20

Solar Energy Development and the Biosphere

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20.1 Introduction

As of April 2017, atmospheric concentration of CO_2 has reached an unprecedented mark of 410 parts per million. Despite support for renewable energy development as a means to combat greenhouse gas emissions to mitigate climate change impacts and reduce reliance on finite energy resources, rapid renewable energy deployment is complicated by environmental trade-offs. Potential environmental impacts of renewable energy development include, but are not limited to, habitat fragmentation, degradation or disruption of valuable ecosystem services, biodiversity loss, and increasing land scarcity [1,2]. These ecological impacts may be overlooked as minor when compared to those of global climate change, which threatens biodiversity on a global scale; however, cumulative disturbances associated with renewable energy development are complex, difficult to mitigate, and poorly understood [3].

The development of solar energy is unique in that adverse environmental impacts and associated costs can be avoided with appropriate siting and decision-making. Increased awareness of these potential tradeoffs is the first step towards achieving greater sustainability in solar energy design and enterprise. Here, we discuss: (1) potential impacts from construction, operation, and decommissioning of solar energy facilities, focusing particularly on ground-mounted, utility-scale solar energy (USSE, > 1 MW_{DC}) USSE installations; (2) potential environmental effects over the lifetime of solar energy installations; and (3) potential ecological responses of wildlife and other biosphere attributes with options for mitigating or reducing those impacts.

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20.2 Solar Energy Effectors and Potential Effects on the Environment

Effectors may be temporally categorized over the lifetime of a photovoltaic (PV) or concentrating solar power (CSP) installation, from construction through decommissioning (Fig. 20.1) and may have one or more potential effects on the environment with multiple potential ecological responses. Additionally, the technology, size, and location of solar energy infrastructure may impact biota and the environment in different ways. For example, integrated solar energy is that which has zero land-use and land-cover change impacts beyond those associated with raw materials acquisition and manufacturing. Thus, it has minimal to zero adverse effects on the biosphere (beyond life-cycle emissions), resources (e.g., cultural), and legal entitlements (e.g., religious rights of indigenous communities)

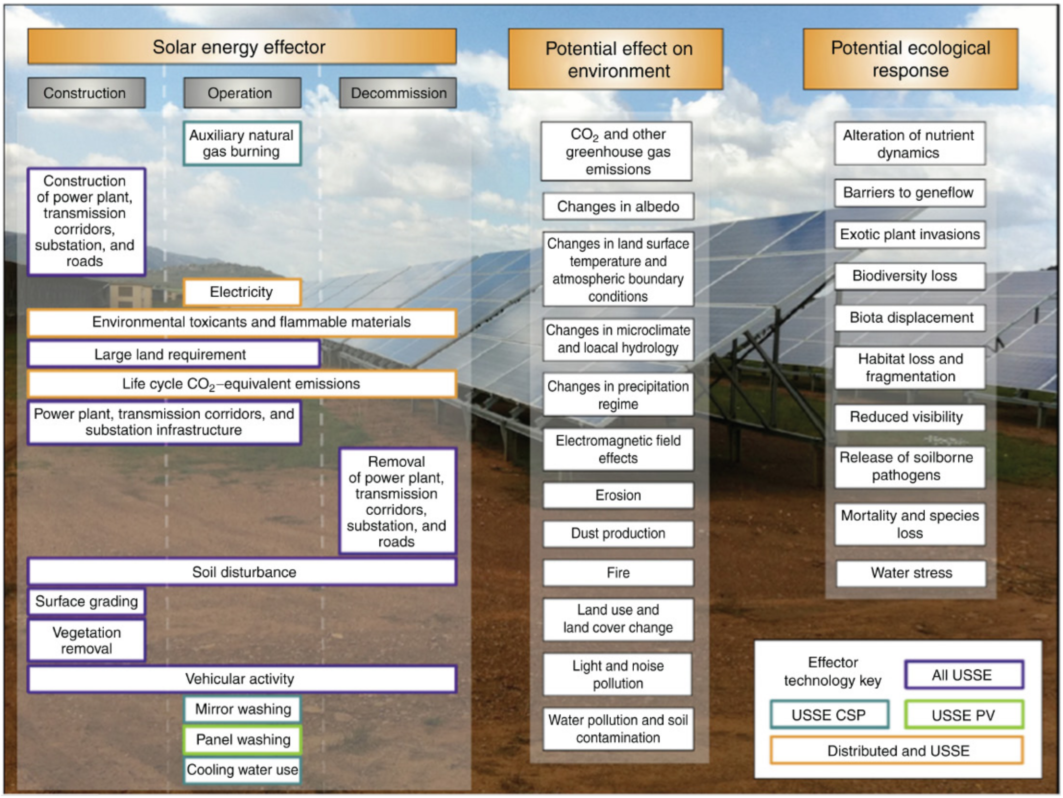

FIGURE 20.1 Solar energy effectors for utility-scale solar energy technologies (ALL USSE), including concentrating solar power (USSE CSP) and photovoltaics (USSE PV), and for both utility-scale and distributed schemes (Distributed and USSE). *Photo credit: Rebecca R. Hernandez. From Hernandez RR, Easter SB, Murphy-Mariscal ML, Maestre FT, Tavassoli M, Allen EB, et al. Environmental impacts of utility-scale solar energy. Renew Sust Energy Rev 2014;29:766–79.*

FIGURE 20.2 Aerial view of 4.1 MW of integrated solar energy at the UC Davis West Village. West Village is the largest net zero energy community in the United States, combining energy efficient technology with on-site energy production via rooftop and vertical photovoltaic installations (Davis, California). *Photo courtesy of UC Davis.*

[3a]. Integrated solar energy is cohesively constructed into elements of the built environment in urban and suburban areas (e.g., commercial and residential building rooftops, parking garages, and carports) relatively close to consumers (Fig. 20.2). Although geographically diffuse, integrated solar energy offers high levels of solar energy potential [4]; it has been estimated that 20%–27% of all residential rooftop space and 60%–65% of commercial rooftops in the United States are conducive to photovoltaic and solar thermal systems [5]. In contrast, displacive solar energy is that which incurs additional land-use or land-cover change and therefore reduces biophysical capacity or facilitates the loss of other resources of value (e.g., cultural) across the Earth's surface. These installations are typically ground-mounted and large in capacity (e.g., utility-scale solar energy [USSE]) They are often geographically far from demand loads and preexisting transmission, and have large land area requirements (i.e., installed capacity increases concomitantly with land area).

20.2.1 Land Requirements

To meet projected 2040 energy consumption demands, it is estimated that approximately 800 000 km^2 of additional land (with spacing), an area two times that of the state of

California, would be affected by carbon-intensive and renewable energy development [6]. Ground-mounted solar energy requires relatively large expanses of land to support power plant infrastructure, mirrors and towers (e.g., CSP), and panels (e.g., PV), and therefore, such installations are often sited far from urban population centers where most electricity is consumed. This may necessitate additional transmission infrastructure (i.e., power line corridors, roads, and substations) to transport electricity, expanding impacts beyond the immediate footprint of facilities themselves. Hernandez and colleagues [7] found that PV and CSP ground-mounted USSE installations in California have a land-use efficiency of 35.1 and 33.9 Wm^{-2}, respectively, based on the nominal (i.e., nameplate) capacity. Land use efficiency can vary significantly from these averages. For example, Zichella and Hladik [8] reported that a currently operational, 354 MW USSE facility in the California desert, United States, occupies over 645 ha, equal to 54.9 Wm^{-2} and is a more efficient installation based on nameplate capacity. In California, it was also found that installations on public land required significantly more land per installed MW of capacity than those sited on private land (10 more Wm^{-2}), demonstrating flexibility in USSE design perhaps driven by differences in the price of land [7]. This agrees with land estimates comparing PV with coal life-cycles by Fthenakis and Kim who showed that coal with surface mining in the U.S. uses more land than PV installed in the Southwest [63]. Also, they found that integrated PV and CSP technologies incorporated into the built environment had the lowest land-use intensity across all sources of electricity, underscoring the potential to avoid negative impacts on the biosphere through appropriate siting decisions.

20.2.2 Land-Use and Land-Cover Change

In light of the land area requirements of displacive solar energy installations, land-use and land-cover change is a significant conservation concern. Relative to other energy production systems, renewable sources of energy may occupy a relatively small percentage of new land area being affected by energy development in the United States under the assumption that PV and CSP would comprise only 0.5% and 0.04% of United States energy production from 2012 to 2040 [6]. However, if larger percentages of displacive installations are realized, it would scale accordingly. Additionally, displacive facilities may be disproportionately sited in areas where high biological endemism (species with very limited distributions that are often highly adapted to their environments), fragile habitats, and high solar resources co-occur, such as the Mojave Desert in the southwestern United States. Indeed, deserts and xeric shrubland habitat types in the United States are expected to experience the greatest land-cover change impacts due to PV and CSP siting by 2030 [9]. Hernandez and colleagues [7] found that the plurality of USSE developments in California are sited in shrublands and scrublands, the land cover type with the highest inherent biodiversity of those included in the study, necessitating 375 km^2 of additional land. Additional conflicts may arise when solar facilities are sited in areas where land has agricultural value; for example, 118 km^2 of land categorized as cultivated cropland has been converted to or is earmarked for USSE development in California [7]. Lastly, USSE may also be disproportionately sited in areas with biophysical capacity to support ecosystem services, including carbon sequestration and storage. De Marco and colleagues [10] found that 42 of the 82 permitting requests for new USSE sites in Leece, Italy (238.4 km^2) were in ecologically unsuitable areas, comprising 18 563 ha of land-cover change, including in places with century-old olive groves notable for their cultural value and that provide the largest contribution to carbon sequestration, relative to other land-cover types evaluated (>1.5 million tons of CO_2).

20.2.3 Surface Grading and Vegetation Removal

During the construction phase of a solar energy power plant, preparation of the facility site may include grading and scraping, which removes all aboveground biomass [9]. Grading reduces wildfire risks on-site and prevents the panels from being shaded by vegetation [10]; however, from an ecological perspective, these activities constitute a loss of habitat within the footprint of the facility and degradation of surrounding land, which may result in mortality of wildlife or species displacement. Ecosystems with limited resources (e.g., precipitation, nutrients) may be slow to recover from disturbance, either from the construction of the USSE facility itself or its decommissioning, making restoration an inviable and/or costly option. For example, natural recovery times for desert plant communities to return to predisturbance species composition is 215 years based on a meta-analysis of 31 individual studies [10a]. If topsoil has been removed from the site, this recovery time may be longer and thus restoration potential may be diminished depending on the size and intensity of the disturbance [11,12]. Additionally, more carbon is sequestered in soils than in the atmosphere and terrestrial vegetation combined [13]. Therefore, soil disturbance resulting from site development may release a significant amount of stored organic (and possibly inorganic) carbon, potentially offsetting benefits of establishing the renewable energy source (in terms of reducing greenhouse gas emissions). Significant soil processes are negatively impacted by disturbance, including nutrient cycling and water holding capacity [14]; soil biota that contribute to these processes, such as biological soil crusts, may take 20–1000+ years to recover in aridland environments [12], necessitating costly active restoration techniques that require salvaged material to expedite recovery [14a]. Disturbed soils are more prone to wind erosion, thus potentially impacting human health (e.g., valley fever), reducing fertility of biological soil crusts and vegetation through reduced photosynthesis, and contributing to sedimentation in surface water [15].

20.2.4 Hydrologic Changes and Water Degradation

Construction activities may impact surface-water flow pathways and water quality, especially when projects are sited on bajadas, individual alluvial fans, floodplains, or near washes. Flood control structures may be constructed on-site to intentionally divert water around facility footprints in an effort to reduce soil erosion near facility infrastructure. Modifications to surface-water flow may alter geomorphological processes and downstream aquatic ecosystems and habitats by altering transport of organic matter, nutrients, minerals, and sediments [16].

Large concentrating solar power facilities require large quantities of water for operation, which may stress water resources, especially in arid environments where water scarcity contrasts abundant sunlight levels optimal for solar energy production. Wet-cooled CSP facilities, which need steam to generate electricity and water for cooling, may use between 5551 and 17 886 $m^3\ a^{-1}\ MW^{-1}$ (4.5–14.5 ac-ft of water per year per MW of electricity produced), where "a" refers to annum [15]; this amount equals or exceeds nuclear and coal power plants [17]. Alternatively, dry-cooled CSP technology requires between 247 and 1234 $m^3\ a^{-1}\ MW^{-1}$ (0.2–1.0 ac-ft $year^{-1}\ MW^{-1}$) of electricity produced [15]. Additionally, CSP installations require water for mirror washing, potentially equating to 617 $m^3\ a^{-1}\ MW^{-1}$ (0.5 ac-ft $year^{-1}\ MW^{-1}$) or more [15]. It is noted that PV in the southwestern United States uses marginal amounts of water for panel washing, and therefore, has a clear advantage to any thermoelectric power generation in arid areas.

20.2.5 Changes in Land-Surface Temperature, Albedo, and Microclimate

Photovoltaic panels have low reflectivity, owing to a large proportion of solar radiation that reaches them being converted to electricity and heat [18]. There is growing concern that PV installations may cause a “heat island” effect similar to those that occur in urban areas, especially in desert environments, whereby mean air temperatures surrounding the installation increase due to a decrease in albedo. The effective albedo of a PV panel (current upper maximum >35.2%) is the sum of its reflectivity (e.g., 0.06–0.1) and solar conversion efficiency (e.g., 0.12–0.252 [e.g., SunPower panels for upper limit] [19]). Ultimately, the variation in the albedo of natural and built environments where solar energy installations are sited and the variation in the effective albedo of PV can lead to different results; thus additional research in diverse environments is needed to determine generalized patterns of altered land-surface temperature by solar energy. A modeling study by Taha [19] found that a large scale PV installation in Los Angeles—characterized by common roofing materials, concrete, and asphalt—would reduce the urban heat island effect and cool cities up to 0.2°C. Another modeling study in the desert found that local night-time temperatures were 3–4°C higher in solar facilities than nearby control areas [20]. Furthermore, panels and mirrors may create an insulation effect due to physical shading and airflow alterations. This was demonstrated at a CSP plant in China, where soil temperatures were reported as being 0.5–4°C lower in spring and summer and higher by the same range in winter relative to control sites [21]. However, Nemet [22] found that the effect of albedo change due to widespread deployment of PV globally would be negligible in comparison to the benefits of reducing greenhouse gas emissions from the same deployment intensity.

20.3 Ecological Impacts and Responses

Ecological responses to disturbance and development are well studied, although few studies have quantified effects of displacive installations on the biota, habitats, and ecosystems occurring within or near their footprints. Displacive and large (e.g., USSE) installations may negatively or positively affect a diversity of biota (Table 20.1). Effects likely depend on the

Table 20.1 Known or Expected Impacts of USSE on a Subset of Taxa

		Habitat Fragmentation	Panels and Mirrors	Fences	Air-Cooled Condenser (CSP Only)	High Energy Flux Field (CSP Only)
Birds	Passerines and insectivorous birds	–	–	o	–	–
	Raptors	o	–	o	o	–
	Ravens	+	o	+	o	+
	Waterbirds	o	–	o	o	o
Mammals	Bats	–	o	–	–	o
	Bighorn sheep	–	o	–	o	o
	Coyotes	–	o	–	o	o
	Kit foxes	–	+	–	o	o
Reptiles	Desert tortoise	–	o	–	o	o
Insects	Flying insects	–	–	o	–	–
Plants	Native annuals	–	o	–	o	o
	Native perennials	–	–	–	o	o
	Invasive plants	o	o	+	o	o
Total type disturbance known effect	Negative	14	10	10	6	5
	Positive	1	2	2	0	0

Impacts are listed as positive (+), negative (–), or neutral (o) based on experience and judgment of the authors and the literature.
Source: From Moore-O'Leary R, Hernandez R, Johnston, DS, et al. Sustainability of utility-scale solar energy—critical ecological concepts. Front Ecol Environ 2017. doi:10.1002/fee.1517.

design, technology, size, siting, and land-use efficiency of each facility. At the individual species scale, disturbance may elicit behavioral responses (e.g., avoidance of noise and light), reduce resource acquisition opportunities, and alter social dynamics, each of which concurrently occur with physiological responses (e.g., increased heart rate). These responses may result in energy and nutritional expenditures, which lead to reduced vitality, reduced fecundity, and increased mortality in wildlife species [23], although the effects often are species- and habitat-specific. For example, desert tortoises (*Gopherus agassizii*) translocated to adjacent habitats outside of a solar facility footprint prior to construction activities have been shown to experience higher body temperatures and increases in energy expenditure during the first year following displacement; however, negative effects on tortoise growth and body condition were not documented [24]. Displacive installations may also lead to ecological effects spanning beyond individual taxa, affecting species–species and species–process interactions (e.g., trophic interactions) in ecosystems [25,26]. In addition to direct impacts experienced on-site, wildlife communities and habitats may be affected outside of facility footprints. For example, wildlife abundance and composition downstream of a large power plant may be modified due to altered magnitudes of stream surface flow, timing, duration, and velocity [16]. Wildlife responses may vary temporally, including temporary movement of individuals away from disturbance during construction activities and permanent displacement of individuals due to habitat loss. Such has been reported for bird densities and diversities, which are lower within USSE development footprints than surrounding areas [27–29].

However, not all wildlife responses to USSE development are negative; some species, especially generalist species that do not require specialized habitats or diets, may benefit from human development and disturbance. For example, common raven (*Corvus corax*) abundance has been positively correlated with development in the desert region of California [30], potentially due to subsidies of anthropogenic resources (e.g., food, nest and roost sites, water; [31]). While this translates to increased fecundity for the subsidized predator [31], it is often to the detriment of native prey (i.e., desert tortoise; [32]). Similarly, mammalian scavengers, such as coyotes (*Canis latrans*), may be attracted to solar energy facilities by availability of unmanaged refuse [33] and carcasses of birds that succumbed to operation-related injuries (e.g., collision with infrastructure) [29]. Furthermore, during operation of a displacive solar energy facility, wildlife and plants may acclimate to development. Wildlife species, such as invertebrates and small reptiles, may recolonize installations sited in natural or other valuable environments where vegetation is allowed to reestablish in between panels, which may, in turn, attract larger predators. At a PV facility in South Africa, Visser [29] found that raptors and terrestrial birds utilized the installation for foraging and hunting, flocking birds used the evaporation pond as a drinking site, and several species of birds nested on the mountings directly beneath the panels or on the ground.

20.3.1 Habitat Fragmentation

Perhaps the least debated ecological impact of displacive solar energy is habitat loss and concurrent habitat fragmentation resulting from its development. This impact is of paramount concern because habitat fragmentation is among the leading causes of global biodiversity decline [34]. Habitat fragmentation occurs when once contiguous tracts of natural landscape are disturbed or converted, resulting in spatially distinct patches of remnant habitat [35]. Among other impacts, long-term ecological studies have demonstrated that habitat fragmentation results in decreased species richness [36], impaired ecosystem function, increased edge effects, and isolation of resident populations or communities from adjacent patches [37]. Hernandez and colleagues [38] found that of the USSE installations planned and under construction in the state of California, over 73% of PV and 90% of CSP installations were sited less than 10 km away from the nearest protected area, thereby increasing edge effects and undermining the effectiveness of those protected areas as corridors for wildlife movement. While wide-ranging wildlife species may have the ability to circumvent USSE infrastructure during seasonal migration or movement associated with resource acquisition and mating, displacive solar energy projects may prohibit movement of less-mobile wildlife species and plant propagates, thus increasing gene flow disruption between populations [2].

20.3.2 Roads, Transmission Lines, and Fences

The roads, transmission lines, and fencing that radiate from and surround large and displacive facilities contribute to habitat fragmentation and degradation and may cause a considerable amount of negative ecological impacts. The effects of both paved and dirt roads on wildlife have been well documented [39], including direct mortality from vehicle collision, modified behavior (e.g., avoidance), and edge effects (e.g., altered microclimate, increased predation risk and invasion of exotic species). Larger, motile wildlife may easily traverse roadways; however, their risk of collision increases with traffic volume. In contrast, roadways may be insurmountable linear barriers to less-motile species, potentially leading to inbreeding and greater vulnerability to catastrophic events, such as wildfire. Additionally, roads impact species spatial distribution and habitat use, as demonstrated by the decreasing density of desert tortoises with increased proximity to roadways [40]. Invasive plant species often colonize disturbed areas and thus benefit from disturbance associated with the construction of roadways [41]. Propagules of exotic species may be carried by vehicles and construction equipment along roadways [11], aiding in their invasion and spread across the landscape [42]. In contrast, road edges may enhance the vigor of some perennial shrubs and the germination of some annual species, which benefit from water runoff from impervious surfaces and support greater densities of herbivorous arthropods than sites further away from roadways [11]. However, wildlife may be attracted to road edges by the availability of forage, thus increasing their risk of collision.

Transmission and distribution lines are essential for transporting electricity generated from any type of power generation facility. Similar to roadways, the construction of transmission corridors may degrade surrounding habitats; furthermore, maintenance of transmission corridors (e.g., vegetation removal to decrease fire risk) is a continual source of disturbance. Because of these factors, the ecological impacts of transmission infrastructure include their potential to become linear barriers to wildlife movement (e.g., species may avoid the degraded or altered habitat within the corridor), edge effects, and altered community compositions. For example, in Australia, the community composition and abundance of small mammals was shown to differ between transmission corridors and adjacent forested habitat [43,44], with introduced and grassland species being favored over native, forest species. Bird diversity may be lower in corridors than surrounding forested habitat in the United States, with generalist forest species and shrubland birds dominating transmission corridors [45]. However, mid-seral vegetation management that retains structural complexity of vegetation in the corridor (as opposed to complete and frequent vegetation removal) may promote biodiversity and maintain connectivity for forest species [44], highlighting the need for site- and habitat-specific management within transmission corridors to reach conservation goals.

In addition to indirect ecological effects, overhead transmission lines may pose direct collision and electrocution risks to birds. On the basis of known fatality rates, an estimated 10^9 (1 billion) bird strikes may occur annually in the United States alone [46]. Weak fliers (based on wing morphology and wing loading [i.e., ratio of weight to wing area]), were found to have high probabilities for powerline collision in Spain; birds of prey, ravens, and thermal soarers also were among electrocution victims [47]. Several studies have identified powerline electrocution as a conservation problem for several species of rare and endangered raptors worldwide, including California condor (*Gymnogyps californianus*; [48]), Spanish imperial eagle (*Aquila adalberti*; [49]), Bonelli's eagle (*Aquila fasciata*; [50]), and the Eurasian eagle owl (*Bubo bubo*; [51]). Guidelines for reducing electrocution risks, such as minimum conductor spacing, may help mitigate some avian mortality [52]. Lastly, steel towers and power poles provide hunting perches for opportunistic predatory birds, which may increase predation risk for slow or sedentary wildlife (e.g., ravens predating desert tortoise; [11]). These effects are not unique to USSE and no studies to date have studied ecological impacts from transmission lines specifically associated with solar energy power plants.

In addition to fragmenting habitat, fence lines surrounding USSE developments for security may act as dispersal barriers to some species of wildlife. Bats and most birds can fly over fences, with a few exceptions (e.g., roadrunners), and insects and small bodied animals (e.g., lizards, snakes, and rodents) may travel unimpeded through some fences. However, larger bodied animals (e.g., kangaroo rats—*Dipodomys* spp.) and animals with small home ranges (e.g., desert tortoises) may be excluded. This may prevent gene flow between individuals located on either side of the fence line. Promisingly, fences may be engineered to accommodate the needs of some species (e.g., kit foxes in the San Joaquin Valley of California, United States; [53]).

20.3.3 Panels and Mirrors

Large expanses of PV panels and mirrors may be perceived by flying species as flat-water bodies [54]. This phenomenon, known as "the lake effect", occurs when flying species mistake flat surfaces of mirrors and modules for water. Some species may suffer impact trauma from collision as they attempt to land whereas others (e.g., waterfowl) may strand themselves because they are unable to easily take off from a terrestrial surface. Both scenarios increase risk of mortality or injury leading to starvation or predation [55]. Non-fatal collisions of large-bodied birds with panels were documented at PV facilities in South Africa [29] and southern California [55], and impact trauma was the leading cause of avian death documented at a PV and parabolic trough facility in the Mojave Desert, United States [55]. Additionally, the presence of ponds at PV facilities may serve as an attractant to waterbirds and flocking birds [29,55]. No positive effects of panels or mirrors are documented for waterbirds or flocking birds. Polarized light from PV panels and mirrors can attract insects [56], which, in turn, may attract insectivorous raptors (e.g., kestrels—*Falco* spp.) and insect gleaning bats that might utilize PV fields and evaporation ponds for foraging [29]. Subadult bats have been observed attempting to drink off of panels [57], suggesting that they are attracted to and confused by the panels; it is not known if these wasted attempts cause detrimental energy expenditures. If vegetation is allowed to regrow between panels, terrestrial foraging birds may utilize those areas for shade and shelter. Birds may also utilize the underside of panels or the ground beneath panels as nesting sites [29]. Nesting success may depend upon the presence of predators within the facility footprint. Small carnivores (e.g., kit fox, *Vulpes macrotis*) may be able to establish natal dens within PV arrays [58].

PV panels and mirrors may have a negative impact on both annual and perennial native plant species, which are well adapted to their local, unshaded environments. For example, desert plants tolerate high temperatures and solar radiation levels and low precipitation; however, plants within solar arrays experienced altered microclimates, including 11°C cooler temperatures from panel shading and increased water from water runoff at the edges of panels [59]. These altered conditions may be beneficial to generalist, invasive annual plant species. Meanwhile, altered microhabitat conditions in solar facilities may decrease seed production, density, species richness, and community abundance of native annual species [59]. In aridlands, decreased plant cover and biomass is associated with decreases in diversity and abundance of small reptiles and other wildlife species [11].

20.3.4 Air-Cooled Condensers and High-Energy Flux

Impacts from air-cooled condensers and high-energy flux are unique to CSP power plants. Bats may collide with the fans of air-cooled condensers while foraging or in their search to locate roosting sites, although acoustic deterrents may mitigate this impact. Insects may collide with fans and are expected to be negatively impacted. Passerines are not expected to be negatively impacted by air-cooled condensers [60]. More research is needed to better understand potential effects of air-cooled condensers on wildlife.

Solar flux is created by the high intensity concentration of light reflected off mirrors, creating temperatures exceeding 800°C. Insects are attracted to the flux field as a source of polarized light [56,61], resulting in potential incineration of flying insects. Mortality from solar flux has been documented for both dragonflies and butterflies [55]. Attracted to their insect food source, insectivorous birds experience singeing of flight feathers when foraging near flux towers, resulting in mortality. Minor singeing causes impairment of flight, which may lead to inability to forage and evade predators, while severe singeing may cause loss of flight leading to impact trauma and mortality from collision with mirrors [54,55,62]. Scavenger species (e.g., corvids, small carnivores) may benefit from bird fatalities at USSE facilities (i.e., from flux and impact; [29]). Bat carcasses have been retrieved from CSP facilities. While the cause of death remains unknown, bats may be lured into flux fields while foraging, although neutral effects are expected due to bat activity being concentrated after sunset. Flux fields and air-cooled condensers are not expected to negatively impact annual or perennial plants, ungulates, small mammals, carnivores, or reptiles, although no research on any of these taxa has been conducted.

20.4 Summary

Globally, solar energy can provide great environmental benefits, not the least of which is reduced greenhouse gas emissions when substituted for carbon-intensive sources of energy. Indeed, integrated solar energy and other appropriate siting decisions (e.g., reclamation of contaminated land) provide additional benefits associated with land sparing. These benefits should be conjunctively considered in contrast to the environmental costs of solar energy development in places with high biophysical capacity, including natural aridland environments. Displacive USSE development requires land and, to date, rapid deployment of USSE facilities associated with power purchase agreements have emphasized displacive environments. Ecological impacts of displacive USSE development on the biosphere likely are exacerbated when solar facilities are sited in ecosystems with low rates of recovery from disturbances like sensitive areas within the Mojave Desert. Ecological effects of USSE may span the lifetime of a solar facility, from construction to decommissioning. Specifically, siting, site preparation, construction, operations and maintenance, and decommissioning of displacive facilities all may affect ecosystem integrity. Alterations to geohydrology and microclimate from USSE infrastructure may disrupt the physical, chemical, and biological properties of soils, which, in turn, can affect plants, animals, and ultimately "bottom-up" ecosystem processes and interactions. At the landscape-level, new solar energy development beyond the built environment can disturb and fragment habitat. In terms of wildlife response to disturbance, most often sensitive, specialist species are negatively affected, while generalist species typically benefit. Further, invasive plant species often thrive on disturbance and may outcompete native plant species not adapted to disturbance following environmental perturbations. Habitat fragmentation from solar energy infrastructure, including roads, may reduce animal movement and dispersal capacity near solar facilities, which may, in turn, lead to decreased gene flow among subpopulations. Plants and animals may be affected by displacive development directly (e.g., mortality) and indirectly (e.g., displacement). In general, studies on direct or indirect effects of infrastructure associated with solar energy on biota are few, but current research efforts will soon lead to an influx of literature on this subject. However, studies have shown that displacive solar energy projects may cause mortality and extirpation of some species. Assessment of the true sustainability of solar energy hinges on understanding both environmental benefits and costs to the biosphere. Engineering focused on capturing the full potential of integrated solar and the design of solar energy to support positive technological and ecological outcomes simultaneously will contribute to conservation of the biosphere and greater sustainability for humans.

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