982 and 1983 by McCrary et al. [13]. These survey results were used to calculate a site-wide avian mortality estimate for the facility (see Supplemental Information for more details on avian mortality estimation). The CVSR facility is an operational PV project with a name plate electrical capacity of 250 MW. Annual systematic surveys on CVSR's 1902 ha (4700 acre) project area were used to calculate site-wide avian mortality estimates [44]. The ISEGS facility is an operational CSP power tower project with a name plate electrical capacity of 377 MW. Annual systematic surveys on ISEG's 1457 ha (3600 acre) project area were used to calculate site-wide avian mortality estimates [45].

Avian mortality estimates at each of the three USSE facilities were adjusted to account for scavenger and searcher efficiency biases. These adjustments were included in the mortality estimates determined for CVSR and ISEGS [44,45]. However, McCrary et al. [13] did not present an adjusted mortality rate for CSO. To calculate an adjusted mortality rate for CSO, we used average estimates of carcass persistence and searcher efficiency from nearby studies using the formula developed by Shoenfeld [31]. In addition, separate mortality rates were calculated at CVSR and ISEGS for those carcasses with a cause of death that could be attributed to known site-related factors (e.g., collision trauma) as well as those carcasses found on site that did not show observable site-related causes of death [44,45]. These separate estimates were used to compute the total potential site-wide mortality rate (which is the sum of the known and unknown mortality rates). At CSO, McCrary et al. [13] attributed 100% of the fatalities to a project-related cause of death. At the CSO facility; therefore, the mortality rate for carcasses with unknown causes of death was assumed to be zero (Table 1). See the Supplemental Information for more information on data collection and mortality rate estimation at each of these facilities.

There was considerable variability in mortality rates for carcasses with known project-related causes of death at USSE facilities (ranging between 0.50 and 10.24 birds/MW/year) (0.23 and 3.90 birds/GWh/year) (Table 1). However, incorporating mortality of carcasses with no observable project-related cause of death resulted in less variable total potential mortality rates across USSE facilities (ranging between 9.30 and 10.70 birds/MW/year) (3.55 and 4.08 birds/GWh/year). Calculating the capacity-weighted average mortality rate of known USSE-related mortalities and total potential mortality rate results in a range of 2.7–9.9 birds/MW/year (1.06–3.78 birds/GWh/year) (Table 1). This range represents the uncertainty in including fatalities with no observable USSE-related cause of death to the total mortality estimate. Presumably, some carcasses found on site that showed no signs of USSE-attributable cause of death would actually be associated with other causes (e.g., natural background mortality, predation, disease, etc.). Based on SEIA [7], there is a total name plate electric capacity of 6 GW for current and planned USSE facilities in the study region. Applying

Table 1
Avian mortality estimates from systematic surveys at utility-scale solar energy (USSE) facilities.

Project name	Technology type and MW (in Parentheses)[a]	Mortality rate for known USSE-related fatalities[b]	Mortality rate for unknown USSE-related fatalities[c]	Total mortality rate for known and unknown USSE-related fatalities[d]	Source of mortality estimate[e]
California Solar One	CSP – Power tower (10)	10.24 (3.90)	0 (0)	10.24 (3.90)	McCrary et al. [13]; See also Supplemental Information
California Valley Solar Ranch	PV (250)	0.50 (0.23)	10.20 (3.89)	10.70 (4.08)	H.T. Harvey & Associates [44]
Ivanpah	CSP – Power tower (377)	3.96 (1.53)	5.34 (2.05)	9.30 (3.55)	H.T. Harvey & Associates [45]
Capacity-weighted average mortality rate (birds/MW/year)		**2.7 (1.06)**	**7.3 (2.79)**	**9.9 (3.78)**	

[a] CSP = Concentrating Solar Power; PV = Photovoltaic.
[b] Mortality rate for fatalities known to be attributable to the facility (e.g., observable collision trauma or singed feathers). Mortality rate represents the annual number of estimated bird deaths per megawatt of name plate electric capacity. Values in parentheses represent the annual mortality rate estimated by the amount of electricity produced in gigawatt hours (GWh), assuming a 30% capacity factor.
[c] Mortality rate for carcasses found on the project site of unknown cause (e.g., show no observable USSE-associated cause of death). Mortality rate represents the annual number of estimated bird deaths per megawatt of name plate electric capacity. Values in parentheses represent the annual mortality rate estimated by the amount of electricity produced in gigawatt hours (GWh), assuming a 30% capacity factor.
[d] Total mortality rate includes the mortality rate calculated for carcasses found at USSE facilities with known and unknown causes of death (i.e., sum of known and unknown mortality rates). Mortality rate represents the annual number of estimated bird deaths per megawatt of name plate electric capacity. Values in parentheses represent the annual mortality rate estimated by the amount of electricity produced in gigawatt hours (GWh), assuming a 30% capacity factor.
[e] Refer to Supplemental Information for summary of data collection and mortality estimation at each solar energy facility.

the range of USSE capacity-weighted average mortality rates to the total USSE electric generation potential for the region, we estimate between 16,200 and 59,400 avian fatalities per year from USSE facilities within the southern California study region. Across all USSE facilities in operation or under construction in the United States (approximately 14 GW name plate electric capacity), between 37,800 and 138,600 bird deaths are estimated each year associated with USSE developments (Table 2).

3.2. Contextualizing avian mortality to other sources

Based on turbine locations mapped by the USGS through July 2013 [37], we calculated 4402 MW of total electric energy production of wind energy facilities in the study region. Of the wind energy facilities known to occur in the region, avian mortality data were available for 5 facilities (Table 3). These projects contain a wide range of avian mortality estimates (0.55–38.62 mortalities/MW), most likely due to changes in turbine technology over time. Taking a capacity-weighted average mortality rate across projects in the region results in an estimate of 6.71 bird deaths/MW/year. In addition, based on Smallwood's [23] national mortality estimate of 573,093 birds across a total installed wind energy capacity of 51,630 MW in the United States (as of 2012), we estimated a national avian mortality rate of 11.10 birds/MW. Applying this range of annual wind-related mortality rates (6.71–11.10 birds/MW) to the total electric generation potential for wind energy facilities in the study region results in an estimate of 29,537–48,862 bird mortalities per year among wind energy facilities in the region (Table 2).

Sovacool [25] estimated approximately 14.5 million birds die annually across the United States as a result of fossil fuel power plant operations, at a rate of approximately 74.2 birds/MW/year of nameplate electrical generation. Based on information obtained from the California Energy Commission, the total electric capacity rating of fossil fuel power plants in the study region was approximately 48,000 MW. Combining this electricity production capacity with the fossil fuel mortality estimate from Sovacool [25] (74.2 birds/MW/year) results in a regional mortality estimate of 3,561,600 birds associated with fossil fuel power plants (Table 2).

The following BCRs occur in the study region [33]: Sonoran and Mojave Deserts (57%), Coastal California (42%), and Sierra Nevada (1%). Based on avian mortality estimates from Longcore et al. [33] at communication towers in the United States and adjusting for the percentage of BCRs occurring in the region, we estimated avian mortality resulting from collision with communication towers in the study region to be 70,552 birds per year (Table 2).

Based on roadway GIS data obtained from the U.S. Census Bureau [42], there are approximately 167,700 miles of paved roadways in the study region. Banks [40] and Bishop and Brogan [41] estimated avian road mortality to range from 2.7 to 96.2 bird deaths/mile. Multiplying that range by the number of paved miles in the

Table 2
Estimated annual avian mortality from various sources in the Southern California Region and United States.

Mortality source	Southern California region	United States
Utility-scale solar energy (USSE) developments	16,200–59,400	37,800–138,600[a]
Wind energy developments	29,537–48,862	140,000–573,000[b]
Fossil fuel power plants	3,561,600	14.5 million[c]
Communication towers	70,552	4.5–6.8 million[d]
Roadway vehicles	>453,000[e]	89–340 million[f]
Buildings and windows	>7,800,000[g]	365–988 million[h]

[a] Based on approximately 14 GW total name plate capacity of utility-scale solar facilities in operations or under construction across the United States [7].
[b] Sources: Loss et al. [36], Smallwood [23], Erickson et al. [24].
[c] Source: Sovacool [25].
[d] Sources: Erickson et al. (2005), Longcore et al. [33].
[e] Represents a minimum estimate using only estimated mortality for paved roadways in the southern California study region.
[f] Source: Loss et al. [49].
[g] Represents a minimum estimate using only estimated mortality for residential structures in the southern California study region.
[h] Source: Loss et al. [34].

Table 3
Avian mortality estimates at wind energy facilities within the Southern California study Region[a].

Project name	Location	Electric generation capacity (MW)	Estimated mortality rate (per MW per year)	Source of mortality estimate
Alite Wind Energy Facility	Kern County, CA	24	0.55	Chatfield et al. [50]
Dillon Wind Energy Facility	Riverside, CA	45	4.71	Chatfield et al. [51]
Tehachapi Wind Resource Area (West Ridge)	Kern County, CA	11.88	38.62	Smallwood [23]
Tehachapi Wind Resource Area (Middle Ridge)	Kern County, CA	19.56	5.67	Smallwood [23]
Tehachapi Wind Resource Area (East Slope)	Kern County, CA	30.24	2.72	Smallwood [23]
Capacity-weighted average mortality rate within the study region			**6.71**	
Estimated average mortality rate for wind energy projects in the United States [23]			**11.10**[b]	

[a] Mortality estimates are based on studies that calculated avian mortality for all birds (e.g., passerines and raptors).
[b] National estimate calculated by Smallwood [23] based on estimated total mortality of 573,093 birds at installed wind energy capacity of 51,630 MW.

region results in 452,790–16,132,740 bird deaths/year due to road mortality in the study region (Table 2).

Based on data provided by the U.S. Census Bureau American Housing Survey [43] and information provided by each of the county assessor's offices, there are approximately 6,000,000 residential structures in the southern California study region. Applying the residential 95% confidence interval (CI) of the avian mortality estimate calculated by Loss et al. [34] results in an estimated 95% CI of 7,800,000 to 18,200,000 bird fatalities per year in the study region resulting from collisions with residential structures. The lower 95% CI mortality estimate of 10,500,000 birds represents a lower-bound estimate intended only for comparison purposes in this study (Table 2). Additional avian fatalities associated with collision with low-rise and high-rise buildings that were not evaluated in this study would contribute to total avian mortality associated with building collisions in the study area.

4. Discussion

To our knowledge, this is the first systematic assessment and contextualization of avian mortality at USSE facilities in the United States. Like all industrial developments, USSE developments have the potential to impact birds and bird communities in a number of ways, including direct fatality as a result of collision with USSE infrastructure or solar flux-related injuries. The studies reviewed in this article revealed that avian fatalities occur at USSE facilities employing both CSP and PV technologies. Systematic data collection and science-based methodologies to estimate adjusted mortalities to account for bias factors (e.g., predation, searcher efficiency, etc.) are important to understand avian impacts of USSE developments in the context of other human activities. The studies at the three USSE facilities from which systematically-derived avian mortality estimates could be calculated were all located in a region of southern California currently experiencing an accelerated rate of USSE development. According to SEIA [7], this region accounts for nearly 80% of all USSE developments in the state of California and nearly 50% of all USSE developments in the United States (Fig. 3).

Our evaluation of existing avian mortality information at USSE facilities provided a multi-scalar contextualization of USSE-related avian mortality in relation to other human activities at a regional and national scale. At both spatial scales, we found that avian mortalities at USSE facilities were considerably lower than most other human activities (Table 2). Within the southern California study region, avian mortalities at USSE facilities were within the range of mortalities estimated for utility-scale wind energy facilities. Estimated across the United States, however, avian mortality was greater at wind energy facilities, presumably due to the greater amount of wind energy development in other parts of the country. Total electric capacity of installed wind energy facilities in the United States was nearly 69 GW by the end of 2014 (>48,000 turbines; [46]), as opposed to total electric capacity of installed USSE facilities of approximately 14 GW by the end of 2015 [7].

Although USSE-related avian mortality was estimated to be orders of magnitude less than estimated mortality from other human activities across the United States (except wind energy development; Table 2), the number of avian fatalities at solar facilities may increase in future years as more solar facilities are constructed. The amount of planned future USSE development in the United States is nearly 4 times the current installed electric capacity [7]. Based on the current USSE avian mortality rates examined in this study, full build-out of the nearly 48 GW of potential future USSE developments may account for as many as 480,000 bird deaths annually in the United States. However, avian activity and abundance varies regionally [26,27,47] and may result in regional variation in avian mortality risk to human activities [25,27]. Because of this variation, additional systematic monitoring of avian fatality from various geographic regions where USSE projects are being developed would be needed to better understand overall avian mortality at USSE facilities across the United States.

Our preliminary assessment identified several opportunities to improve consistency in avian monitoring and data collection efforts at existing USSE facilities. For example, not all USSE facilities in the United States operate with an existing avian monitoring and reporting protocol, nor is there consistency in the survey design and reporting among the facilities that do implement such protocols. Only three USSE facilities were reported to have systematic avian fatality information that could be used to estimate project-specific avian mortality, and all of these facilities were located in southern California. Even among these facilities, there were differences in survey design and analytical approaches. For example, methods to estimate mortality based on carcasses with observable USSE-related cause of death separately from all other carcasses with unknown cause of death were developed at two of the three USSE facilities [44,45]. Moving forward, several data needs and recommendations can be made to improve understanding of avian fatality issues at USSE facilities:

1 There is a basic need to better understand the causal factors that contribute to fatalities, such as siting considerations, the potential for avian attraction to USSE facilities (e.g., the "lake effect" hypothesis), and project design (e.g., whether evaporative cooling ponds are used).
2 There is a need for more standardized, consistent, and science-based avian monitoring protocols to improve comparability of

the data being collected. Standardized monitoring methodologies will improve the scientific certainty of conclusions about avian mortality.

3 As efforts get under way to improve the quality of avian mortality data collected from USSE facilities, researchers should focus on (a) uncertainties related to avian risks; (b) population-level impacts to migratory birds; (c) development of more effective inventory and monitoring techniques; and (d) developing appropriate and cost-effective mitigation measures and best management practices to reduce mortality risk.

While our study provides a preliminary assessment of avian mortality at USSE facilities, it could serve as a reference for future study as more avian monitoring is conducted at USSE facilities. There still remains uncertainty in the population-level impacts of USSE avian mortality. Despite this uncertainty, available information suggests that USSE-related avian mortality is considerably lower than mortality from other human activities. However, USSE facilities may still contribute to the cumulative effects of all avian mortality risk factors (including all other energy developments, vehicle and building collisions, etc.). Additional study is needed to understand the combined influence of all avian mortality risk factors, including USSE-related mortality, on avian populations.

Over time, it is possible for mortality rates to change, or even decrease, as the USSE industry works to address avian–solar issues through more environmentally-conscious siting decisions and the implementation of more effective minimization and mitigation measures. In fact, cost effective mitigation measures have already been identified to reduce mortality risk. For example, Walston et al. [48] reported that measures to alter the standby positioning of heliostats at USSE facilities employing power tower technologies could significantly reduce the amount of heat flux around the tower receiver and thus reduce flux-related mortality risk at CSP facilities. Additional studies to identify optimal project siting locations that avoid major avian migratory routes, stopover sites, and important habitats will also work to reduce regional mortality risk. These activities hold promise for the future of solar energy industry to become a low cost and low conflict source of electricity.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2016.02.041.

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