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Review of Avian Mortality Studies at Concentrating Solar Power Plants

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Abstract. This paper reviews past and current avian mortality studies at concentrating solar power (CSP) plants and facilities including Solar One in California, the Solar Energy Development Center in Israel, Ivanpah Solar Electric Generating System in California, Crescent Dunes in Nevada, and Gemasolar in Spain. Findings indicate that the leading causes of bird deaths at CSP plants are from collisions (primarily with reflective surfaces; i.e., heliostats) and singeing caused by concentrated solar flux. Safe irradiance levels for birds have been reported to range between 4 and 50 kW/m^2. Above these levels, singeing and irreversible damage to the feathers can occur. Despite observations of large numbers of "streamers" in concentrated flux regions and reports that suggest these streamers indicate complete vaporization of birds, analyses in this paper show that complete vaporization of birds is highly improbable, and the observed streamers are likely due to insects flying into the concentrated flux. The levelized avian mortality rate during the first year of operation at Ivanpah was estimated to be 0.7 – 3.5 fatalities per GWh, which is less than the levelized avian mortality reported for fossil fuel plants but greater than that for nuclear and wind power plants. Mitigation measures include acoustic, visual, tactile, and chemosensory deterrents to keep birds away from the plant, and heliostat aiming strategies that reduce the solar flux during standby.

INTRODUCTION

Recent reports of birds being burned and killed by solar flux at concentrating solar power (CSP) plants have drawn a significant amount of attention and negative publicity. [1, 2] The Associated Press (AP) released a statement suggesting that birds were being killed by concentrated sunlight at a rate of one bird every two minutes (28,000 per year), but these reports were based on anecdotal observations. These numbers appear to be inflated and misinformed based on previously published scientific studies. This paper presents a summary of those avian mortality studies at CSP plants, along with additional analyses and suggested mitigation measures. As stated by Walston et al.,[3] collision-related bird fatalities at solar energy facilities can also occur, but this paper focuses on avian mortality and risks caused by concentrated solar flux produced by concentrating solar power plants. The CSP plants and facilities that are reviewed include Solar One in California, the Solar Energy Development Center in Israel, Ivanpah Solar Electric Generating System (ISEGS) in California, Crescent Dunes in Nevada, and Gemasolar in Spain.

OVERVIEW OF AVIAN MORTALITY STUDIES AT CSP PLANTS

Solar One (Daggett, California)

Solar One was a 10 MW_e direct-steam pilot demonstration project. During 40 weeks of study from 1982 to 1983, McCrary et al. [4] estimated a mortality rate of 1.9 – 2.2 birds per week. The entire facility was searched for any evidence of bird mortality, and bird carcasses were counted. McCrary et al. [4] stated that the bird carcasses were easily found since vegetation was sparse at Solar One. Missing carcasses due to scavengers were also considered. Of the 70 documented bird deaths, 57 (81%) died from collisions with Solar One structures (mainly heliostats), and

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13 (19%) died from burns (singed flight and contour feathers) while flying through high-flux standby points (**FIGURE 1**). The impact of this mortality on the local bird population was considered minimal.

The study recommended that the occurrence and intensity of standby points be kept to a minimum to reduce avian impacts. In a related report, McCrary et al. [5] stated that nearly all cases of observed incinerations at Solar One, which appeared as "small flashes of light within the standby points, accompanied by a brief trail of white vapor," involved aerial insects rather than birds. The rate of insect incinerations in standby points was observed to be as high as 400 – 500 insects per hour. These insect incinerations are the likely cause of the observed "streamers" that led to the inflated AP report of 28,000 bird deaths (one observed streamer every two minutes).

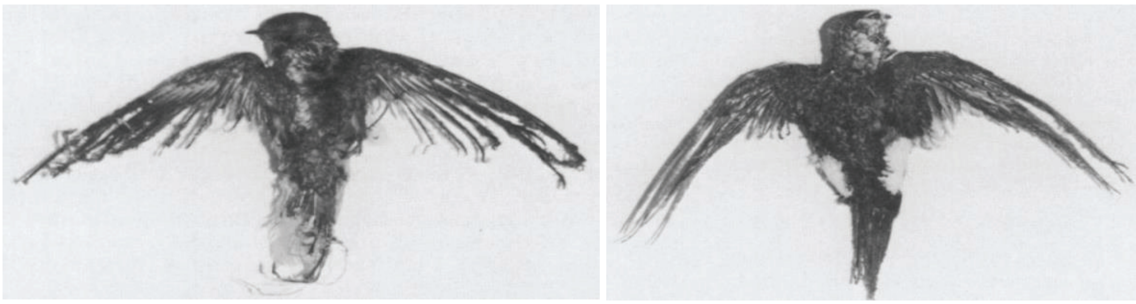

FIGURE 1. Barn Swallow (left) and White-Throated Swift (right) found burned at Solar One [4].

Solar Energy Development Center (SEDC) (Negev Desert, Southern Israel)

The SEDC is a solar demonstration facility with a 6 MW_{th} heliostat field and power tower. They report that no bird singeing was reported in four years of operation while following U.S. Fish & Wildlife Service protocols of four surveys per week over 20 m transects [6]. As part of the assessments for the proposed Hidden Hills and Rio Mesa power tower plants, Santolo [7] performed tests at SEDC using bird carcasses instrumented with thermocouples under the skin beneath the feathers. The bird carcasses were exposed to different solar flux levels at the SEDC (**FIGURE 2**), and internal temperatures were taken before and after each test. Following exposure, the carcasses were examined for external effects. If feather effects were observed, the carcasses were examined further for tissue effects through post-exposure dissection. A reference group of birds without feather effects was also examined for tissue effects.

FIGURE 2. Tests conducted by Santolo[7] using bird carcasses exposed to different solar flux levels.

Santolo concluded "no observable effects on feathers or tissue were found in test birds where solar flux was below 50 kW/m^2 with exposure times of up to 30 seconds." Santolo estimated that exposures up to 30 seconds corresponded to a distance covered in flight of up to 420 m at average flight speeds. At solar fluxes above 50 kW/m^2 with exposure times of 20 to 30 seconds, feather effects were observed in 19 of 22 birds, and muscle tissue effects were observed in 8 of the 19 birds with feather effects.

In contrast, Tyler et al. [8], in testimony for the California Energy Commission Staff, found that "a threshold of safe exposure does not exist above a solar flux density of 4 kW/m^2 for a one-minute exposure" due to a compromise in the keratin molecular structure of feathers at 160 °C. According to their thermodynamic analysis (assuming steady-state heat transfer with irradiation, convection, and thermal radiation), exposure to solar flux greater than 4 kW/m^2 can result in temperatures above 160 °C with 60 seconds of exposure. Exposures below 4 kW/m^2 can be considered a "no observed adverse effect level" (NOAEL). A shortcoming in the heat transfer analysis is that Tyler et al.[8] assumed laminar flow over a flat plate to determine the convective heat transfer coefficient representing air flow over the bird's wing at a prescribed flight velocity. However, additional turbulent convective cooling can be expected over a non-smooth wing, especially when the wing is flapping. Additional convective cooling would reduce the surface temperature of the wing and yield greater allowable solar fluxes before a surface temperature of 160°C is reached.

Ivanpah Solar Electric Generating System (ISEGS) (Ivanpah, California)

ISEGS is a 390 MW_e plant developed by BrightSource Energy consisting of three direct-steam power tower units. Kagan et al. [9] performed a survey of bird mortality at ISEGS (in addition to Desert Sunlight, a photovoltaic facility, and Genesis, a parabolic trough system; solar-flux related avian fatalities were found only at ISEGS). They found that of the 141 bird remains found at ISEGS, 47 (33%) were caused by solar flux, which caused singed feathers, loss of flight ability, and subsequent death. The remaining deaths were caused by trauma from impact or predation. Kagan et al. [9] did not find any evidence of significant tissue burns or eye damage from solar flux.

H.T. Harvey and Associates performed a detailed avian mortality survey at ISEGS and provided a summary of their findings for the first four seasons from October 29, 2013, to October 20, 2014.[10] The spatial extent of the surveys included 1) the power tower consisting of the power block and inner heliostats surrounding each power tower on approximately 154 acres, which was surveyed with 100% coverage; 2) the remaining heliostat area on approximately 720 acres, which was surveyed with 24.1% coverage in randomly selected arc-shaped plots; and 3) other areas consisting of fencelines and offsite transects. All bird and bat fatalities and injuries were referred to as "detections." During the first four seasons, 703 avian detections (including 25 injured birds that died) were found. **TABLE 1** summarizes the avian detections from singeing, collision, and other causes during the first four seasons of monitoring.

TABLE 1. Number of avian detections at ISEGS during the first year of monitoring.[10]

	Number of Detections				
Cause	**Winter**	**Spring**	**Summer**	**Fall**	**Total**
Singed	27	100	42	147	316
Collision	14	15	10	45	84
Other*	5	5	2	3	15
Unknown	51	82	61	94	288
Total	**97**	**202**	**115**	**289**	**703**

* Includes detections in ACC buildings without evidence of singeing or collision effects.

Due to uncertainty in search efficiency and carcass removal, which were evaluated as part of the study, H.T. Harvey and Associates estimated that the total avian mortality for the first year was 1492 (42.6%) of birds of known causes and 2012 (57.4%) of birds from unknown causes. Of the bird deaths due to known causes, 47.4% were singed, and 51.9% died of collision effects, and 0.7% died from other causes (e.g. entrapment in air cooled condenser (ACC) buildings).

Since the first year of operation, ISEGS has implemented best management practices and deterrents to reduce avian mortality. These include heliostat repositioning software upgrades to minimize the number of heliostats in standby mode to reduce the solar flux (**FIGURE 3**). Software upgrades have also reduced the amount of time the heliostats are in the maintenance (or vertical) position, which lowers the risk of collision. LED lighting, which is not attractive to insects, has also been installed. Anti-perching devices, chemosensory deterrent systems, and avian sonic deterrent systems have also been deployed. These practices and deterrents are expected to reduce avian mortality at the plant.

FIGURE 3. Illuminated standby aim points near the receiver at ISEGS before changes were made to spread the standby aim points to reduce the concentrated flux.

Crescent Dunes Solar Energy Project (Tonapah, Nevada)

Crescent Dunes is a 110 MW_e power tower being developed by SolarReserve with 10 hours of molten-salt storage. In January of 2015, during preliminary tests, 3,000 heliostats were aimed at standby points above the receiver, resulting in 115 bird deaths as the birds flew through the concentrated flux. [11] SolarReserve decided to spread the standby aim points over several hundred meters to reduce the peak flux to less than 4 kW/m^2 (4 suns). SolarReserve reported that they have had zero bird fatalities in the months following that change, despite being in standby position and having flux on the receiver for most days since then. [11]

Gemasolar Thermosolar Plant (Andalusia, Spain)

Gemasolar is a 20 MW_e power tower developed by Torresol Energy with 15 hours of molten-salt storage in Andalusia, Spain. The area has a high avian population, but a 14-month study conducted by Dr. Pleguenzuelos (Dept. of Zoology, U. Granada) revealed no avian fatalities in the vicinity of the tower. [6]

DISCUSSION

Feasibility of Bird Vaporization

Some reports have expressed concern that bird mortality at CSP plants is being underestimated because some birds are being completely "vaporized," and these vaporized birds are not included in the mortality count.[1] Some reports state that the observed "streamers" or smoke trails observed in the high-flux regions are evidence of complete vaporization of birds. This section provides an analysis to determine the feasibility of bird vaporization.

For a bird to be completely "vaporized" beyond recognition at a CSP plant, the following scenario would need to occur: (1) the bird is exposed to sufficient solar flux to combust its wings and plumage; (2) while burning, the energy released during combustion together with the solar flux heats up the body to vaporize the liquid (water) content; and (3) the remaining carcass (e.g., skeleton) is further exposed to solar flux and is combusted or pyrolized beyond recognition. A major flaw in this scenario is that if the feathers combust, the bird will fall from the sky and will not be exposed to concentrated solar flux. Most of the energy from combustion will be released to the environment by convection and radiation. As stated by Tyler et al.,[8] heating of the feathers by concentrated solar flux (and, presumably, combustion) would be isolated from the body and internal features due to the insulating effect of the plumage. Thus, it is unlikely that the energy of combustion from the feathers would cause significant heating of the body. Nevertheless, if the entire energy of feather combustion heated the body (and no energy was lost to the environment by convection or radiation), the heat from combustion is still insufficient to vaporize the water content of the body. The heat of combustion of bird feathers, which compose up to ~10% of a bird's total mass,[12] is ~20 MJ/kg.[13, 14] For a given bird mass, the heat of feather combustion is only 80% of the total energy required to vaporize an equivalent mass of water. Thus, if the entire heat of combustion were transferred to the body to volatilize the liquid content, the rest of the carcass (e.g., skeleton) would still require considerably more energy to combust or pyrolize it into an unrecognizable form.

A more probable scenario is that if a bird spontaneously combusts in the concentrated solar flux, most of the heat of combustion will be lost to the environment by convection and radiation. Then, assuming the bird is still in the concentrated solar flux (also improbable), additional energy from the solar flux would be required to volatilize the liquid content of the body and incinerate the bones. Assuming the majority of the liquid content is composed of water, the energy required to vaporize a mass of water is determined by summing the sensible energy, $E_{sensible}$, required to raise the water temperature from 40 °C (average body temperature of a bird)[15] to the boiling point (97 °C at the elevation of Ivanpah), and the latent heat of vaporization, E_{latent}, to convert the mass of liquid water to vapor. The total vaporization energy can then be divided by the cross-sectional area of the body exposed to solar flux and the exposure time to determine the irradiance, Q (W/m^2), required to vaporize a mass of water.

$$E_{sensible} = mc_p\left(T_{boil} - T_{body}\right) \tag{1}$$

$$E_{latent} = mh_{fg} \tag{2}$$

$$Q = \frac{E_{sensible} + E_{latent}}{At} \tag{3}$$

where m is the mass of water (kg), c_p is the specific heat of water (4200 J/kg-K for T between 270 – 390 K), T_{boil} is the boiling point of water (97 °C for atmospheric pressure at Ivanpah), T_{body} is the average body temperature of a bird (40 °C)[15], E_{latent} is the latent energy (J) to volatilize liquid water (J), h_{fg} is the latent heat of vaporization (2.27e6 J/kg at 97 °C), A is the cross-sectional area (m^2) of the body of the bird, assumed to be spherical,[*] and t is the time of exposure. The cross-sectional area, A, and exposure time, t (s), are determined as follows:

$$A = \frac{\pi^{1/3}}{4}\left(\frac{6m}{\rho_w}\right)^{2/3} \tag{4}$$

$$t = \frac{v_\infty}{g}\cosh^{-1}\left(\exp\left(\frac{Hg}{v_\infty^2}\right)\right) \tag{5}$$

$$v_\infty = \text{terminal velocity} = 1.286 m^{1/6} \rho_w^{\ 1/3}\left(\frac{g}{\rho_a C_D}\right)^{1/2} \tag{6}$$

where the exposure time, t, is assumed to be equal to the free-fall time through the beam of concentrated solar flux, g is the gravitational acceleration (9.81 m/s^2), H is the free-fall distance through the beam (assumed to be equal to the receiver height of 22 m at Ivanpah), ρ_a is the density of ambient air (1.2 kg/m^3), ρ_w is the density of water (992 kg/m^3 at 40 °C), and C_D is the drag coefficient (~1 for passerine birds).[17] The free-fall time through the beam is about 2 – 3 seconds, depending on mass.

The minimum irradiance required to volatilize a mass of water assuming both a free-fall exposure time and a conservative 10-second exposure time are shown in **FIGURE 4**. Results show that the minimum irradiance required is considerably larger than a typical peak irradiance at the receiver of ~600 kW/m^2, such as at the Ivanpah Solar Electric Generating System. Thus, even if all of the feathers were burned off of a bird, there would be insufficient solar flux from a concentrating solar power plant to vaporize an equivalent mass of water.

In short, complete vaporization of bird with concentrated solar flux less than 1 MW/m^2 is highly improbable. For most common birds between 10 – 1000 g, the irradiance would need to be 4 – 20 MW/m^2 with an exposure time of 10 seconds to volatilize an equivalent mass of water. Additional energy would be required to incinerate or vaporize bones, muscle, and other body parts.

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[*] Assumed to be equal to the cross-sectional area of a sphere, which is larger than estimates from Pennycuick16. C. J. Pennycuick, *Bird flight performance : a practical calculation manual*. (Oxford University Press, Oxford, England ; New York, 1989). for body frontal area, S_b: S_b=0.00813m$^{0.666}$.

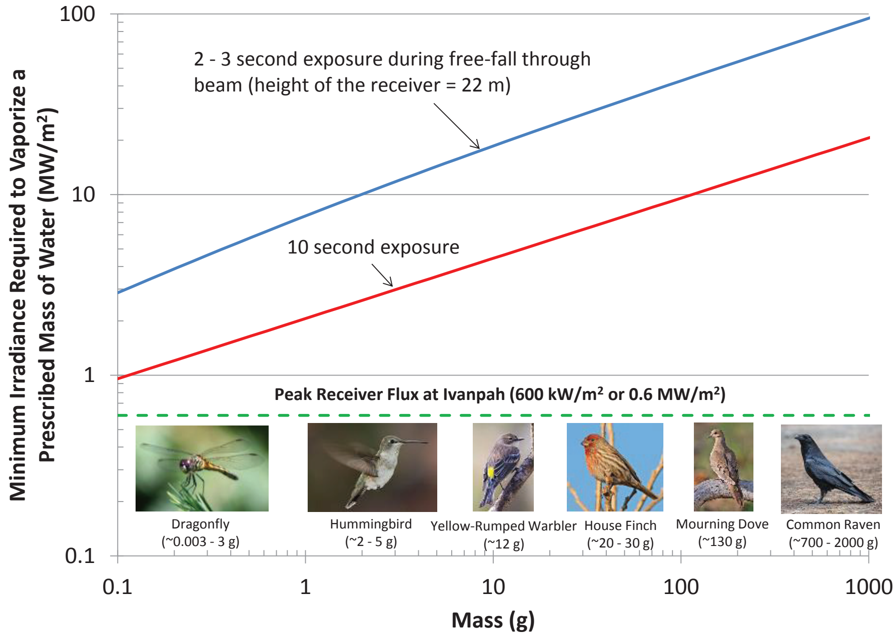

FIGURE 4. Minimum irradiance required to vaporize a prescribed mass of water with corresponding bird mass (mass of birds provided in Appendix 8 of Coles (2007).[18]

Levelized Avian Mortality for Energy

Even though there is limited data on avian mortality at concentrating power plants, it is interesting to evaluate the levelized avian mortality for different energy producing sources. Sovacool[19] performed a study investigating the cause of bird deaths per year in the United Stated in 2009 from various sources. The listed causes of annual bird deaths included feral cats (110 million), building windows (97 million), pesticide poisoning (72 million), fossil-fuel energy sources (14.1 million), communication towers (4 million), nuclear power (332 thousand), and wind energy (20 thousand). Focusing on energy producing sources, the levelized avian mortality was found to be 5.18 fatalities per GWh for fossil fuels, 0.416 fatalities/GWh for nuclear power, and 0.269 fatalities per GWh for wind energy. The estimates for fossil fuels includes operating experience from two coal facilities and indirect damages from coal mining, acid rain pollution, mercury pollution, and anticipated impacts of climate change. Estimates for nuclear power were based on four nuclear power plants and two uranium mines/mills. Estimates for wind energy were based on operating experience from 339 wind turbines at six wind farms. It is unclear if the studies reported in Sovacool[19] included uncertainty in search efficiency and carcass removal.

With regard to the levelized avian mortality for CSP, the data available from the first year of operation at Ivanpah can be used. According to H. T. Harvey and Associates [10], the avian detections for the first year was 703, with an estimated avian mortality of 3500 based on uncertainty in search efficiency and carcass removal. Given that the annual energy production at ISEGS is on the order of 1000 GWh,[20] the levelized avian mortality for the first year of operation before mitigation measures and deterrents were added was 0.7 – 3.5 fatalities per GWh. The fatalities are expected to decrease after the deterrents have been implemented.

At Solar One, McCrary et al.[4] estimated that ~2 birds per week were killed (primarily from collisions) or ~100 birds per year at Solar One. Radosevich[21] reports that the annual energy production from Solar One during the second year of operation was 10.5 GWh. Thus, the levelized avian mortality was ~10 fatalities per GWh at Solar One. No fatalities were identified at Gemasolar, and no bird singeing was identified at SEDC.

Mitigation Measures

In order to mitigate avian mortality at CSP plants, several measures have been recommended to keep birds away from the site.[3] These include acoustic, visual, tactile, and chemosensory deterrents. Acoustic deterrents produce painful or predatory sounds that birds tend to avoid. Visual deterrents can include intense lights and decoys, and tactile deterrents include bird spikes or other anti-perching devices. Chemosensory deterrents include aversive scents or chemicals that are irritating to birds, such as methyl anthranilate, which is used in grape-flavored powder drinks such as Kool Aid. Ivanpah has implemented several of these deterrents, but results are still pending.

Additionally, mitigation measures can be implemented to reduce the risk of burning birds or damaging feathers caused by high solar fluxes in the heliostat standby aim points. Both Ivanpah and Crescent Dunes have implemented strategies to spread out the aim points of standby heliostats to reduce the flux and "hot spots" that birds may fly through. At Crescent Dunes, after over 100 birds were burned during preliminary testing, the heliostat standby aiming positions were spread out to reduce the flux to less than 4 kW/m^2, and they have not had any reported bird deaths since then.[11] Ideally, the aim points would not only reduce the solar flux, but also minimize the slew time to the receiver to maintain operational performance.

CONCLUSIONS

Recent reports of extreme numbers of birds being killed by concentrated sunlight at CSP plants appear to be misinformed and inflated. A review of past and current avian mortality studies at several CSP sites (Solar One, SEDC, Ivanpah, Crescent Dunes, and Gemasolar) was performed and key observations are summarized as follows:

- Collisions and concentrated solar flux are the leading causes of avian mortality at CSP plants[4, 9, 10]
- The large number of "streamers," or smoke plumes, observed and attributed to vaporization of birds is likely caused by insects flying into the concentrated flux[4]
- Complete vaporization of birds flying into concentrated solar flux is highly improbable
  - Analyses were performed in this work that showed neither the heat of combustion of feathers nor the peak irradiance at typical CSP plants would produce enough energy to completely vaporize a bird
  - If a bird died from concentrated solar flux, a recognizable carcass would still remain that could be identified as part of the avian mortality surveys
- Safe irradiance levels for birds have been reported to range from 4 kW/m^2 to 50 kW/m^2
  - Above these levels, damage to the feathers and keratin structure can occur at expected exposure durations
- Mitigation measures
  - To keep birds away from the CSP plant, deterrents include acoustic, visual, tactile, and chemical deterrents
  - To reduce concentrated flux when heliostats are in standby position, measures include spreading the aim points and choosing appropriate standby aiming strategies to minimize both solar flux and heliostat slew time to maintain operational performance
  - ISEGS has deployed a number of these technologies, and results are pending[10]
- In the ISEGS[10] and Solar One[4] CSP studies, the impact of avian mortality on the local and migratory bird populations was determined to be low
- The levelized avian mortality rate for the first year of operation at ISEGS (before mitigation measures and deterrents were implemented) was found to be 0.7 – 3.5 fatalities per GWh, which is less than the levelized avian mortality reported for fossil fuel plants but greater than that for nuclear and wind power plants

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