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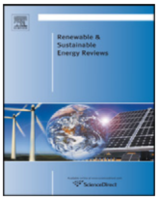

Environmental impacts from the installation and operation of large-scale solar power plants

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ABSTRACT

Large-scale solar power plants are being developed at a rapid rate, and are setting up to use thousands or millions of acres of land globally. The environmental issues related to the installation and operation phases of such facilities have not, so far, been addressed comprehensively in the literature. Here we identify and appraise 32 impacts from these phases, under the themes of land use intensity, human health and well-being, plant and animal life, geohydrological resources, and climate change. Our appraisals assume that electricity generated by new solar power facilities will displace electricity from traditional U.S. generation technologies. Altogether we find 22 of the considered 32 impacts to be beneficial. Of the remaining 10 impacts, 4 are neutral, and 6 require further research before they can be appraised. None of the impacts are negative relative to traditional power generation. We rank the impacts in terms of priority, and find all the high-priority impacts to be beneficial. In quantitative terms, large-scale solar power plants occupy the same or less land per kW h than coal power plant life cycles. Removal of forests to make space for solar power causes CO_2 emissions as high as 36 g CO_2 kW h^{-1}, which is a significant contribution to the life cycle CO_2 emissions of solar power, but is still low compared to CO_2 emissions from coal-based electricity that are about 1100 g CO_2 kW h^{-1}.

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1. Introduction

Solar powered electricity generation is experiencing rapid growth. Current worldwide installed capacity is more than 22 GWp and increasing at ~40% per year [1,2]. Many state or provincial governmental organizations are enforcing renewable portfolio standards, requiring a percentage of utility supplied power to come from renewable sources. Consequently, large-scale solar projects are expanding into a wide range of locations and ecosystems. For example, New Jersey is pursuing a goal of 22.5% renewable energy by 2021. New York is pursing a 24% renewable energy standard by 2013, and will soon complete a 37 MWp photovoltaic array on Long Island. The Canadian province of Ontario has an 80 MWp solar power plant already in operation. Published research provides a

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good understanding of environmental impacts from the manufacturing and end-of-life phases of solar power equipment [3,4], but such is not the case for the installation and operation phases where little scientific research has been performed. This lack of information is particularly true for solar power applied in forested regions. There is much motivation to improve this situation. Lessons learned during the rapid expansion of wind turbines highlight the benefits of a thorough understanding of environmental impacts from the installation and operation phases [5]. Additionally, a rate-limiting step for construction of large-scale solar power plants is the permitting process for the installation and operation phase. Delays in permitting occur largely because the impacts have not been studied or understood. In this paper we develop an improved understanding of the environmental impacts of the installation and operation phases of solar power. We identify and appraise 31 impacts related to issues of land use, human health and well-being, wildlife and habitat, geohydrological resources, and climate.

Most published investigations of environmental impacts from solar power use a life cycle assessment (LCA) framework, and typically focus on greenhouse gas emissions and energy payback time [4,6–8]. A smaller number of papers consider other impacts, i.e., hazardous materials emissions [3,4,9], land use intensity [10–12], water usage [13], wildlife impacts [14], and albedo effects [15]. The LCA method details mass and energy flows throughout a product's life cycle, from extraction of raw materials, to manufacturing necessary equipment, to installation and operation phases, and finally to disposal or recycling phases. In the case of solar power, the installation and operation phases of the life cycle have received little scientific attention. The few existing studies of the operation phase [16–19] are brief and contain no quantitative information. Several informative environmental impact statements (EISs) have been made public in recent years, most notably the U.S. BLM and DOE Programmatic Environmental Impact Statement (PEIS) [20]. Since tens of thousands of acres of U.S. land are proposed for development into solar power in the upcoming years, the environmental impacts from the installation and operation phases deserve comprehensive research and understanding. For example, the most up-to-date LCA results for CO_2 emissions are 16–40 g CO_2 kW h^{-1} [4,6–8], but these numbers do not account for CO_2 emissions that arise if the power plant is installed in a forested region, in which case the removal of vegetation during installation needs consideration. Further, regarding impacts to wildlife, we are aware of only one report that collected primary data on impacts from a solar power facility, i.e., Ref. [14]. In spite of this lack of previous research, a significant need exists for understanding the environmental impacts. Construction of large-scale solar power plants is currently bottlenecked due to permits needed from local agencies concerned with environmental impacts. Our analysis accomplishes the following: (i) identifies impacts, (ii) assesses each impact relative to traditional power generation, (iii) classifies each impact as beneficial or detrimental, and (iv) appraises the priority of each impact. The results form a comprehensive description of the impacts of installation and operation of solar power, in a variety of climates, and afford a first picture of the impacts of solar power in forested regions.

2. Characteristics of the installation and operation of solar power plants

Solar power plants are being developed in a wide range of locations and ecosystems, ranging from forests in England, to deserts in California, to nearly tropical locations in Florida and elsewhere. The environmental impacts of a solar power plant change depending on its location. In this section we describe the relevant characteristics of location of installation, categorized by biomes as forests, grasslands, desert shrublands, true deserts, and farmland. Latitudes from 0° to 50° are considered adaptable to solar power plants. Section 4 describes that the main environmental parameters affecting solar power plants are solar insolation, biomass density, and biodiversity, and we focus on these parameters here. Biodiversity is measured by species density (species ha^{-1}), and is correlated with sunshine and precipitation [21].

Forests require precipitation of at least 50 cm yr^{-1} and the absence of sustained periods of freeze or drought [22]. Cloud cover in forested regions commonly reduces insolation by factors of 25–50%. Vegetation height ranges from 5 to 100 m, and rooting depths range from 1 to 5 m, with deeper roots occurring in drier soils [23]. Biomass density in temperate or tropical forests ranges from 100 to 500 Mg C ha^{-1} [24], the variation due to the age of the forest as well as tree species and local climate. Tropical rainforests have the greatest biodiversity, as measured by species density, of any biome on the planet, close to doubling any other location. Multivariable regressions show that mean annual insolation and precipitation explain 60% of the global variability of biodiversity [21]. Important natural services provided by forests include generation of wood and pulp, mitigation of flood waters by tempering the runoff hydrograph, filtration of pollutants from rainwater and air, moderation of local air temperatures, creation of scenic and recreational opportunities, and hosting of endangered and protected species [25]. The only burden forests cause on local resources is use of groundwater through evapotranspiration.

Grasslands receive between 30 and 100 cm yr^{-1} of precipitation. Often they experience periods of freeze or drought that prohibit dense populations of trees [22]. Biomass density in grasslands ranges from 10 to 50 Mg C ha^{-1} [26,27] with the majority lying in the soil. Biodiversity is comparable to forests but usually $\sim$25% less. Grasslands offer the same natural services as forests, minus the generation of wood and pulp but with the addition of more livestock grazing capacity.

Desert shrublands receive between 5 and 30 cm yr^{-1} of precipitation. Cloud cover is much lower than in forests or grasslands. Biomass density is also lower, in the 10–30 Mg C ha^{-1} range [28]. Surprisingly, biodiversity in desert shrublands is roughly as high as in grasslands [29]. Desert shrublands offer the same natural services as grasslands, but with less flood risk mitigation and grazing capacity.

True deserts are distinct from desert shrublands, have extremely low rainfall, i.e., less than 3 cm yr^{-1}, and have practically zero biomass or biodiversity [29]. Examples are the Sahara or Arabian deserts. These locations are best suited for solar power since they have nearly zero cloud cover, very little wildlife or biomass, low human populations, and offer few natural services to human interests.

Our final landscape category is farmlands, which is unique because it is manmade. Farmlands can be built in replacement of forests, grasslands, or desert shrublands. Therefore, on farmland, cloud coverage varies over the full range depending on location. However, biomass is usually similar to grasslands, and biodiversity is usually lower than grasslands or shrublands but higher than true deserts. Fig. 1 summarizes the geographic parameters of top importance, i.e., biodiversity, biomass density, and cloud cover. The locations of installation are organized into the biomes: forests, grasslands, desert shrublands, and true deserts. The values in the Fig. 1 are normalized by those that occur in tropical forests, because tropical rainforests have the greatest cloud cover, biomass density, and biodiversity. As shown in Sections 4 and 5 of this paper, environmental impacts of large-scale solar power installations are low when the values of these geographic parameters are low.

Installation of solar power equipment requires removing trees, brush, and root balls [20,30]. Photovoltaic or mirror panels are mounted onto steel and aluminum supports $\sim$1 m above ground level, either on concrete footings or by driving steel posts into the

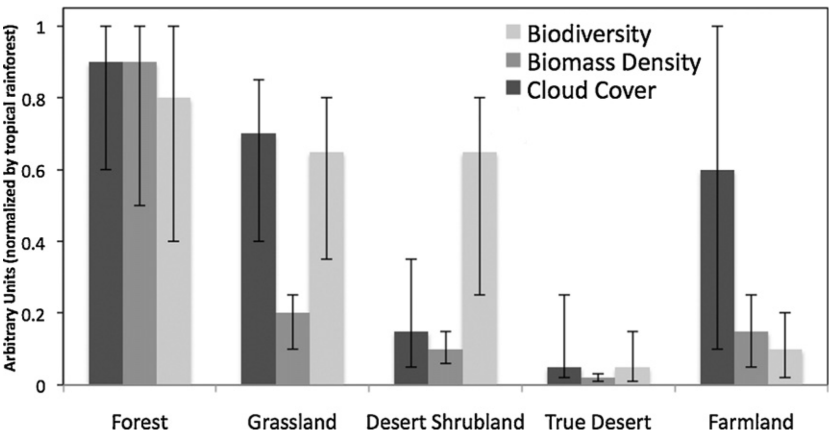

Fig. 1. Geographic parameters of top importance for environmental impacts during the installation and operation are shown. Values are normalized to those in tropical rainforests, which hold the greatest biodiversity, biomass density, and cloud cover. The error bars represent variability that occurs within a particular biome as the latitude or climate conditions change.

ground. The ground slope is usually kept below 5%, by grading, if necessary. After installation of the solar panels, the vegetation is periodically mowed to prevent shading of the panels, which limits vegetation height to below 1 m height. Herbicides are sometimes used instead of mowing [20]. Inverters, transformers, and collector boxes are built for every ∼1 MWp of panels, and sit on concrete pads sized at roughly 5 × 5 m. Trenching for electrical and communications cables is usually required. The power plants are currently engineered for a lifetime of 30 years, with most projects anticipating a longer lifetime. With solar-tracking systems and solar thermal power, the panels require washing, which uses water at a rate of roughly 500–1000 gallons per MWp of panels per year [31]. In a forested environment the rainfall will likely reduce the need for washing. Access roads, electrical equipment, and spacing interlace the panel array, causing the power plant footprint to be ∼2.5 times great than the area directly overlain by panels. Typically the spatial density of commercial solar power equipment is 35–50 MWp per km^2, i.e., 5–8 acres per MWp [10–12]. Maintenance vehicles travel the access roads between the panels for washing and mowing, a few times per year during normal operation.

3. Metrics for environmental impact categories

Power generation technologies are best compared by use of LCA methods with consistent and transparent metrics for each impact category. A metric is the item tracked by life cycle analysis (LCA), and comprises the physical unit of measurement, the methods of data gathering, and the methods of data analysis. For the creation of accurate LCA comparisons, it is crucial that metrics are as objective and consistent as possible. Some environmental impacts have well-defined metrics that are followed by a majority of LCA practitioners, e.g., kg CO_2-eq yr^{-1} for greenhouse gas emissions or decibels above the auditory threshold for noise impacts. Other impact categories do not have well-defined metrics or have no consensus among LCA practitioners. For example, with wildlife and habitat impacts, there is ongoing research on measurement methods for habitat fragmentation, for multiple stressors on the health of individuals, and for risk of collapse of complex ecosystems. Similarly, some of the impacts to human health and well-being are not well understood, particularly those resulting from climate change, e.g., food security or disease release. In Section 4.5 we discuss impacts to geohydrological resources from large-scale power, a topic where no previous research on environmental impact metrics is reported.

The complexity encountered with assessing wildlife and habitat impacts encourages the use of proxy impact categories that are more tractable, such as land use intensity. Land use intensity is therefore an important impact category, but there is not yet a consensus on which metrics best describe the variety of uses of and effect on the land. An analysis of land use metrics is presented in Section 4.2. Although metrics for impacts to ecosystems and geohydrological resources are similarly underdeveloped, we avoid an analysis of possible metrics as this is beyond the scope of this paper. The remainder of our impact categories, have well defined metrics, e.g., albedo effects, noise, or emissions of greenhouse gases, priority pollutants, or heavy metals. Each of these impacts is well defined by "midpoint" metrics, i.e., mass of the pollutant emitted per energy production basis. Also, metrics for impacts to visual resources have been created and managed by the U.S. Forest Service [25], the result being a mixture of qualitative and quantitative methods. Metrics for recreational resources have not been developed but will likely be similar to those for visual resources.

4. Environmental impacts

4.1. Methods

To identify the environmental impacts due to installation and operation of large-scale solar power we reviewed the published science literature and sought expert opinion. We organized our findings into 32 impacts, which are described in the following subsections: Section 4.2 – land use, Section 4.3 – human health and well-being, Section 4.4 – wildlife and habitat, Section 4.5 – geohydrological resources, and Section 4.6 – climate and greenhouse gases. Each subsection holds a table that lists relevant impacts. In the second column of these tables a description is given of the physical effect on the measurable impact indicator that arises from solar power displacing U.S. traditional power. In the third column each impact is appraised in comparison to impacts from traditional U.S. electricity generation, e.g., 45% coal, 23% natural gas, 20% nuclear, 7% hydro, 1% petroleum, and 4% other renewables [32]. This appraisal classifies the impact from solar power as beneficial or detrimental. The justification for a comparative method is that solar electricity generation capacity will displace traditional generation capacity. A comparative approach was also used by the International Energy Agency's assessment of renewable energy technologies [33] and the National Research Council's assessment of wind energy environmental impacts [5]. The fourth column lists a priority for each respective impact. Our determination of priority follows a protocol similar to that of "significance" from the U.S. National Environmental Protection Act, 40 CFR 1508.27 [34], i.e., a "low" priority impact does not require any mitigative action for the project to proceed, a "moderate" priority impact warrants mitiga-

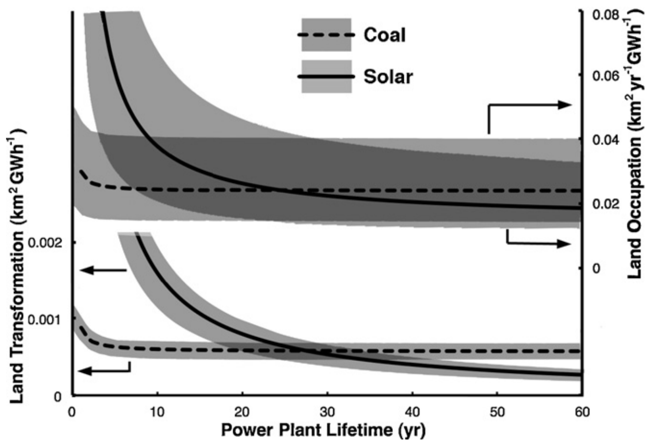

Fig. 2. Comparisons of land use intensity metrics for large-scale solar and coal power. The left ordinate shows land transformation, and right ordinate shows land occupation. For both ordinates the dashed line is the average result for coal powered electricity while the solid line is the average result for solar powered electricity. The gray shaded areas give the range of sensitivity of the calculations as the input parameters are varied over their possible values, as described in the supplemental information.

tion that can be obtained at low cost or can be left semi-mitigated, and a "high" priority impact requires mitigative action that is both costly and required to be fully completed.

When possible we obtain quantitative results and make a numerical comparison with traditional U.S. power generation. For example we use this approach in the next section to compare land use intensity of large-scale solar power plants to coal-fired power plants. In section 4.6 we make a quantitative comparison of CO_2 emissions. We also find previous literature that allows further quantitative comparisons, as in the case of mercury or cadmium emissions.

4.2. Land use

Land use intensity is an important impact because it is often used as a proxy for other impacts. Land-use intensity may be quantified by the following metrics: (i) land area "transformation" per unit of time-averaged power output ($\mathrm{km^2\,GW^{-1}}$) or per nameplate "peak" capacity ($\mathrm{km^2\,GWp^{-1}}$), (ii) land area transformation per unit of electric energy generated ($\mathrm{km^2\,TW\,h^{-1}}$), and (iii) land area "occupation" per unit of electrical energy generated ($\mathrm{km^2\,yr\,TW\,h^{-1}}$). The metric "transformation" focuses on the one-time action of changing the physical nature of the land, i.e., installation. Alternatively, the metric "occupation" is a measurement of land being used for a known period of time, defined as land area multiplied by the length of time that the land area is held in use. The length of time needed for the land to recover from use should be included in this length of time. The occupation metric captures the impact from both the installation and operation phases, whereas the transformation metric captures only the installation phase.

Here we compare land use intensity for the life-cycles of photovoltaic power and coal power. Fig. 2 shows the calculations of land transformation and occupation as a function of lifetime of the operation phase. Solar power plants are currently designed for 30+ years of operation. As the lifetime of a solar power plant gets longer, the land transformation per capacity is unchanged, but the land occupation per energy generated decreases. The coal power life-cycle on the other hand requires mining to obtain the fuel. In the United States 70% of produced coal is obtained by strip-mining [35], wherein the land yields a one-time amount of coal per land surface area. Mining for coal can be described as a land transformation per unit of energy generated ($\mathrm{km^2\,TW\,h^{-1}}$). Additionally, since the topsoil of mined land takes several decades to restore itself, it can be described as land occupation per unit of energy generated ($\mathrm{km^2\,yr\,TW\,h^{-1}}$). Coal power also requires land for the power plant itself, and land for railways to transport the coal from the mine, both of which should be described with either of the previous two sets of units. Land use for solar power, on the other hand, does not require mining for fuel, and is often described with units of land per rated capacity (e.g., $\mathrm{km^2\,GW^{-1}}$). However, to compare the two life cycles, both are described herein in units of land occupation or transformation units per energy generated. The land occupation metric captures the most information and allows the best comparison of solar power to coal power.

A calculation of the above metrics requires the following information: (i) the power plant lifetime, (ii) area used for gathering and transporting fuel, e.g., mining and railway, (iii) area used for the generating facilities (e.g., the furnace, turbine, solar panels, etc.), (iv) the land and energy required for manufacturing the components, and (v) the recovery time of land transformed. All input parameters and methods of calculation are described in the supplemental text to this paper, but for example we assume surface-mined typically transforms $0.004\,\mathrm{km^2\,GW\,h^{-1}}$ [12], and coal power plants cover an average of $2\,\mathrm{km^2\,GW^{-1}}$. We use a 73% capacity factor for coal power [36] and capacities determined by local irradiation for solar power plants. Recent commercial solar power plants cover an average of $25\,\mathrm{km^2\,GWp^{-1}}$. Manufacturing of photovoltaic modules typically requires $\sim 3\,\mathrm{kW\,h\,Wp^{-1}}$ [37]. Full recovery of the forest following strip-mining requires 50+ years [38–50], thus we assume a 50-year recovery time for soil and ecosystems to return to equivalent value or function as prior to mining. Forest recovery time for a photovoltaic power plant is assumed to average 10 years, as the disturbance is significantly lower than for coal mining. To better understand the parameter sensitivity we make our calculations with a range of input values as described in the supplemental text. Fig. 2 plots the calculations for land use metrics. The results for land transformation show parity between solar and coal at 26 years, whereas those for land occupation show parity at 24 years. The latter is a more informed metric since it includes information about the recovery times of land following disturbance. A 30-year old photovoltaic plant is seen to occupy ~15% less land than a coal power plant of the same age. As the age of the power plant increases, the land use intensity of photovoltaic power becomes significantly smaller than that for coal power. The sensitivity in the calculations, as dependent on input parameters, is shown by the shaded belts in Fig. 2. Land transformation per plant capacity $\mathrm{km^2\,GW^{-1}}_{ac}$ show parity between solar and coal after 30 years, with a range from 27 to 40 years (data not plotted).

4.3. Human health and well-being

Table 1 lists the impacts to human health and well-being from solar energy in forested regions. Most of the impacts are beneficial, due to a reduction in toxics emissions arising from the combustion of fossil fuels. For example, a recent study found that 49% of lakes and reservoirs in the U.S. contain fish with concentrations of mercury (Hg) above safe consumption limits [51]. Solar power equipment releases 50–1000 times less direct Hg emissions than traditional electricity generation, i.e., $\sim 0.1\,\mathrm{g\ Hg\ GW\,h^{-1}}$ as compared to $\sim 15\,\mathrm{g\ Hg\ GW\,h^{-1}}$ from coal [4,52,53]. In the US, at least 65% of the mercury deposited in lakes and reservoirs originates from burning fossil fuels [54]. Photovoltaics made with CdTe emit $\sim 0.02\,\mathrm{g\ Cd\ GW\,h^{-1}}$ when manufactured with clean electricity, which is 100–300 times smaller than emissions from coal power generation [4,52,53]. Emissions of NO_x, SO_2, and many other pollutants, are orders of magnitude smaller than those from traditional power [4]. Emissions of these toxics and others, including particulates, are significant burdens on human health [55,56]. Carbon dioxide emissions also pose risks to human health and well-being,

Table 1
Impacts to human health and well-being relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Emissions of mercury	Reduces emissions	Beneficial	Moderate	Solar emits ~30× less
Emissions of cadmium	Reduces emissions	Beneficial	High	Solar emits ~150× less cadmium
Emissions of other toxics	Reduces emissions	Beneficial	Moderate	Solar emits much less
Emissions of particulates	Reduces emissions	Beneficial	High	Solar emits much less
Other impacts				
Noise	Reduces noise	Beneficial	Low	Less mining noise; less train noise
Recreational resources	Reduces pollution	Beneficial	Moderate	Cleaner air; cleaner fishing
Visual aesthetics	Similar to fossils	Neutral	Moderate	Solar farms vs. open pit mines
Climate change[a]	Reduces change	Beneficial	High	Solar emits ~25× less g h g
Land occupation	Similar to fossils	Neutral	Moderate	See Section 4.1

[a] We discuss climate change in Section 4.6.

due to climate change and the associated effects: sea level rise, extreme weather, food security, and socioeconomic change [57]. Fossil fuel power plants emit ~64% of greenhouse gases worldwide [58], and most of the remaining emissions are due to petroleum use that can be partly replaced by electricity from clean power sources. Assessment of the greenhouse gas emissions of solar power life cycles are given in Section 4.6.

Impacts on aesthetics and recreational opportunities from solar power are less clear. Recent legislation introduced in California placed large tracts of land out-of-bounds for solar energy plants, partly due to recreational and visual impacts, and partly for ecological concerns [59]. The visual and recreational impacts are difficult, to quantify but much progress has been made by the U.S. Forest Service over the past decades toward appraising visual resources during land development [25]. A similar approach could be used for recreational resources. Regarding recreational resources, note that a switch to solar power would decrease mercury deposition on lakes and rivers, thereby improving their utility for fishing and recreation. Mountaintop mining could also be reduced or displaced by deployment of large-scale solar power, thereby opening vast amounts of highland forest to recreational opportunity.

4.4. *Wildlife and habitat*

The impact on plant and animal life is a major hurdle for permitting the construction of solar power plants. Solar projects in the desert southwest of the United States generate controversy regarding their disruption to wildlife and habitat, and recent environmental impact statements have estimated impacts to wildlife that require extensive mitigation efforts [60]. Large areas of desert land in California may be excluded from solar energy development due partly to concerns for wildlife [59]. The science behind these ecological impacts is poorly understood, mostly because these large-scale power plants are a new technology.

The majority impact to wildlife and habitat is due to land occupation by the power plant itself. The power plant is typically enclosed by a fence [61], limiting movement by animals. Some fences have openings to allow small animals to enter the facilities. With or without these openings, the habitat of the land changes significantly. Hiding spots, preying strategy, food availability will all be affected. The soil is sometimes scraped to bare ground during construction and kept free of vegetation with herbicide [20], while in other cases the vegetation is allowed to grow but is mowed frequently to keep it below a few feet tall. In either case, a significant alteration to the vegetation occurs. The PV panels themselves will cast shadows and change the microclimate, causing an unstudied effect on vegetation.

The only quantitative study of impacts to wildlife from solar power is that of McCrary et al. [14] who measured death of birds, bats, and insects at the Solar One concentrating solar power tower near Daggett, CA in desert land. Six birds per year died and hundreds of insects per hour were incinerated in the intense light [14]. This impact was concluded to be low compared to other anthropogenic sources of bird and insect fatality. Academic publications contain only hypothetical analyses, and are very brief [16–19]. Several environmental impact statements give more thorough projections of the anticipated impacts. For example, environmental impact statement for the Ivanpah Solar Electric Generating System [60] reported that “significant impact” would occur for the threatened desert tortoise, five special-status animal species, and five special-status plants in the local area. Significant impact is a legal term used in conjunction with the U.S. endangered species act, and denotes the anticipated loss of an amount of habitat that will hinder the recovery of the species. An environmental impact report prepared for the 550 MWp Topaz photovoltaic project in grasslands and abandoned farmlands of central California found the potential for significant impact to dozens of protected animal and plant species in the region. Through extensive mitigation efforts, funded by the solar project itself, these anticipated impacts were reduced to be less than significant [62]. However it should be kept in mind that monitoring of impacts is just beginning.

The impact to wildlife will be tightly correlated to the biodiversity of the land on which the power plant is built. Biodiversity, as measured by species density, is documented most thoroughly by the recent Millennium Ecosystem Assessment [29], which ranked biodiversity in the world’s biomes from greatest to least as follows: tropical rainforests, tropical grasslands, deserts and xeric shrublands, tropical/sub-tropical dry broadleaf forests, montane grasslands and shrublands, temperate broadleaf and mixed forests, flooded grasslands and savannas, tropical coniferous forests, temperate coniferous forests, Mediterranean forests and scrublands, boreal forests, and lastly tundra [29]. For our current paper we use fewer numbers of biomes, which are ranked from greatest to least biodiversity as follows: forests, grasslands, desert shrublands, and true deserts. Sunlight and water availability can significantly alter the biodiversity in any of these biomes, by a factor of two, and endangered species can live in any biome. Consequently, a customized study of the wildlife and ecosystem surrounding each power plant is recommended as a best practice.

Although very few measurements of ecological impacts, or mitigation efforts, from large-scale solar projects are published, there is a rich scientific literature for other land disturbances, such as agriculture or suburban sprawl. Farmland management practices have been found to have a large effect on ecological impacts. For example, practices such as crop-rotation, rest-rotation, non-till farming, intercropping, crop-margin habitat maintenance, and mechanical rather than chemical weed management improve biodiversity and habitat quality within the cropland and on nearby lands [63–65]. The main metric for impacts to wildlife will likely be risk of population decline, based on computational models of ecosystem dynamics, e.g., see [66]. An arising concept in restoration ecology is “connectivity” of the land, i.e., how well the wildlife can

Table 2
Impacts to wildlife and habitat of solar energy relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Acid rain: SO NO*x*	Reduces emissions	Beneficial	Moderate	Solar power emits ∼25× less
Nitrogen, eutrophication	Reduces emissions	Beneficial	Moderate	Solar emits much less
Mercury	Reduces emissions	Beneficial	Moderate	Solar emits ∼30× less
Other: e.g., Cd, Pb, particulates	Reduces emissions	Beneficial	Moderate	Solar emits much less
Oil spills	Reduces risk	Beneficial	High	Note: BP Horizon Spill, Valdez Spill
Physical dangers				
Cooling water intake hazards	Eliminates hazard	Beneficial	Moderate	Thermoelectric cooling is relegated
Birds: flight hazards	Transmission lines	Detrimental	Low	Solar needs additional transmission line
Roadway and railway hazard	Reduces hazard	Beneficial	Low	Road and railway kill is likely reduced
Habitat				
Habitat fragmentation	Neutral	Neutral	Moderate	Needs research and observation
Local habitat quality	Reduces mining	Beneficial	Moderate	Mining vs. solar farms; needs research
Land transformation	Neutral	Neutral	Moderate	Needs research and observation
Climate change[a]	Reduce change	Beneficial	High	Solar emits ∼25× less greenhouse gases

[a] We discuss climate change in Section 4.6.

move across tracts of land and interact. Connectivity is a promising metric to gauge disturbance to a habitat from regional patterns in land use [67], and will be particularly important for large-scale solar energy development.

Recovery of the soil and ecosystem following disturbance can require many years or decades. Coal strip mining, for example, disturbs the land to such a degree that recovery takes 50–100+ years [68], mostly because the soil takes several decades to regenerate. The recovery following solar power production will likely occur more quickly because less soil is removed, but this hypothesis needs further research and primary observations.

It is important to consider that positive effects for wildlife are possible, similar to those found in artificial reefs in marine environments [69]. In many cases a large-scale solar power project provides funding for mitigation actions throughout the lifetime of the power plant, which builds potential for the project to be a benefit to local wildlife rather than a burden [66]. Recent regulatory requirements from the US-BLM and US-DOE call for extensive monitoring of wildlife on solar power plant properties, and for habitat restoration if the wildlife shows signs of stress [20]. Examples of such benefits are elimination of invasive or overpopulating species, construction of suitable habitat for endemic species, the exclusion of recreational off-highway vehicles, or increased monitoring of the state of the ecosystem. Furthermore, as noted in Section 4.2, displacement of coal power with solar power leads to less land occupation per kW h on time scales beyond 27 years, and also less deposition of mercury, NO*x*, and sulfates [51,56]. Land use during the life cycle of solar power is typically less hazardous than that during the life cycle of fossil power, e.g., less mining, railway transport, cooling water intake, and global warming potential. Table 2 summarizes ecological impacts of solar power plants displacing power generated by the traditional U.S. technologies.

4.5. *Geohydrological resources*

Table 3 lists anticipated impacts to geohydrological resources, again relative to traditional power production in the United States. Possible impacts to geohydrological resources include the erosion of topsoil, increase of sediment load or turbidity in local streams, reduction in the filtration of pollutants from air and rainwater, the reduction of groundwater recharge, or the increased likelihood of flooding [70,20]. For example, mitigation plans for storm flow surface water were required for the 400 MW Ivanpah power plant in California [60], and the U.S. BLM and DOE require [20]. If solar power plants are built on slopes, access roads between the panels could produce erosion similar to that seen in vineyards [71]. For example, soil infiltration rates, runoff ratios, and evapotranspiration typically change by factors of two or three when the native vegetation is replaced with agriculture [72–77]. Lessons from forestry give caution to removal of trees on sloping hillsides. Recent solar power plants in Spain are expanding into high slope terrain, 10% slopes or greater, and rack mounting manufacturers are pushing the market space in this direction. Forests offer many other natural services, e.g., flood water reduction or stream bank protection. If the forest's capacity to purify water is degraded then additional municipal purification facilities may need construction. Recent assessment of these issues [20] finds that mitigation of these impacts are easily achievable. However, since these assessments are based on scientific projections rather than measurements, studies and monitoring are recommended for conservation of the local hydrological and soil resources.

4.6. *Impacts on climate, and greenhouse gas emissions*

A major motivation for deploying solar power is to reduce emissions of carbon dioxide from traditional power generation. When installing solar power in forested regions, this motivation needs further research because, as mentioned earlier, trees and brush must be removed to prevent shading of solar panels. Typically, any plant taller than ∼0.5 m is cut or removed, and tree roots are removed to allow posts to be driven into the ground [20]. In this subsection we estimate the CO_2 released by the removal of vegetation, and present a full life cycle CO_2 emission rate for large-scale solar power. At the end of the subsection, we discuss possible climate impacts from surface albedo and heat island effects.

The average biomass density in a forest, including soil, ranges from 100,000 kg C ha^{-1} to 500,000 kg C ha^{-1} [24,78] depending on age of the forest and local climate. The soil and root mass accounts for roughly 50% of this carbon [24]. Boreal forests hold considerably more carbon in soils, but we are not considering them as viable locations for large-scale solar technology. The removed timber, brush, and woody debris can be: (i) turned to mulch, (ii) burned, or (iii) used as lumber for construction or in another long-lived wood product. A portion of the third case may be considered carbon sequestration. In the first two cases, a release of CO_2 is made to the atmosphere, whereas in the third case, the release of CO_2 is delayed for decades or centuries. For this study we define carbon sequestration in the context of the 100-year global warming potential (GWP) [79], i.e., a net transfer of carbon out of the atmosphere, or net avoidance of emission to the atmosphere, for which the transfer or avoidance persists for at least 100 years. A study of the Oregon forestry industry found that roughly 20% of forest biomass cut for forestry products is sequestered on long time scales [80,81]. Studies of sawmill operations confirm this view, and show

Table 3
Impacts to land use and geohydrological resources relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Soil erosion				
During construction	Less soil loss	Beneficial	Low	Existing mitigation is sufficient
During routine operation	Unknown	Unknown	Moderate	Needs research and observation
Surface water runoff				
Water quality	Improves water quality	Beneficial	Moderate	Needs research and observation
Hydrograph timing	Unknown	Unknown	Low	Needs research and observation
Waste management				
Fossil fuels waste spills	Eliminates waste stream	Beneficial	Moderate	Solar avoids fly ash spills and oil spills
Nuclear waste stream	Eliminates waste stream	Beneficial	High	Solar avoids need for waste repositories
Groundwater				
Groundwater recharge	Unknown	Unknown	Moderate	Needs research and observation
Water purity	Improves water quality	Beneficial	Moderate	Needs research and observation

more than 50% of roundwood is lost as waste at the sawmill or put into short-lived products such as paper [82,83]. For our present analysis we assume that between 25% and 50% of the deforested carbon is sequestered or is used in products that offset emissions elsewhere, and the remaining 50–75% becomes a new emission of CO$_2$ to the atmosphere. These same numbers also cover the scenario that the cut vegetation becomes firewood, in which case we assume that 25–50% of the deforested carbon displaces firewood production from elsewhere.

The removal of the forest changes the land's natural carbon sequestration rate. Understanding of the sequestration rate is improved due to recent radiocarbon measurements [84,85], measurements of the volume of wood in lumber and other forest products [86,87], and observations of ecosystem chronosequences [24]. The studies show the net exchange of carbon with the atmosphere to follow these phases: (i) carbon emission to the atmosphere occurs for the first 10–20 years following deforestation due to respiration of unsupported soil matter, at a rate of 400–2000 kg C ha^{-1} yr^{-1} [85,88], (ii) carbon sequestration occurs for the subsequent ∼75 years due to growth of trees and soil horizons, at a rate of 500–3000 kg C ha^{-1} yr^{-1} [85,86,88], (iii) a reduction to near zero net carbon exchange sets in after the forest age reaches past ∼100 years age, to rates of ±20 kg C ha^{-1} yr^{-1} [85,89–91]. The range in these numbers is due to differing forest species and forest climate conditions. Recent publications suggest roughly half of the sequestered carbon is quickly returned to the atmosphere via rivers and lakes [92–94]. If a solar power plant is operating on the land then the trees and biomass cannot produce the middle stage of high sequestration, because the vegetation is continually trimmed and the clippings are oxidized back to the atmosphere. For our present study we assume the land will emit carbon for the first 15 years at 400–2000 kg C ha^{-1} yr^{-1}, then subsequently drop to zero net emissions for the remainder of the power plant lifetime. At the power plant's end-of-life, the solar power facilities are removed and the land may reforest, allowing carbon sequestration, but we do not account for these carbon flows in our present study because they occur many decades in the future.

We calculate the emissions of CO$_2$ per kW h of delivered electricity. To accomplish this we assumed that the solar power plant operates for 30 years, under insolation of 1700 kW h m^{-2} day^{-1}, with module conversion efficiency of 13%, a performance ratio of 80%, a land to GW$_p$ ratio of 20 km^2 per GW$_p$, and a degradation rate of 0.5% per year in the module's performance. These numbers are typical for LCAs of CO$_2$ emissions from solar power [4], and give ∼72 GW h km^{-2} yr^{-1} as time-averaged generation for the plant. Emissions of CO$_2$ from the remainder of the life cycle of solar power are 16–40 g CO$_2$ kW h^{-1} for 1700 kW h m^{-2} yr^{-1} insolation [4,6–8], A description of the calculations of CO$_2$ emissions per kW h is given in this paper's supplementary text. The results, which are summarized in Table 4, show the following: (i) the avoidance of ∼650 g CO$_2$ per kW h of delivered electricity (average U.S. power emissions from Kim and Dale [95] and the DOE [96]), (ii) the emission of between 0 and 36 g CO$_2$ kW h^{-1} due to the initial removal of vegetation, iii) the emission of between 0 and 2 g CO$_2$ kW h^{-1} during the 10 years following deforestation, (iv) the emission of between 0 and 9 CO$_2$ kW h^{-1} due to the loss of the forest's natural sequestration, and (v) the emission of 16–40 g CO$_2$ kW h^{-1} due to the life-cycle of the solar system excluding vegetation considerations. The net emission results in Table 4 shows that solar power is still a very low carbon alternative to traditional U.S. power generation.

Methane and nitrous oxide are also important greenhouse gases released by coal power plants. For comparison, the radiative forcing of CO$_2$, methane, and nitrous oxide, respectively, are 1.7, 0.5, and 0.2 W m^{-2} [79], and fossil fuel combustion contributes 73%, 27%, and 8% of the respective amounts [97]. Emissions of CH$_4$ and NO$_2$ from the life cycle of solar power in forests are likely to be much lower than from fossil fuels, suggesting another GHG benefit for switching electricity generation from fossil to solar power.

Land use affects local climate, microclimate, and surface temperatures, e.g., urban heat islands exist near metropolitan areas. Solar panels have low reflectivity and convert a large fraction of insolation into heat, which leads to concern that they may affect global or local climate. Nemet [15] investigated the effect on global climate due to albedo change from widespread installation of solar panels and found the effect to be small compared to benefits from the accompanying reduction in greenhouse gas emissions. Nemet did not consider local climates or microclimates.

Table 5 lists the environmental impacts from solar energy in forested regions. The presence of the forest affects most of the impacts, particularly the CO$_2$ emissions. Field research is needed to establish the effect of the power plant on local climate and microclimates.

5. Net environmental impact

We aggregated the information in Section 4 to produce the net environmental impacts of large-scale solar power displacing grid electricity. Considering Tables 1–5, the following observations are made: (i) twenty two of the thirty two net impacts are beneficial,

Table 4
Emissions of CO$_2$ from the life cycle of large-scale solar power.

	Carbon dioxide emissions (g CO$_2$ kW h^{-1})	
	Best case	Worst case
Loss of forest sequestration	+0.0	+8.6
Respiration of soil biomass	+0.0	+1.9
Oxidation of cut biomass	+0.0	+35.8
Other phases of the life cycle	+16.0	+40.0
Total emissions of solar	+16.0	+86.3
Fossil fuel emissions avoidance	−850.0	−650.0
Total including avoidance	−834.0	−563.7

Table 5
Impacts to climate change from solar power, relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Global climate				
CO_2 emissions	Reduces CO_2 emissions	Beneficial	High	Strong benefit
Other GHG emissions	Reduces GHG emissions	Beneficial	High	Strong benefit
Change in surface albedo	Lower albedo	Neutral	Low	The magnitude of the effect is low
Local climate				
Change in surface albedo	Lower albedo	Unknown	Moderate	Needs research and observation
Other surface energy flows	Unknown	Unknown	Low	Needs research and observation

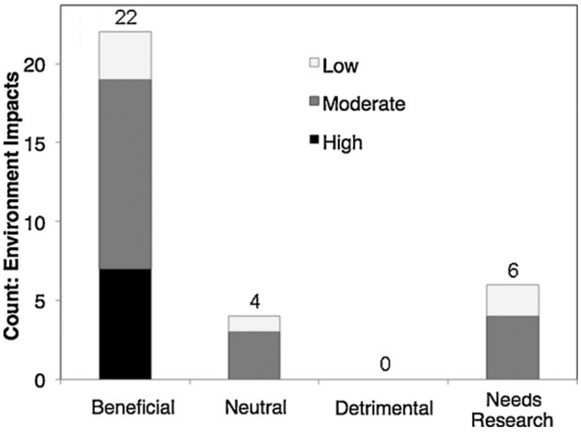

Fig. 3. Summary of the aggregate impact of solar power in forested environments compared to traditional U.S. power generation.

seven of which have high priority, twelve of which have moderate priority, and three of which have low priority, (ii) four of the thirty two net impacts are neutral, three of which have moderate priority and the remaining one has low priority, (iii) none of the net impacts were detrimental relative to traditional power, and (iv) the final six net impacts need further research before they can be classified. Fig. 3 presents these results graphically. In "true desert" regions the benefits of solar power would be more intense, and many of the net impacts would change from neutral (or unknown) to beneficial. These desert locations have the additional benefit that wintertime power generation is considerably stronger than in cloudier, or more polar, locations.

6. Conclusions

We identified and appraised the environmental impacts of large-scale solar power plants. Solar technology is concluded to be much preferable to traditional means of power generation, even considering wildlife and land use impacts. We identified 32 environmental impacts for solar power plants, and found that 22 are beneficial relative to traditional power generation, 4 are neutral, none are detrimental, and 6 need further research. All high-priority impacts are favorable to solar power displacing traditional power generation, and all detrimental impacts from solar power are of low priority. We find the land occupation metric to be most appropriate for comparing land use intensity of solar power to other power systems, and find that a solar power plant occupies less land per kW h than coal power, for plant lifetimes beyond ~25 years. The land transformation rate of solar power is lower than that of coal power for plant lifetime's beyond ~27 years. When comparing deployment of solar power plants in forests to that in grasslands or deserts, there are clear differences. Our calculations shows solar power in forested regions will release significantly more CO_2 than in desert regions, by a factor of 2–4, with a total emission of between 16 and 86 g CO_2 kW h^{-1}, due mainly to clearing of vegetation to make room for the solar power plant but also partly to the reduced insolation in forests due to clouds. All of the environmental impacts per kW h are heightened by the lower insolation in cloudy or high-latitude regions, because less kW h of electricity is generated from the life cycle of the power plant. Solar power plants located in true deserts, and other locations where solar insolation is intense and wildlife is absent, have the most beneficial environmental impact.

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