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Environmental impacts of utility-scale solar energy

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ABSTRACT

Renewable energy is a promising alternative to fossil fuel-based energy, but its development can require a complex set of environmental tradeoffs. A recent increase in solar energy systems, especially large, centralized installations, underscores the urgency of understanding their environmental interactions. Synthesizing literature across numerous disciplines, we review direct and indirect environmental impacts – both beneficial and adverse – of utility-scale solar energy (USSE) development, including impacts on biodiversity, land-use and land-cover change, soils, water resources, and human health. Additionally, we review feedbacks between USSE infrastructure and land-atmosphere interactions and the potential for USSE systems to mitigate climate change. Several characteristics and development strategies of USSE systems have low environmental impacts relative to other energy systems, including other renewables. We show opportunities to increase USSE environmental co-benefits, the permitting and regulatory constraints and opportunities of USSE, and highlight future research directions to better understand the nexus between USSE and the environment. Increasing the environmental compatibility of USSE systems will maximize the efficacy of this key renewable energy source in mitigating climatic and global environmental change.

Contents

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1. Introduction

Renewable energy is on the rise, largely to reduce dependency on limited reserves of fossil fuels and to mitigate impacts of climate change ([58, 110, 150]). The generation of electricity from sunlight directly (photovoltaic) and indirectly (concentrating solar power) over the last decade has been growing exponentially worldwide [150]. This is not surprising as the sun can provide more than 2500 terawatts (TW) of technically accessible energy over large areas of Earth′s surface [82,125] and solar energy technologies are no longer cost prohibitive [9]. In fact, solar power technology dwarfs the potential of other renewable energy technologies such as wind- and biomass-derived energy by several orders of magnitude [150]. Moreover, solar energy has several positive aspects – reduction of greenhouse gases, stabilization of degraded land, increased energy independence, job opportunities, acceleration of rural electrification, and improved quality of life in developing countries [17,126] – that make it attractive in diverse regions worldwide.

In general, solar energy technologies fall into two broad categories: photovoltaic (PV) and concentrating solar power (CSP). Photovoltaic cells convert sunlight into electric current, whereas CSP uses reflective surfaces to focus sunlight into a beam to heat a working fluid in a receiver. Such mirrored surfaces include heliostat power towers (flat mirrors), parabolic troughs (parabolic mirrors), and dish Stirling (bowl-shaped mirrors). The size and location of a solar energy installation determines whether

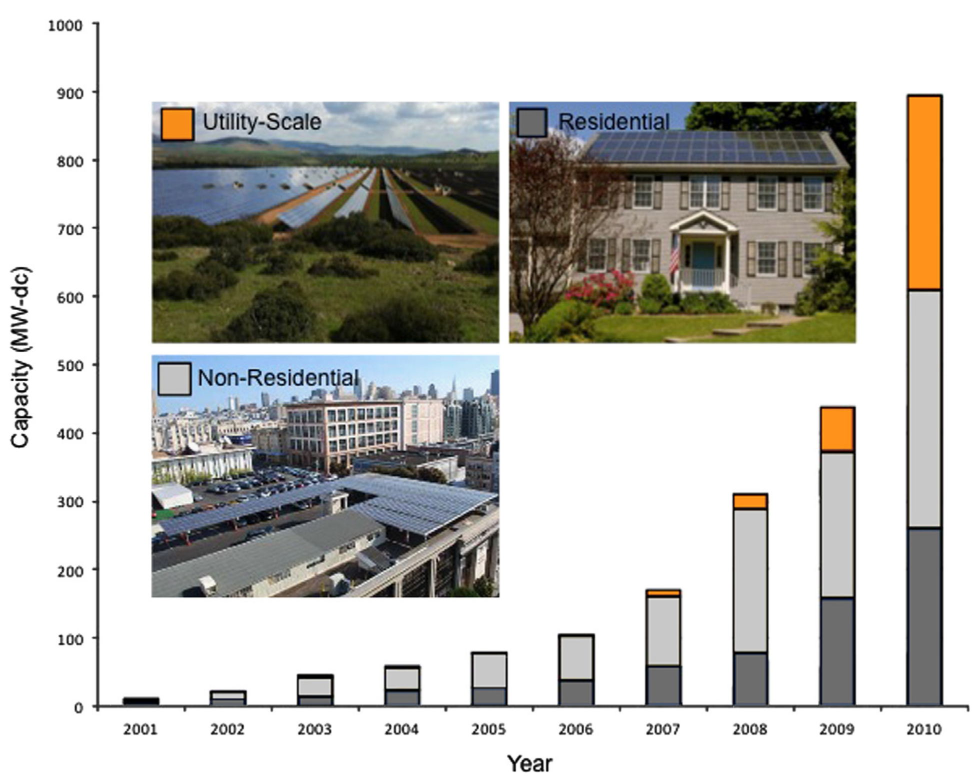

Fig. 1. Annual installed grid-connected photovoltaic (PV) capacity for utility-scale (> 20 MW) solar energy schemes and distributed solar energy schemes (i.e., non-residential and residential) in the United States. Total PV capacity was 900 MW in 2010; approximately double the capacity of 2009. Data reprinted from Sherwood [114]. Photo credits: RR Hernandez, Jeff Qvale, National Green Power.

it is distributed or utility-scale. Distributed solar energy systems are relatively small in capacity (e.g., < 1 megawatt [MW]). They can function autonomously from the grid and are often integrated into the built environment (e.g., on rooftops of residences, commercial or government buildings; solar water heating systems; portable battlefield and tent shield devices; [25,102]). Distributed solar contrasts strikingly with utility-scale solar energy (USSE) enterprises, as the latter have relatively larger economies of scale, high capacity (typically > 1 MW), and are geographically centralized —sometimes at great distances from where the energy will be consumed and away from population centers. In the United States (US), solar energy has grown steadily over the past decade and rapidly in recent years (Fig. 1). The USSE capacity in this country quadrupled in 2010 from 2009, while both residential and nonresidential capacity increased over 60% during that same period. Similar increases in USSE have also been observed in Australia, China, Germany, India, Italy, and Spain [90,111,113,128,139].

As a paradigm of clean and sustainable energy for human use, reviews on the environmental impacts of solar energy date back to the 1970s [49,71]. For example, Lovins [71] provided a conceptual framework by which an energy scheme's position along a gradient from soft (benign) to hard (harmful) is determined by the energetic resiliency (or waste) and environmental conservation (or disruption) for its complete conversion from source to final end-use form. More recent reviews of the environmental impacts of solar energy systems have emphasized fundamental life-cycle elements (upstream and downstream environmental impacts associated with development; [126]) or were focused on specific regions (e.g., Serbia; [90]) or fauna of interest (Lovich and Ennen, 2012). The observed increase in USSE and studies elucidating their environmental properties underscores the importance of understanding environmental interactions associated with solar energy development, especially at regional and global scales and how these impacts may reduce, augment, or interact with drivers of global environmental change.

Here, we provide a review of current literature spanning several disciplines on the environmental impacts of USSE systems, including impacts on biodiversity, water use and consumption, soils, human health, and land-use and land-cover change, and land-atmosphere interactions, including the potential for USSE systems to mitigate climate change. Drawing from this review, we show (1) mechanisms to integrate USSE environmental co-benefit opportunities, (2) permitting and regulatory issues related to USSE, and (3) highlight key research needs to better understand the nexus between USSE and the environment.

2. Environmental impacts of utility-scale solar energy systems

Environmental impacts (see Fig. 2 for complete list) of USSE systems may occur at differential rates and magnitudes throughout the lifespan (i.e., construction, operation, and decommission) of a USSE power plant, which varies between 25 and 40 years. Drawing from experiments evaluating direct and indirect impacts of USSE systems and studies evaluating processes that are comparable in likeness to USSE activities, we discuss impacts related to biodiversity, water use and consumption, soils and dust, human health and air quality, transmission corridors, and land-use and land-cover change.

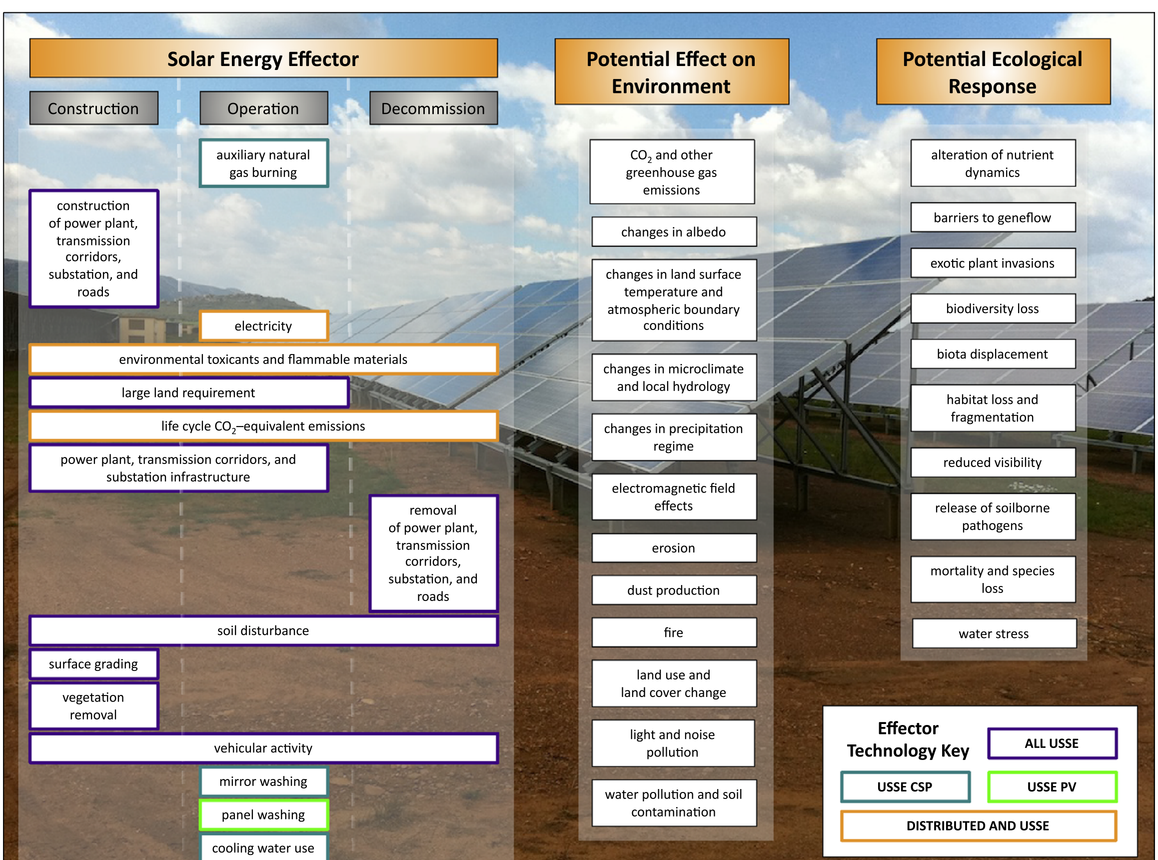

Fig. 2. Solar energy effectors for utility-scale solar energy technologies (ALL USSE), including concentrating solar power (USSE CSP) and photovoltaics (USSE PV), and for both utility-scale and distributed schemes (distributed and USSE). Effectors have one or more potential effects on the environment with one or more potential ecological responses. Photo credit: RR Hernandez.

2.1. Biodiversity

In general, distributed and USSE installations integrated into the existing built environment (e.g., roof-top PVs) will likely have negligible direct effects that adversely impact biodiversity [25]. Studies quantifying the direct impact of USSE on biodiversity in otherwise undisturbed habitats are few ([75,107]; Lovich and Ennen [70]; Cameron et al. [142]; [81]); however, these combined with other disturbance-related studies provide insight into how USSE power plants may impact biodiversity losses locally within the USSE footprint (i.e., all areas directly transformed or impacted by an installation during its life cycle), where the aboveground vegetation is cleared and soils typically graded, and regionally by landscape fragmentation that create barriers to the movement of species and their genes [101].

2.1.1. Proximate impacts on biodiversity

As USSE sites typically remove vegetation and soils are graded, locating USSE on land where biodiversity impacts are relatively small has been shown to be a feasible strategy for meeting both renewable energy and conservation goals ([39]; Cameron et al., 2012). For example, Fluri [39] showed that the strategic siting of USSE infrastructure in South Africa could create a nominal capacity of 548 gigawatts (GW) of CSP while avoiding all habitats supporting endangered or vulnerable vegetation. After a site has been chosen, solar energy projects may employ repatriation and translocation programs—when individuals of key native species are collected from impacted habitat, moved, and released into reserve areas previously inhabited and not previously inhabited by the species, respectively. The low success rates of repatriation and translocation programs (e.g., $<20\%$; [29,38]) have rendered them an expedient when all other mitigation options are unavailable [19]. These and other 'post-siting' compliance measures to minimize biodiversity impacts (e.g., land acquisition, road fencing) are expensive, usually target a single species, and do not guarantee benefits to the organisms they are designed to support [70]. The repatriation and translocation of organisms is complicated by climate change, which requires taking into account the dynamic character of species' distributions for both assessing biodiversity impacts of single and collective USSE projects and for determining suitable habitat for repatriation or translocation. Additionally, some species, such as birds, cannot be moved and may be attracted to certain USSE infrastructural elements. McCrary [75] found mortality rates, compared to other anthropogenic impacts on birds, low for USSE systems, and Hernandez (unpublished data) observed nests on the backside of PV module infrastructure (Fig. 3). Soil disturbances and roads can further increase mortality rates of organisms or serve as conduits for exotic invasions, which can competitively extirpate native species [42,140].

2.1.2. Indirect and regional effects on biodiversity

Less proximate impacts on biodiversity may also occur indirectly within the USSE footprint (i.e., all areas directly transformed or impacted by an installation during its life cycle), beyond the footprint, and regionally by landscape fragmentation that create barriers to the movement of species and their genes [101]. In the southwest US, anthropogenic sources of oxidized and reduced nitrogen may be elevated due to emissions from increased vehicle activity or the use of CSP auxiliary natural gas burners, promoting invasions by exotic annual grasses that increase fire frequencies [5,94]. Additionally, environmental toxicants required for USSE operation (e.g., dust suppressants, rust inhibitors, antifreeze agents) and herbicides may have insalubrious, and potentially

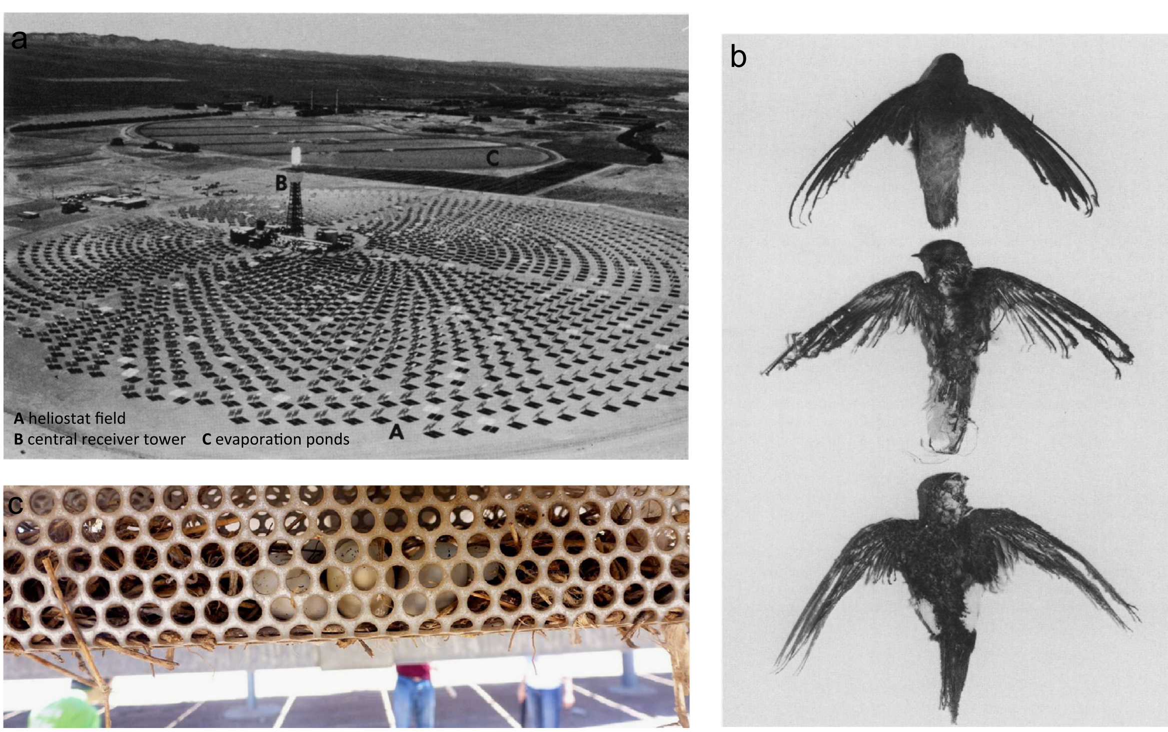

Fig. 3. ((a) and (b)) McCrary et al. [76] documented the death of 70 birds (26 species) over 40 weeks, including effects of scavenger bias, resulting from the operation of a 10 MW concentrating solar thermal power plant (Solar One, Mojave Desert, CA; 1). This equates to a mortality rate of 1.9–2.2 individual birds per week. Two causes of death were identified: most prevalent was collision with site infrastructure (81%), particularly with heliostats, and to a lesser degree, burning when heliostats were oriented towards standby points (19%), especially for aerial foraging species. Additionally, they found that the large, man-made evaporation pools increased the number of species five-fold in the local area. Impacts on bird mortality may increase non-linearly with increasing USSE capacity. (c) Hernandez (unpublished data) observed several bird nests on the backside of PV module infrastructure at a USSE power plant in the Central Valley of California (San Joaquin Irrigation District PV Plant, Valley Home, CA, USA). Photo credit: Madison Hoffacker.

long-term, consequences on both local and regional biodiversity [1,70].

Habitat loss and fragmentation are recognized as the leading threats to biological diversity [35,136]. The land-use efficiency, footprint, and infrastructural design of individual USSE installations vary significantly [51] and therefore individual power plants affect landscapes in unique ways. Utility-scale solar energy infrastructure may fragment habitat and serve as linear barriers to the movement patterns of certain wildlife species. Whereas highly mobile or wide-ranging species may be able to circumvent USSE infrastructure, some features may be insurmountable to less mobile species, increasing the risk of gene flow disruption between populations. Decisions regarding the placement of USSE infrastructure likely take into account current species distributions, but climate change may alter future distributions and wildlife dispersal corridors [52]. Determining species' responses to novel climate shifts is inherently uncertain and scale dependent, but nevertheless tools exist to model such distributional shifts (e.g., [11]).

2.2. Water use and consumption

Energy and water are interdependent [129]. USSE technologies vary in their water withdrawal (total volume removed from a water source) and consumption (volume of withdrawn water not returned to the source) rates, creating unique tradeoffs. Photovoltaic energy systems have low rates (0.02 m^3/megawatt hours [MW h]), consuming water only for panel washing and dust suppression in places where dust deposition is problematic [41]. Currently, washing panels or mirrors with water is the most common strategy for dust removal in large solar installations [73]. A recent analysis of water use by USSE installations in the southwestern US indicates that water for dust control is a major component (60–99%) of total water consumption in both dry cooled CSP and PV installations (Ravi et al., in review), whereas no information is available for other regions where USSE installations are expected to increase in the near future. Even though other cleaning technologies (e.g., electrostatic) exist, most are not yet commercially available, and the impacts of conventional technologies (e.g., cleaning using chemical sprays) on the environment are not completely understood [50,65].

In the case of CSP, the water consumption depends on the cooling system adopted—wet cooling, dry cooling, or a combination of the two (hybrid cooling) [108]. Concentrating solar power consumes vast quantities of water in wet cooling (i.e., 3.07 m^3/MW h), which is greater than coal and natural gas consumption combined [18,108]. The use of dry cooling, which reduces water consumption by 90% to 95%, is a viable option in water-limited ecosystems. Historically, reduced efficiency and higher startup costs have been an economic deterrent to dry cooling [108]. However, Holbert and Haverkamp [53] found that dry cooling startup costs are offset by 87–227% over a 20-year time interval, owing to cost savings in water use and consumption. Global regions already water stressed, such as many arid and semiarid habitats, may be vulnerable to changes in local hydrology [133], such as those incurred by USSE activities. In water-constrained areas, the deployment of USSE projects may also conflict with the use of water by other human activities (e.g., domestic use, agriculture), at least at the local scale [18,108]. Ultimately, the choice of dry or wet cooling in a CSP plant can lead to highly divergent hydrological impacts for USSE facilities.

2.3. Soil erosion, aeolian sediment transport, and feedbacks to energetic efficiency

Aridlands, where USSE facilities are often concentrated [51], are also areas where high winds result in aeolian transport of sand and dust. Some of that sediment transport is controlled by desert vegetation, but the installation of USSE infrastructure requires extensive landscape modification. Such modifications include vegetation removal, land grading, soil compaction, and the construction of access roads; activities that increase soil loss by wind and water [14,37].

The major agents of natural degradation are soil particulates (silt and clay), as well other particulate pollutants such as industrial carbon (C) [98,99]. Given its variable composition, dust emissions have a broad spectrum of impacts ranging from human health, global biogeochemical cycle, hydrologic cycle, climate, and desertification (e.g., [46,87,88,95]). In one semiarid ecosystem, Li et al. [68] recorded a 25% loss of total organic C and total nitrogen in the top 5 cm of soil following devegetation. Studies conducted in southeast Spain have found that 15 years after the removal of vegetation in a semiarid site, the total organic C remained ~30% lower compared to undisturbed areas, which also showed greater microbial biomass and activity levels [12]. Decreases in the availability of resources resulting from soil erosion can result in biodiversity losses and impede the recovery of vegetation [4,47,104]. Moreover, reduction in vegetative cover are strongly linked to increased dust production and even modest reductions in grass or shrub cover have been shown to dramatically increase dust flux [68,80].

Dust deposition can incur a negative feedback to solar energetic performance by decreasing the amount of solar radiation absorbed by PV cells [45]. Even suspended dust in the near surface atmosphere decreases the amount of solar radiation reaching the panel surface [45]. Deposition on solar panels or mirrors is site-specific and modulated by several factors, including soil parent material, microclimate, and frequency and intensity of dust events, but several studies have demonstrated energy production losses exceeding 20% [33,34,45,85]. Nonetheless, long-term field studies to quantify dust impacts on solar energy production are limited. For example, Ibrahim [55] experimentally demonstrated that solar modules installed in the Egyptian desert that have been exposed to dust for a period of one year showed an energy reduction of about 35%. Kimber et al. [61] investigated the effects of deposition on energy production for large grid-connected systems in the US and developed a modeling framework for predicting soiling losses. These authors found that for North American deserts, PV system efficiency declines by an average of 0.3% per day during periods without rain [61]. The National Renewable Energy Laboratory analyzed 24 PV systems throughout the US and calculated a typical derate factor (percentage decrease in power output) due to dust deposition of 0.95% [74]. In many desert ecosystems dust deposition rates are sufficiently high as to adversely impact solar power generation [67,98].

Challenges to manage dust loads may be amplified by increases in dust production related to land-use change, climate change (e.g., increases in aridity) or disturbance to biological soil crusts (e.g., fires, grazing, agriculture, energy exploration/development; [13]; Field et al.[37]; [95]). Even if USSE-related dust production is kept at bay, climate models predict an increase in aridity and recurrent droughts in dryland regions of the world (e.g., [109]), which may enhance soil erosion by wind and subsequent dust emissions. As these emissions can compromise the success of a USSE installation itself when they reduce its potential to generate electricity, effective dust management is advantageous to ensure efficient power generation while minimizing deleterious environmental and health impacts.

2.4. Human health and air quality

As with the development of any large-scale industrial facility, the construction of USSE power plants can pose hazards to air quality, the health of plant employees, and the public [122]. Such hazards include the release of soil-borne pathogens [91], increases in air particulate matter (including $PM_{2.5}$, [46,100]), decreases in visibility for drivers on nearby roads, and the contamination of water reservoirs [70]. For example, disturbance of soils in drylands of North and South America, which are places targeted for USSE, aids transmission of *Coccidioides immitis,* a fungus causing Valley Fever in humans [10]. In areas where surface soil contains traces of chemical and radioactive contaminants (e.g., radionucleotides, agrochemical residues), increased aeolian transport resulting from soil disturbances increases contaminant concentrations in airborne dust [95].

During the decommissioning phase, PV cells can be recycled to prevent environmental contamination due to toxic materials contained within the cell, including cadmium, arsenic, and silica dust [144,145]. In the case of inappropriate handling or damaged cells, these industrial wastes can become exposed, which can be hazardous to the public and environment [144]. For example, inhalation of silica dust over long periods of time can lead to silicosis, a disease that causes scar tissue in the lungs and respiratory decline. In severe cases, it can be fatal [148]. In addition, chemical spills of materials such as dust suppressants, coolant liquids, heat transfer fluids, and herbicides can pollute surface ground water and deep water reservoirs [70,126].

On rooftops, solar PV panels have also been shown to reduce roof heat flux, conferring energy savings and increases in human comfort from cooling [31]. In that vein, the insulating properties of rooftop solar PV may serve co-beneficially to mitigate heat wave-related illness and mortality [131]. The fire hazard potential of both rooftop and ground-mounted USSE infrastructural materials (e.g., phosphine, diborane, cadmium), and their proper disposal, presents an additional challenge to minimizing the environmental impacts of USSE facilities [43]. This is particularly true in light of the dramatic increases in the frequency and intensity of wildland fires in arid and semiarid regions of the world as a result of climate change ([134], [15]).

2.5. Ecological impacts of transmission lines and corridors

Centralized USSE operations require transmission of generated electricity to population centers where consumption occurs. This necessitates the development of expanded transmission infrastructure, the availability of which has not kept up with demand [21,30]. As of 2007, over 333 kilometers (km; 207,000 miles) of high-voltage transmission lines ($>$230 kV) were constructed in the US electricity transmission system [78] and this number is expected to rise as transmission infrastructure expands to growing population centers and connects with new renewable energy sources. As the potential for solar resources in other countries are being discovered so too are the plans to harness that energy and transmit it across international borders [27]; such plans are being actively developed to transmit energy from Middle Eastern and North African regions to European countries (requiring over 78,000 km of transmission lines by project completion in 2050; [124]). Although essential for transporting energy, the construction of such extensive transmission line networks has both long- and short-term ecological effects, including displacement of wildlife, removal of vegetative cover, and degradation of habitat quality [8], the degree of which may depend on land-use history, topography, and physical features of the sites, as well as productivity and vegetation types. For example, Lathrop and Archbold [66] estimated that biomass recovery at Mojave Desert sites disturbed for transmission line tower construction might take 100 years whereas recovery of disturbed transects directly beneath the transmission lines might take 20 years.

Fragmentation created by transmission corridors in forested habitats may displace permanent resident species and disrupt regular dispersal patterns [7,97,107]. While wide transmission corridors may facilitate new habitat types resulting in higher diversity or the introduction of new communities [7,58,81], they also experience greater edge effects. Sites at different stages of vegetative recovery have exhibited distinct recolonization patterns, with lower native and higher introduced species diversity at primary successional stages and an increase in native diversity at mid- and late-successional stages [20]. The ecological effects of transmission lines and corridors have proven to be varied and depend on a multitude factors, making appropriate siting crucial.

2.6. Land-use and land-cover change

2.6.1. Land-use dynamics of energy systems

Land and energy are inextricably linked [25]. When energy systems are developed, biophysical characteristics of the land may change (land-cover change, m^2), the human use or intent applied to the land may change (land-use change, m^2), and the land may be used for a specific duration of time (land occupation, m^2 x yr; [40,64]). Terrestrial ecosystems vary in their net primary productivity (rate of accumulation of organic C in plants), from tropical evergreen forests (1 to 3.2 $kg/m^2/yr^1$) to deserts (up to 0.6 $kg/m^2/yr^1$), and in their ability to sequester C in soil [105]. When land-use and land-cover change occurs – for example, when vegetation or biological soil crust is cleared or when soils are disturbed – above- and below-ground pools may release C back into the atmosphere as carbon dioxide (CO_2; [26]). Hence, developing energy-related infrastructure on previously disturbed or contaminated land may result in lower net C losses than infrastructure erected on undisturbed lands [26,62,89].

Other key land-use characteristics of energy include land-use efficiency and reversibility. Land-use efficiency (e.g., watts per square meter, $/m^2$) defines the installation′s power relative to its footprint; the "footprint" being the land area transformed or impacted by the installation throughout the energy system′s complete conversion chain [40,51]. As energy systems may impact land through materials exploration, materials extraction and acquisition, processing, manufacture, construction, production, operation and maintenance, refinement, distribution, decommissioning, and disposal, energy footprints can become incrementally high [40]. Some of this land may be utilized for energy in such a way that returning to a pre-disturbed state necessitates energy input or time, or both, whereas other uses are so dramatic that incurred changes are irreversible [79]. Irreversibility cost assessments can be employed to monetize restoration and irreversibility; a function of the original land cover type and properties of the land-use and land-cover change incurred [138,141].

2.6.2. Land-use of utility-scale solar energy

Likely due to its nascent expansion [9], studies evaluating land-use characteristics of USSE systems are relatively recent, few, and focused geographically. Hsu et al. [54] described the complete energy conversion chain of PV USSE systems, which necessitates materials acquisition, infrastructure and module manufacture, construction, operation and maintenance, material disposal, and decommissioning. The complete energy conversion chain of CSP is similar, but complicated by auxiliary natural gas and electricity consumption [16]. Fthenakis and Kim [40] stated that indirect land impacts related to materials (e.g., modules and balance-of-system) and energy for PV is negligible – between 22.5 and 25.9 m^2/GWh^1 – compared to direct land use. Data on land occupation are rare; however, the lifetime of USSE infrastructure, including modules, is typically assumed to be between 30 and 60 years [40].

Studies targeting the direct impact of USSE on land-cover change are few [51,143,149]. Furthermore, factors controlling sequestration of C in soils, particularly in aridlands, are not well understood [72,106], complicating the ability to quantify C losses from USSE-related land-cover changes in the ecosystems where they are most likely to occur [51]. In western US, 97,000 ha (ha) of federal lands were approved or have pending leases for the development of USSE while over 18 million ha of land in this region were identified as suitable for USSE development [135]. In the same region, Pocewicz et al. [92] found that USSE development may impact shrublands greater than any other ecosystem type, with estimates of conversion ranging from 0.60 to 19.9 million ha, and especially for North American shrubland ecosystems. Smaller leases on grasslands and wetland ecosystems were approved, and therefore may also be impacted but to a lesser extent. Hernandez et al. [51] found that USSE (> 20 MW; planned, under construction, and operating) in California may impact approximately 86,000 ha; concentrated in the agricultural center of the state (the Central Valley) and the arid, interior of southern California. In the Mojave Desert, over 220,000 ha of Bureau of Land Management land has pending applications for USSE development. If constructed, creosote-white bursage desert scrub, the Mojave mid-elevation mixed desert scrub, and over 10,000 ha of desert tortoise habitat would be converted (Cameron et al., 2012).

Land-use efficiency of USSE is determined by the architectural and infrastructural design and capacity of the power plant but indirectly influenced by a project′s geography, capacity factor, technology type, and developer priorities. Hernandez et al. [51] found the nominal LUE efficiency of USSE in California to be 35 W/m^2 where a capacity factor of 13% and 33% would generate a realized LUE of approximately 4.6 and 11.2 W m^{-2} for PV and CSP, respectively. Fthenakis and Kim [40] used a nominal packing factor (based on a single footprint specification) to determine the land use efficiency of PV and their results, ranging between 229 and 552 m^2/GWh[1], were comparable to [51].

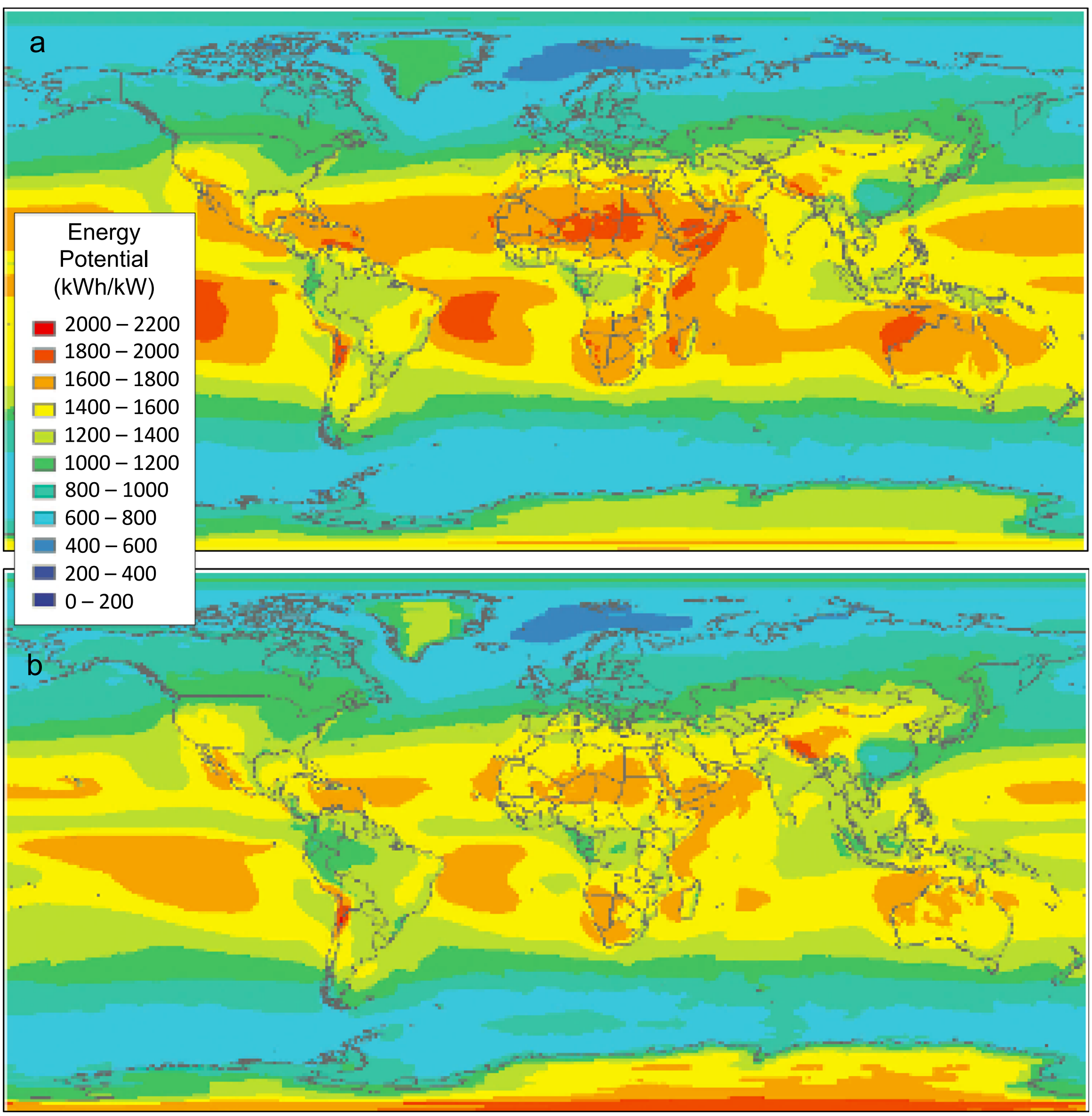

Fig. 4. Impact of temperature on global photovoltaic solar energy potential. In general, photovoltaic (PV) solar energy output increases with increasing irradiance but decreases with increasing ambient temperatures. These maps show (a) the global potential of PV energy (kWh/kW PV) for a crystalline silicon (c-Si) module, the most widely employed in the current market, without considering temperature effect, and (b) the global potential of PV energy (kWh/kW pV) for a crystalline silicon (c-Si) module including temperature effect. High irradiance coupled with low temperatures render the Himalayas, the Southern Andes, and Antarctica high in potential, > 1800 kWh/kW. High temperatures reduce PV solar energy potential in places including southwest United States deserts, northern Africa, and northern Australia. Both (a) and (b) include impacts from cloud cover (maps reprinted from Kawajiri et al. [59]). Not well understood is how changes in land surface temperatures from climate change, especially heat waves, will impact future global PV energy output.

To date, no study has evaluated how USSE land use efficiency (W/m^2) and layout – the infrastructural and architectural design of a USSE power plant – may impact ecosystem recovery or reversibility. However, the natural recovery of aridlands and other ecosystems after disturbance can be exceptionally slow. For example, leases for USSE development on public land in southern California deserts are typically at the decadal-scale, while complete ecosystem recovery from USSE activities there may require over 3000 years [69].

2.6.3. *Comparing land-use across all energy systems*

Land-use and land-cover change impacts from USSE are relatively small when compared to other energy systems [146]. In five ecosystems in western United States, Copeland et al. [21] found that *actively producing* oil and gas leases impact 20.7 million ha of land (4.5% of each terrestrial ecosystem evaluated) but the total potential for lands to be disturbed exceeded 50 million ha (11.1%). In contrast, potential land-cover change impacts from USSE development was $<1\%$ of all ecosystems combined. In terms of land-use efficiency, PV energy systems generate the greatest amount of power per area among renewables, including wind, hydroelectric, and biomass [40,51]. Notably, ground-mounted PV installations have a higher land use efficiency (when incorporating both direct and indirect effects [e.g., resource extraction]) than surface coal mining, which is how 70% of all coal in the United States is extracted [40]. These results underscore the environmental potential solar energy development may have on land-cover and land-use change impacts, relative to carbon-intensive energy and other renewable energy sources.

3. Utility-scale solar energy, land-atmosphere interactions, and climate change

Assessments of USSE impacts on land-atmosphere interactions, especially those with climate feedbacks, are increasing in number. While there are two principal types of solar technologies (i.e., PV and CSP) recent research on land-atmosphere attributes of USSE have focused largely on PV [31,76,121], given their relatively larger deployment globally (65 GW of PV versus 1.5 GW of CSP; International Energy Agency, 2013).

3.1. *Utility-scale solar energy and albedo*

The radiative balance at the land-atmosphere interface can shift when the albedo of a PV solar installation differs from the former background albedo. Given their absorptivity, PV panels have an *effective albedo* (averaging 0.18–0.23), a function of its inherent reflectivity *and* solar conversion efficiency [83]. Using a fully coupled regional climate model, Millstein and Menon [76] showed that a 1 TW PV USSE installation (at 11% efficiency) in the Mojave Desert would decrease desert surface albedo, thereby increasing temperatures up to 0.4 °C. In cities, albedos average 0.15 to 0.22 and consequently installed PV arrays can potentially increase albedo for a cooling effect. Taha [121] modeled a high-density deployment of roof-mounted PV panels (i.e., a distributed scheme) in the Los Angeles Basin and found no adverse impacts on air temperature or the urban heat island and predicted up to 0.2 °C decrease in air temperatures under higher efficiency panels.

Although local- and regional-scale land-atmosphere impacts are important to consider, particularly in environmentally sensitive ecosystems, the global-scale substitution of carbon-intensive energy for solar energy cannot be understated. Nemet [84] found that when PV is substituted for fossil fuels at the global scale, the reduced radiative forcing is 30 times larger than the increase in radiative forcing from reduced albedo. Further underscoring their potential, as PV technologies increase in efficiency over time so too will their effective albedo.

3.2. *Utility-scale solar energy and surface roughness*

Changes in radiative balance can also occur due to changes in surface roughness. In the built environment, changes in roughness length (mean horizontal wind speed near the ground) is likely to be negligible given that PV panels are typically roof-embedded or resting slightly above the roof. In natural environments, specifically deserts, roughness length typically increases given the tall infrastructure of USSE plants. Indeed, Millstein and Menon [76] found that the solar arrays influenced local and regional wind dynamics up to 300 km away.

3.3. *Utility-scale solar energy and climate change*

Complicating our understanding of land-atmosphere interactions with USSE is climate change. Arguably one of the biggest challenges to the deployment of these facilities will be anticipating reductions in water resources in areas that are already water-stressed [80]. In 2009, all operating CSP facilities in the US were wet cooled [18]. Reductions in water availability will have consequences for both USSE facility operation and dust deposition on mirrors or panels (utility-scale and distributed). In places where more frequent, intense storms may occur, managing operational and ecological impacts of erosion will be an exigent concern [93].

Another part of the challenge lies in the shifting of climate envelopes and incidence of extreme weather. Photovoltaic technologies use both direct and diffuse light to convert energy from the sun into electricity, but high ambient temperatures reduce panel efficiency almost linearly (Fig. 4). Consequently, cool places with high irradiance are the best locations for capturing solar with PV [59]. Currently, combined uncertainty (i.e., standard deviation) of PV yield is roughly 8% during the PV system lifetime [123]. Uncertainty may increase if climate change projections are taken into consideration. Concentrating solar power efficiency increases linearly with increasing ambient temperature and proportionally to direct light and therefore changes in climate also impact CSP output. Indeed, site-specific favorability for PV and CSP are projected to vary over time under different climate change scenarios; for example, CSP may increase up to 10% in Europe under the Intergovernmental Panel on Climate Change A1B scenario [22].

The substitution of carbon-intensive energy sources for solar energy has enormous potential to mitigate climate change by directly reducing greenhouse gas emissions [150]. In the US, Zhai et al. [137] modeled a reduction of CO_2 emissions from 6.5% and up to 18.8%, if PV were to comprise 10% of the grid. Recently, a suite of studies harmonized (i.e., standardized and performed a meta-analysis of data from a large number of studies) current life cycle analysis literature to evaluate life cycle greenhouse gas emissions from various solar energy technologies, including upstream (e.g., resource and raw material acquisition, product manufacturing), operational, and downstream (e.g., selling and distribution of product, decommissioning and disposal) processes (Table 1). Photovoltaic solar technologies ranged from 14 to 45 g CO_2-eq kWh^{-1} [54,60], where CO_2-eq is the carbon dioxide equivalent, a measure for quantifying the climate-forcing strength of greenhouse gases by normalizing for the amount equivalent to CO_2. Concentrating solar power ranged from 26 to 38 g CO_2-eq kWh^{-1}, for parabolic trough and power tower, respectively [16]. These emission values were a magnitude of order less than greenhouse gas emissions from coal, gas, or oil Varun and Prakash [132].

4. Utility-scale solar energy co-benefit opportunities

Solar energy is one of the most promising alternatives to fossil fuels, especially as an attractive climate change mitigation option [150]. Clear-cut advantages of solar energy such as utilizing the sun as a renewable source of electrons and heat, and the reduction of air and water pollution by fossil fuels, can be complemented by additional environmental co-benefit opportunities [118,127]. Opportunities include, but are not limited to the (1) utilization of degraded lands, (2) co-location of solar panels with agriculture, (3) hybrid power systems, (4) floatovoltaics, and (5) novel panel architecture and design that serves to concomitantly conserve water and land resources (Fig. 5).

Table 1
Comparison of life cycle emissions for solar (grams of carbon dioxide equivalent per kWh) and conventional, carbon-intensive (grams of carbon dioxide per kWh) energy generation.

Conventional systems		Renewable systems[a]	
System	g-CO_2/kWh	System	g-CO_2-eq/kWh
Coal[c]	975	*Concentrating solar power*[b]	
Gas[c]	608	Parabolic trough[d]	26
Oil[c]	742	Power tower[d]	38
Nuclear[c]	24	*Photovoltaics*	
		Crystalline-silicon[e]	45
		Thin-film amorphous silicon[f]	21
		Thin-film cadmium telluride[f]	14
		Copper indium gallium Diselenide[f]	27

[a] Median values, assuming life span of 30 years.
[b] Excludes auxiliary natural gas combustion and electricity consumption.
[c] Varun and Prakash [132].
[d] [16].
[e] [55].
[f] [61].

4.1. Utilization of degraded lands

Degraded lands comprise approximately one-fourth of all land on Earth [63]. The development of "brightfields" on degraded lands [153]—including brownfields, landfills, mine sites, and other types of contaminated lands—confer several environmental co-benefits, including obviating additional land-use or land-cover change. For example, 12,000 ha of salt-contaminated agricultural land in the San Joaquin Valley (California, USA; Fig. 5a) are planned for conversion into a 2.4 GW solar power plant (www.westlandssolarpark.com). Employing water-efficient PV solar technology, the park's location stands to divert large amounts of water to active, water-stressed agricultural sites nearby; hence garnering broad support from various interest groups.

Utilizing degraded land can offer additional environmental benefits when reclamation of these lands is prioritized. On-site landscaping using native plants and soil amendments can add to ecosystem service provisioning (e.g., soil stability, C sequestration) without the use of additional water and fertilizer inputs. A 550 MW PV power plant spread over 1400 ha of private, non-prime agricultural land in San Luis Obispo (California, USA) will use economical, thin-film PV cells that operate efficiently in the relatively low light conditions characterizing this area (Fig. 5b). This mesic site reduces water consumption for panel cleaning and is also the location of an effort to re-establish the native grasslands that once dominated [6]. Under and around the panels, sheep will graze the taller grasses every two months to prevent obstruction of panels.

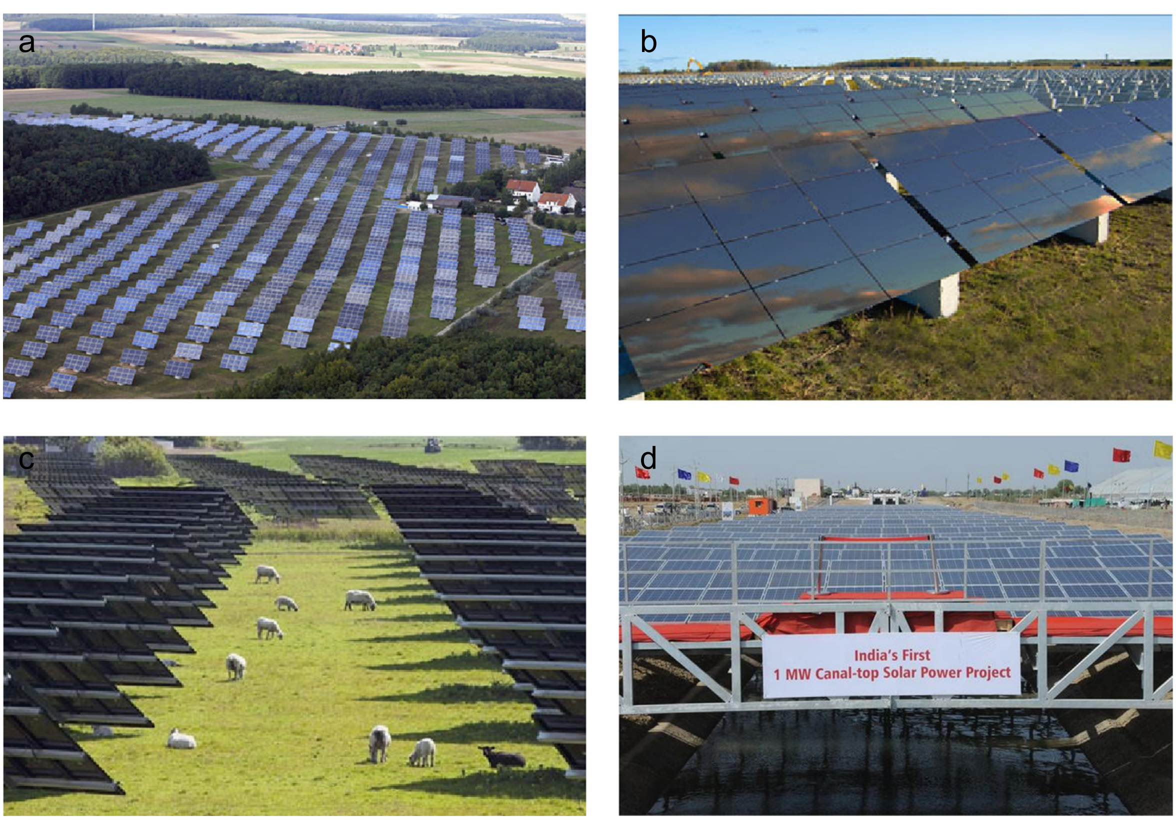

Fig. 5. Environmental co-benefit opportunities of utility-scale photovoltaic solar energy: ((a) and (b)) Utilization of degraded lands, (c) Co-locating solar energy and agriculture, and (d) Photo credits: Westlands Solar Park, Optisolar, Bert Bostelmann/Getty Images, [111].

4.2. Co-location with agriculture

Environmental co-benefits can occur when existing agricultural land is co-located with solar. With potential minimal risks to food security, co-location schemes can reduce land deficits for energy, food, and fiber production [25]. A preliminary study by Dahlin et al. [24] found that US electricity production could be met by utilizing approximately 11% of of US cropped land. The co-existence of grazing habitat for livestock, such as sheep and goats, may curtail the need for vegetation removal and maintenance, or both, and limit erosion, while supporting both energy and food/fiber production (Fig. 5c). Yet such sites need not be agricultural land *sensu stricto*. For example, Japan announced a co-location plan to diversify their grid by integrating 30 MW of PV in the unoccupied spaces adjacent to and on top of livestock barns, agricultural distribution centers, and parking lots [84]. Where land for agriculture is limited in aridlands, coupled USSE infrastructure and biofuel cultivation has been suggested as a strategy to minimize the socioeconomic and environmental issues resulting from biofuel cultivation in agricultural lands [96].

4.3. Hybrid power systems

The United States Department of Energy [130] estimates that more than one million ha of land would be required in the US to achieve the USSE 2030 SunShot scenario of 642 TW h. In the US and other countries where land is limited, co-location with other energy systems (e.g., wind, biomass, conventional thermal or natural gas power plants) may prove advantageous [115,120]. Hybridization and optimization methodologies for co-locating solar and wind power are currently being implemented in diverse geographic regions [115,120]: Charanka village in India provides an example of a wind-solar colocation region with 0.5 GW of combined wind and solar energy capacity [113]; a conventional fossil fuel 44 MW coal plant in Cameo, Colorado has been co-located with a 4 MW USSE trough for preheating feed water (IEA, [56]); and, Ordos City, Mongolia is co-locating the largest USSE facility in the world at a capacity of 2 GW PV alongside nearby wind and coal facilities [28]. Uncovering novel synergies between solar and other energy sources will continue to require diverse project implementations and industry-relevant field experiments, along with modeling studies on the energetic advantages and trade-offs of co-locating USSE with other facilities.

4.4. Floatovoltaics

A unique water-based design element is the use of “floatovoltaics”. Innovative designs for reservoir-based PV modules – such as polyethylene floating arrays that utilize elastic fasteners to adapt to varying water levels – are beginning to proliferate globally [36]. Such water-borne PV systems are also being deployed in diverse water features including the muddy waters of a wastewater treatment site (Richmond, CA; NRG [86]), a pond where electricity is generated for the adjacent vineyard located in the Napa Valley, California [116,117], and an irrigation canal in Gujarat, India (Fig. 5d; [112]). This 750-m stretch of irrigation canal in India has been covered by 1 MW of PV panels, thereby reducing the need for land transformation and conserving roughly 9-million liters of water per year owing to reduced evaporation.

4.5. Photovoltaics in design and architecture

Integrating PVs into infrastructure and architectural elements can create numerous co-benefits, first by obviating the need for additional land-use or land-cover change. One study [103] found PV noise barriers to be economically profitable when ecological benefits were included in the cost benefit analysis. Photovoltaic noise barriers originated in Switzerland in 1989, and today over 9 MW of PV noise barriers have been erected alongside rail and highway systems in Europe, Australia, and China.

In addition to ground-mounted panels, PV installation on rooftops has enhanced solar energy production as well [118]. Government incentives known as feed-in-tariffs used in 48 countries encourage the use and growth of renewable energy in both commercial and residential sectors, including PV deployment on rooftops as it has the potential to contribute energy on a utility scale. For example, the Canadian province of Ontario has begun a large-scale PV integration into infrastructure since 2009 and it is estimated that its total area of viable rooftops can produce up to 30 GW of solar energy as compared to 90 GW from ground-mounted panels in utility-scale solar plants [118]. Similar to Ontario, USSE companies in Amsterdam are capitalizing on PV integration into the built-environment through rooftop installations on residential homes [155].

While land and rooftop-based PV installations are typically connected to a grid system, PV panels can also be used to generate power for off-grid domestic and non-domestic environments [156]. This setup offers a reliable source of energy for communities and villages in remote locations that lack access to a central utility power-line. Off-grid PV systems are vital to rural communities by providing electricity for basic needs and have a particularly large impact in developing countries such as India, Indonesia, Sri Lanka, and Kenya, where only a small percent of rural communities are grid-connected [147,154].

5. Minimizing adverse impacts of solar energy: Permitting and regulatory implications

Permitting and regulatory constraints for USSE vary with land ownership (e.g., public versus private land), ecological characteristics (e.g., undisturbed versus previously degraded, critical habitat for rare species) and cultural significance [152]. From the perspective of the public, the benefits of renewable energy development ought to be weighed against the loss of ecological function, loss of public access, and the loss of irreplaceable cultural resources [126,151]. From a perspective of energy development alone, possible delays from permitting requirements and regulatory reviews may be seen as having negative effects on financial returns.

Like other forms of renewable energy, each USSE project will ineluctably have its own unique set of social, cultural, environmental, technical, and political characteristics [152]. Project implementation may be further complicated by wavering market prices for land acquisition and materials in addition to environmental regulations and legislation that may vary across county, state, and national boundaries. Collectively, the wide variation in requirements to develop USSE marks a discrepancy in solar energy implementation amongst different regions.

In general, policies underlying the development of energy systems in all countries have yet to address all key impacts and externalities. Consequently, all the actors and entities involved in a single enterprise may be working independently to minimize adverse impacts in ways not regulated or incentivized by policy. Ways to minimize impacts include: (1) understanding the environmental implications of siting decisions using adequate inventories of species and processes Tsoutsos et al. [126], (2) monetizing the actual value of natural capital and ecosystem services attributed to a parcel of land, (3) siting USSE systems on land that maximizes energetic output and minimizes economic and environmental costs Tsoutsos et al. [126] [19]), (4) having individuals and entities involved with long-term commitments to the project, and (5) requiring developers to internalize costs.

In addition, standardizing the rigidity and quality of regulations for all USSE projects may serve to streamline USSE development.

6. Solar energy and the environment: Future research

Below, we suggest a list of research questions to springboard future studies aimed at expanding our understanding of the interaction between USSE and the environment. We have developed these questions to bridge empirical gaps that were identified as a result of this review. Where applicable, we have provided citations for studies that have addressed each question, in part, or existing studies that prompted our proposed research questions. Gaps in the literature where empirical research is lacking are indicated by the absence of citations.

6.1. *Research questions addressing environmental impacts of utility-scale solar energy systems*

Direct, indirect, and regional effects on biodiversity
- How do infrastructural design, module configuration, and shape of a USSE power plant affect biodiversity?
- To what degree are native species impacted by USSE power plants? ([75]; Lovich and Ennen, [70]) Are there certain taxa, life histories, or functional types that are more compatible with USSE than others?
- To what degree does USSE infrastructure serve as a corridor or impasse for the movement of species and their genes?

Water use and consumption
- How much water is displaced from agricultural and domestic use for USSE construction and operation? [44]

Soil erosion, aeolian sediment transport, and feedbacks to energetic efficiency
- What is the relationship among USSE electrical generation, location, and dust?
- Does vegetation beneath panels reduce dust deposition on modules?

Human health and air quality
- What are best practices for use of dust suppressants, coolant liquids, heat transfer fluids, and herbicides at USSE facilities? (Lovich and Ennen,)[70].

Ecological impacts of transmission lines and corridors
- How can existing transmission infrastructure and corridors be maximized for USSE development? [39]

Land-use and land-cover change
- What are the land-use and land-cover impacts of USSE globally and compared to other energy systems? [40,51,92]
- What is the relationship between land use efficiency and reversibility? For example, is it better to arrange modules as close together as possible or spread them out? [51]

6.2. *Research questions addressing utility-scale solar energy, land-atmosphere interactions, and climate change*

Utility-scale solar energy and albedo
- To what extent can the spatial arrangement and materials of USSE infrastructure be used to enhance cooling (e.g., in urban heat islands)? ([31]; Taha, *In press*)

Utility-scale solar energy and surface roughness
- How does USSE impact local and regional wind dynamics [76]

Utility-scale solar energy and climate change
- How will climate change impact utility-scale solar energy? [22]
- What is the potential of USSE to mitigate climate change in various regions worldwide and globally [137]

6.3. *Research questions addressing utility-scale solar energy co-benefit opportunities*

Utilization of degraded lands
- To what extent are USSE power plants erected on degraded lands?
- Does USSE infrastructure (e.g., shading) and maintenance requirements (e.g., panel washing) increase soil C sequestration in degraded lands?

Co-location with agriculture
- What are the environmental tradeoffs between allocating lands to USSE development versus agriculture?
- What are the socioeconomic consequences of USSE development in agricultural areas? How does USSE development impact local food security and employment opportunities?
- Can transpiration from vegetation/agriculture reduce solar panel temperature thereby increasing efficiency?
- When combining USSE systems and agriculture, what are the effects on crop yield? [24]

Hybrid power systems
- What environmental and economic advantages and disadvantages lie in the co-location of solar energy with other energy technologies?
- How can solar hybrid energy systems be optimized? [115,120]

Photovoltaics in design and architecture
- What is the technical potential of USSE as deployed in the built environment?
- What is the cost-benefit of roof-embedded and roof-top solar, including savings derived from reduced cooling needs? [31]
- What are the economic and environmental impacts of distributed/built environment solar schemes versus USSE in undeveloped lands? Is there an ideal portfolio ratio?

6.4. *Research questions addressing permitting and regulatory implications*

- How do environmental regulations and legislation impacting USSE development vary across county, state, and national boundaries?
- How effective are renewable energy policy measures in facilitating USSE growth? [118]

7. Conclusion

Utility-scale solar energy systems are on the rise worldwide, an expansion fueled by technological advances, policy changes, and the urgent need to reduce both our dependence on carbon-intensive sources of energy and the emission of greenhouse gases to the atmosphere. Recently, a growing interest among scientists, solar energy developers, land managers, and policy makers to understand the environmental impacts – both beneficial and adverse – of USSE, from local to global scales, has engendered novel research and findings. This review synthesizes this body of knowledge, which conceptually spans numerous disciplines and crosses multiple interdisciplinary boundaries.

The disadvantageous environmental impacts of USSE have not heretofore been carefully evaluated nor weighted against the numerous environmental benefits – particularly in mitigating climate change – and co-benefits that solar energy systems offer. Indeed, several characteristics and development strategies of USSE systems have low environmental impacts relative to other energy systems, including other renewable energy technologies. Major challenges to the widespread deployment of USSE installations remain in technology, research, and policy. Overcoming such challenges, highlighted in the previous sections, will require multidisciplinary approaches, perspectives, and collaborations. This review serves to induce communication across relatively disparate disciplines but intentional and structured coordination will be required to further advance the state of knowledge and maximize the environmental benefits of solar energy systems at the utility-scale.

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