

Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States

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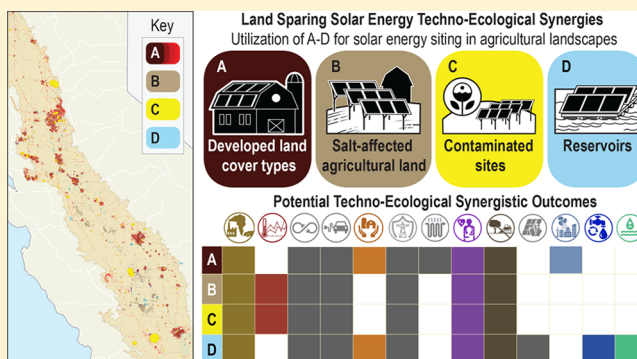
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Supporting Information

ABSTRACT: Land-cover change from energy development, including solar energy, presents trade-offs for land used for the production of food and the conservation of ecosystems. Solar energy plays a critical role in contributing to the alternative energy mix to mitigate climate change and meet policy milestones; however, the extent that solar energy development on nonconventional surfaces can mitigate land scarcity is understudied. Here, we evaluate the land sparing potential of solar energy development across four nonconventional land-cover types: the built environment, salt-affected land, contaminated land, and water reservoirs (as floatovoltaics), within the Great Central Valley (CV, CA), a globally significant agricultural region where land for food production, urban development, and conservation collide. Furthermore, we calculate the technical potential (TWh year^{−1}) of these land sparing sites and test the degree to which projected electricity needs for the state of California can be met therein. In total, the CV encompasses 15% of CA, 8415 km² of which was identified as potentially land-sparing for solar energy development. These areas comprise a capacity-based energy potential of at least 17 348 TWh year^{−1} for photovoltaic (PV) and 2213 TWh year^{−1} for concentrating solar power (CSP). Accounting for technology efficiencies, this exceeds California's 2025 projected electricity demands up to 13 and 2 times for PV and CSP, respectively. Our study underscores the potential of strategic renewable energy siting to mitigate environmental trade-offs typically coupled with energy sprawl in agricultural landscapes.



INTRODUCTION

In the 21st century, agricultural landscapes are a complex nexus in which land, energy, and water are increasingly limited and interconnected.^{1–4} Food production is intrinsically dependent on the diminishing supply of fresh water and viable land.^{5,6} The pumping of water for irrigation, dependent on declining aquifers,⁷ and other agricultural activities necessitates vast amounts of energy.⁸ In the United States, the most agriculturally productive country globally, expenses related to energy (e.g., fertilizer production and equipment manufacture and use) are one of the primary limitations of food production, while U.S. dependency on foreign energy imports imposes additional limitations.⁴ Additionally, organic emissions and those from carbon-intensive energy sources pose serious health and environmental risks to farming communities and geographically nested urban population centers.^{9–12} In response to such limitations and risks,⁴ solar energy is increasingly adopted

by farmers and other agricultural stakeholders in ways that may spare land (e.g., building integrated photovoltaics [PVs]) for food and fiber production or, conversely, place additional pressure on arable land by displacing such land for energy production.^{13,14}

Unlike conventional energy sources, solar energy can be integrated into pre-existing agricultural infrastructure and under-utilized spaces without adversely affecting commodity production or space required for such activities (e.g., edges of fields, corners of center pivot irrigation fields, and barn rooftops).^{13,15,16} Farms require energy to support machinery, electric fencing, pumping and water filtration for irrigation,

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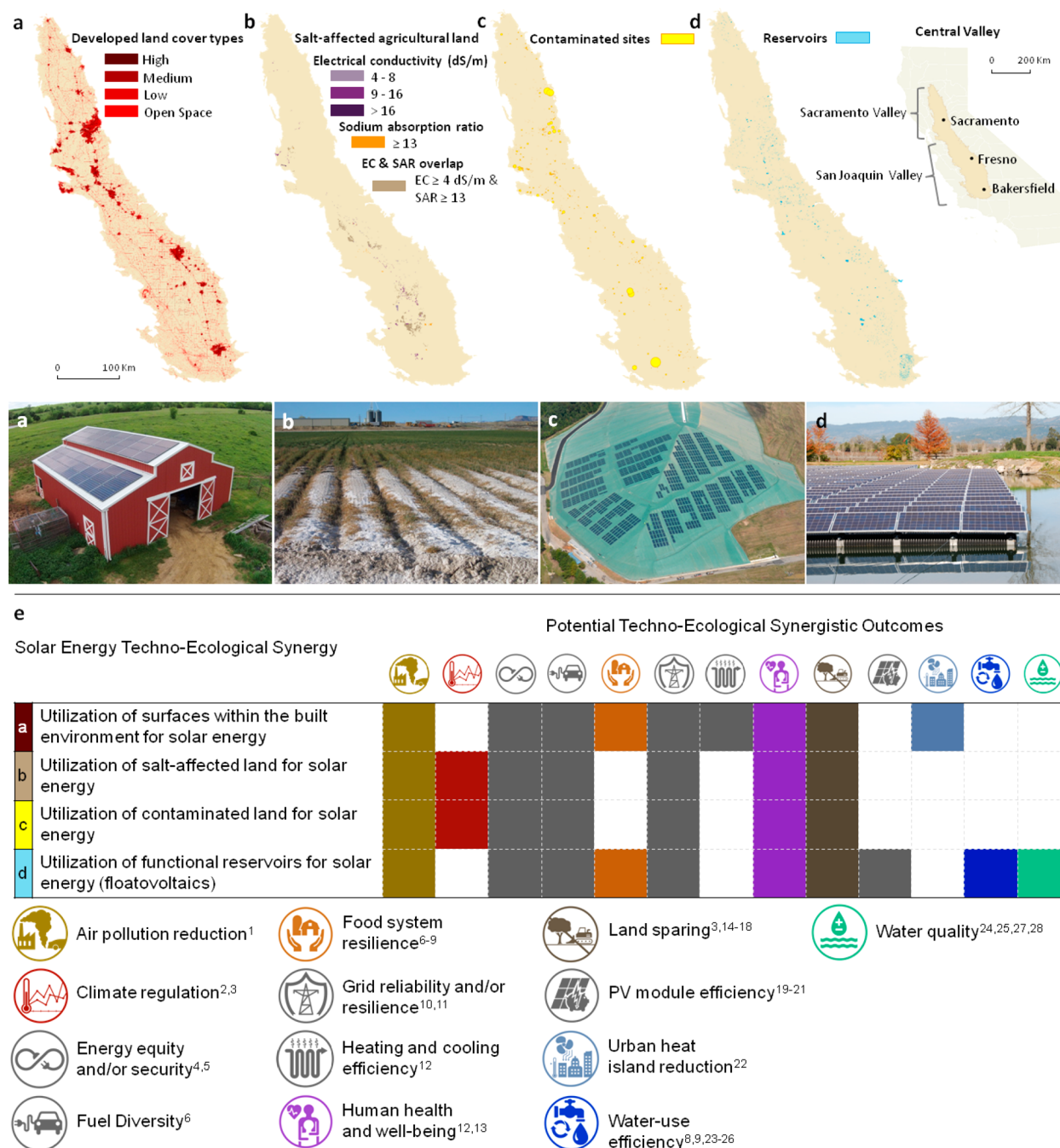


Figure 1. Land sparing solar energy siting opportunities within a 21st century agricultural landscape, i.e., California's Central Valley including within and over (a) the built environment, (b) salt-affected soils, (c) contaminated land, and (d) reservoirs. Contaminated sites are shown accurately according to their actual area but not shape. We posit that these land-sparing siting opportunities for solar energy development may also function individually (e) as a techno-ecological synergy (TES), a framework for engineering mutually beneficial relationships between technological and ecological systems that engender both techno-centric outcomes (gray icons) as well as support for sustainable flows of ecosystem goods and services (colored icons). Numbers refer to citations that provide justification for all potential techno-ecological synergistic outcomes. Larger versions of the map images are available in Figure S4. Photograph credit from left to right: (a) Cromwell Solar in Lawrence, Kansas by Aron Cromwell; (b) Donald Suarez, USDA Salinity Laboratory; (c) Carlisle Energy; (d) Far Niente Winery. All photographs are used with permission. Maps were made using ESRI ArcGIS Desktop (version 10.4) software.

drying and storing crops, lighting, powering heaters, and cooling livestock farmhouses. Previous studies have shown that on-farm solar schemes can provide farmers with reduced electricity pricing while requiring minimal water inputs (relative to other energy sources), thereby improving overall food availability and affordability.^{2,13,14}

However, when large solar industrial complexes are developed on natural or prime agricultural lands, nontrivial land-use and land-cover change (LULCC) may result.¹⁷⁻¹⁹ In California, Hernandez et al. (2015) found 110 km² of cultivated cropland and 37 km² of pasture was converted into use for ground-mounted utility-scale solar energy (USSE, ≥ 1 megawatt [MW]). In the municipality of Lecce, Italy; De

Marco et al. (2014) found that 51% of solar energy installations greater than 20 kW in capacity ($n = 42$) are sited in unsuitable areas, notably natural and agricultural areas, including century-old olive grooves.¹⁹ Reversion of a site used for solar energy generation back to agriculture is typically unlikely, complicated by long-term application of herbicides, stabilizers, gravel, chemical suppressants, and soil compaction from power plant construction and maintenance activities. Further, land lease agreements and payback periods often exceed 15 years.²⁰

The sustainability of energy, food, and water resources and the preservation of natural ecosystems are determined, in part, by how efficiently humans utilize land.²¹ While most research has focused on the negative environmental impacts of ground-mounted USSE installations,^{17,22} there is increasing attention on the design and enterprise of solar energy that produce both technological outcomes favorable for humans (e.g., energy security and fuel diversity) and benefits supporting ecosystem goods and services, including land sparing.²³ In this study, we define land sparing as siting decisions for solar energy infrastructure that obviate the need for LULCC that may have otherwise occurred within prime agricultural land and natural environments, respectively, including intermediates between these land-cover types. We posit that this framework, known techno-ecological synergy (TES), proposed by Bakshi et al. (2015),²⁴ and other studies suggest that several potential techno-ecological outcomes may be concomitantly achieved when nonconventional surfaces within agricultural landscapes are used for siting solar energy. Specifically, the utilization of geographically nested (1) urban population centers, i.e., the built environment (i.e., developed areas characterized by impermeable surfaces and human occupation), (2) land with salt-affected soils, (3) contaminated land, and (4) reservoirs may serve as recipient environments for solar energy infrastructure. These sites may also confer techno-ecological outcomes necessary for meeting sustainability goals in landscapes characterized by complex, coupled human and natural systems, such as those within agricultural landscapes. We explore these potential techno-ecological outcomes first, emphasizing the critical role these recipient environments may play in land sparing, which is the focus of our analysis (Figure 1).

Built Environments for Synergistic Solar Energy Development. Modern agricultural landscapes span 40% of Earth's surface²⁵ and are characterized by complex, heterogeneous mosaics in which natural, agricultural, and built-up elements, infrastructure, and policies intersect.^{19,26,27} Areas characterized as the built environment within agricultural landscapes have considerable potential to accommodate solar energy development: a TES that may spare land for agricultural production and conservation locally,^{17,21,28} reduce urban heat island effects,²⁹ and enhance human health and well-being, energy efficiency, and cost savings to consumers³⁰ (Figure 1). In the state of California (CA), installing small solar energy technology and USSE, including photovoltaic (PV) and concentrating solar power (CSP) technologies, throughout the built environment could meet the state's projected 2020 energy needs 3 to 5 times over.¹⁷ Integrated PV (e.g., on rooftops, vertical walls, and over parking lots) has the lowest land footprint relative to all other energy sources (0 ha [ha]/TWh/year), incurring no LULCC, thus making developed areas environmentally optimal for PV systems. Additionally, solar panels within urban areas may lower local temperatures from increased surface albedo.²⁹ Integrating solar energy

installations within such human-dominated environments generates cost savings directly from generation but also precludes energy losses from transmission and additional construction (e.g., grading, roads, and transmission) and raw material needs (e.g., grid connections, office facilities, and concrete) required for displacive ground-mounted USSE systems. For example, innovative ways of integrating PV technology, such as panels on or alongside transportation corridors (e.g., solar road panels³¹ and photovoltaic noise barriers) and clear modules replacing windows will only increase its appeal within the built environment.^{15,16,32,33}

Salt-Affected Lands for Synergistic Solar Energy Development. Naturally occurring high concentrations of salt (saline soils; Ca^{2+} , Mg^{2+} , Na^{+} , K^{+} , Cl^{-} , SO_4^{2-} , and HCO_3^{-}) or sodium (sodic soils; Na^{+} , Ca^{2+} , Mg^{2+} , Na^{+} , K^{+} , HCO_3^{-} , CO_3^{2-} , Cl^{-} , and SO_4^{2-}) combined with poor irrigation and farming practices can lead to dramatic losses in crop yield and, in severe cases, the cessation of agricultural productivity. An excess quantity of dissolved salt or sodium minerals in soil and water inhibits food production, threatens water quality, and facilitates sedimentation problems and soil erosion. Plant growth is limited by salinity due to the osmotic effect in which excess salts (e.g., chloride [Cl^{-}] and sulfate [SO_4^{2-}]) tightly attach to water molecules, inhibiting plant roots from absorbing "available" water due to the high passage resistance of the electric current. Different salts can affect growth uniquely where plant success is dependent on both the salt compound makeup and the individual plant's tolerance. A high sodium ratio (proportion of sodium [Na^{+}] relative to calcium [Ca^{2+}] and magnesium [Mg^{2+}]) is related to soil dispersion influenced by an excess of cations (Na^{+}) attaching to clay particles causing soil swelling and expansion. Overtime, sodic soils begin to solidify and lose their structure as they fluctuate between dry and moist periods, reducing soil permeability. Salinization impacts about 19.5% (45 million ha) of irrigated land, 2.1% (32 million ha) of dryland agriculture globally,³⁴ and costs the United States approximately \$12 billion a year.³⁵ Developing solar energy on salt-affected land may reduce air pollution (e.g., when substituted for carbon-intensive energy sources), while a concomitant restoration of biophysical capacity of salt-affected land (e.g., composted municipal solar waste amendments³⁶ and native halophytic vegetation out-planting) may support climate regulation. Techno-centric outcomes of solar energy on salt-affected land may include energy equity, fuel diversity, and grid reliability.^{37–39} Heckler⁴⁰ estimates soil lost to salt degradation will continue to increase at a yearly rate of about 0.8–16%, underscoring the potential long-term opportunity of salt-affected land as a potential land-sparing TES of solar energy (Figure 1).

Contaminated Land for Synergistic Solar Energy Development. Reclaiming land to provide sustainable energy has numerous potential techno-ecological outcomes including addressing public health risks, supporting climate regulation (e.g., following reclamation activities), and mitigating air pollution when solar energy generation is substituted for carbon-intensive sources of energy (Figure 1). Contaminated lands include brownfields, federal or nonfederal superfunds, and lands identified by the Resource Conservation and Recovery Act (RCRA), the Abandoned Mine Lands Program, and the Landfill Methane Outreach Program. Brownfields are areas previously designated for industrial or commercial use in which there are remnants of hazardous substances, pollutants, or contaminants. Superfund sites involve the most severely

hazardous wastes requiring federal or state government attention. The RCRA ensures toxic waste storage facility sites responsibly and properly treat, store, or dispose of hazardous waste where cleanup expectations and requirements are determined by individual state governments. Once responsibly reclaimed, a process typically facilitated by government efforts, the land can be repurposed for commercial or industrial development. Contaminated sites typically left idle for extended periods of time, have low economic value, and are challenging to cultivate,^{41,42} none of which undermine their potential for solar energy development. Examples of toxic wastelands that have been repurposed for solar energy development projects include sites formerly involving chemical and explosive manufacturing, steel production, tar and chemical processing, geothermal heating and cooling, and garbage disposal.⁴³ In the United States, the RE-Powering Initiative encourages renewable energy development on contaminated lands, and since the inception of the program, 1124 MW of renewable energy capacity is produced on 171 contaminated land sites.⁴⁴

Floatovoltaics for Synergistic Solar Energy Development. Irrigation is the largest source of water consumption globally.^{45,46} Brauman et al. (2013) found extensive variability in crop water productivity within global climatic zones indicating that irrigated croplands have significant potential to be intensified (i.e., food produced [kcal] per unit of water [L]) through improved water management.⁴⁷ The siting of solar energy panels that float on the surface of water bodies, such as reservoirs and irrigation canals, may minimize evaporation, reduce algae growth, cool water temperatures, and improve energy efficiency by reducing PV temperatures through evaporative cooling (Figure 1). There are vast opportunities for floatovoltaic deployment; collectively, lakes, ponds, and impoundments (water bodies formed by dams) cover more than 3% of the earth's surface area.⁴⁸ Reservoirs allow for relatively seamless solar energy integration compared with natural bodies of water, such as rivers, because their surfaces are relatively placid. This reduces the likelihood that panels will collide with each other or drift and break apart, allowing for easy maintenance. Additionally, unlike rivers and lakes, reservoirs are often located where energy demands are relatively high. Floatovoltaics integrate well into agricultural systems by allaying competition with land resources and providing energy and water savings. Farmers increasingly rely on agricultural ponds as water storage for irrigation, livestock, and aquaculture.⁴⁸ On-farm reservoirs are often wide but shallow making them more susceptible to water loss through evaporation.⁴⁹ Algae growth, a nutrient pollutant, is another costly nuisance for irrigation ponds that can clog pumps, block filters, and produce odors,⁵⁰ conditions attributed to further water losses that can be expensive and challenging for farmers to address. Solar panels reduce light exposure and lower water temperatures, minimizing algae growth and the need to filter water.^{51–53} Finally, when solar panels are placed over cool water instead of land, PV module efficiency may increase 8–10%⁵⁴ where increased thermal transfer limits resistance on the circuit allow the electrical current to move faster.^{55,56}

The Central Valley: A Model System for Land-Energy Interactions. The Central Valley (CV) is an ideal region in which to study land sparing benefits of solar energy TEs and to inform on broader issues related to the intersection between energy and land.⁵⁷ Located in one of the world's five mediterranean climate regions, California is valued as the largest agricultural producer within the United States,

responsible for over half of the country's fruits and nuts, and is productive year-round.^{58,59} This region also includes, in part, the California Floristic Province, an area supporting high concentrations of native and endemic species.⁶⁰ Over the last 150 years, the CV has experienced expansive LULCC owing to agricultural and urban development, which has accelerated habitat loss and fragmentation in areas of native prairies, marshes, vernal pools, oak woodlands, and alkali sink scrublands.⁶¹ Within the last 30 years, LULCC has also occurred within agricultural land owing to energy development and urbanization, a large percent of which were considered prime farmlands.⁶¹

To date, there are few studies assessing the potential of solar energy within agricultural landscapes in ways that may concomitantly facilitate synergistic outcomes on technological and ecological systems beyond avoided emissions.^{62,63} In this study, we sought to (1) evaluate the land sparing potential of solar energy development across four nonconventional land-cover types: the built environment, salt-affected land, contaminated land, and water reservoirs, as floatovoltaics, within the Great Central Valley (CV, CA) and (2) quantify the theoretical and technical (i.e., generation-based) potential of PV and CSP technologies within the CV and across these potential solar energy TEs to determine where technical potential for development is greatest geographically. Further, we sought to (3) determine the spatial relationship of land sparing areas with natural areas, protected areas, and agricultural regions designated as important to determine the proximity of these opportunities to essential landscapes that may have otherwise be selected for energy siting and development. Next, we (4) analyze the spatial density of contaminated sites within 10 km of the most populated CV cities to elucidate relationships between attributes (number and size) of nearby contaminated sites potentially favorable for solar energy generation and urban development centers because urban density is an explicative factor determining electricity consumption for cities.⁶⁴ Lastly, we (5) test the degree to which current and projected (2025) electricity needs for the state of California can be met across all four potential land sparing opportunities.

METHODS

Theoretical and Technical Solar Energy Potential for PV and CSP Technologies. The theoretical, or capacity-based, solar energy potential is the radiation incident on Earth's surfaces that can be utilized for energy production, including solar energy.⁶⁵ We used two satellite-based radiation models developed by the National Renewable Energy Laboratory (NREL) and Perez et al.⁶⁶ to estimate the theoretical solar energy potential of PV and CSP technologies operating at their full, nominal capacity over 0.1° surface cells (~10 km in size).

Photovoltaic technologies use both direct and indirect radiation, while CSP uses only direct-beam radiation. Therefore, the radiation model we used for CSP capacity-based energy estimates is representative of direct normal irradiance (DNI) only, whereas the PV model incorporates both DNI and diffuse irradiance. Areas with DNI values of less than 6 kWh m⁻² day⁻¹ were not considered economically adequate for CSP deployment and therefore excluded from solar potential estimates (Figure S1).

To evaluate the technical, or generation-based, solar energy potential within identified areas for land-sparing PV development, we multiplied the theoretical potential by a capacity

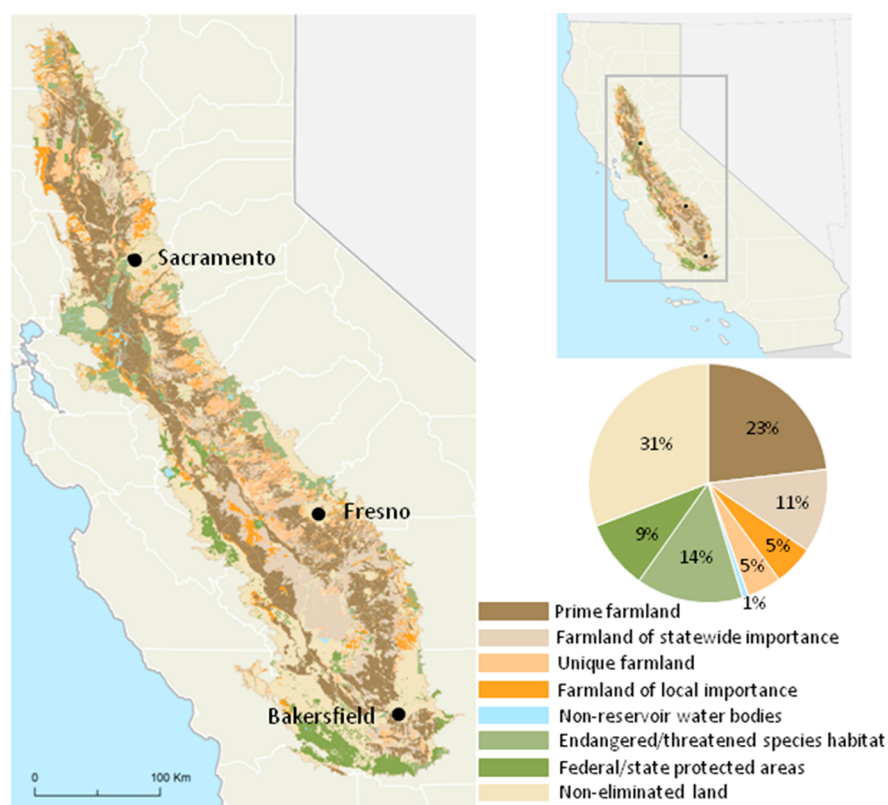


Figure 2. Map of California showing land-cover types eliminated when identifying solar energy potential over salt-affected soil. The pie graph depicts the relative proportion of area that each land cover type makes up within the Central Valley, which is not visible in the map due to overlap (e.g., areas identified as both endangered species habitat and state-protected). Land-cover types include: important farmlands (prime, unique, and of state-wide or local importance), nonreservoir bodies of water, endangered and threatened species habitat, federally and state-protected land, and non-eliminated land that was further evaluated for solar energy potential. The map was made using ESRI ArcGIS Desktop (version 10.4) software.

factor. The capacity factor values are derived from a satellite-based, spatially explicit capacity factor model⁶⁷ that has identical cells as the radiation models described above. The PV capacity factor model comprises estimates for three primary technology subtypes including fixed mount, south facing with a 25° tilt (TILT25); one-axis tracking, rotating east–west with a $\pm 45^\circ$ maximum tracking angle (AX1FLAT); and two-axis tracking, rotating east–west and north–south of the sun across the horizon (AX2). For CSP generation-based calculations, we incorporated a five DNI class value scheme resembling estimates for a trough system.⁶⁸ Full details are provided in the [Supplementary Methods](#).

Next, we calculated solar energy potential for both small and large-scale solar energy projects, where a minimum parcel size of 28 490 m² and 29 500 m² were required for PV and CSP facilities, respectively, producing 1 MW or more. These values are based on the average USSE land-use efficiency of 35.1 and 33.9 W m^{−2} for PV and CSP, respectively.⁶⁹ All CSP installations are utility-scale, and therefore, only these data are reported.

Solar Energy Potential of Land Sparring Opportunities in the Central Valley. We delineated the CV (58 815 km²) based on the Great Central Valley Region⁷⁰ (Figure 1), composed of the geographic subdivisions of the Sacramento Valley, San Joaquin Valley, and all Outer South Coast Ranges encompassed within the San Joaquin Valley polygon. We overlaid the PV and CSP radiation models with the four land sparing land-cover types within the CV and calculated total area (km²) and solar energy potentials (TWh year^{−1}). Across the

salt-affected land solar energy TESSs, we eliminated lands protected at the federal and state levels and threatened and endangered species habitats (Figure 2). Furthermore, all water bodies (e.g., wetlands and rivers), occurring in salt affected areas, with the exception of reservoirs, were removed as they may function as essential habitats for birds and other wildlife. Salt-affected soils within farmlands identified as primary, unique, or of state-wide or local importance⁷¹ were also not included in the final estimates for solar energy potential. See the [Supplementary Methods](#) for explicit details on data and analysis for each land-cover type.

Spatial Relationships between Synergies and across Land-Cover Types. To ensure that energy potentials were not double-counted (e.g., salt-affected lands within the built environment), we calculated the spatial overlap across three solar energy TESSs. Specifically, we observed overlap of land sparing potential among the built environment, salt-affected regions, and reservoirs. We did not include Environmental Protection Agency (EPA) contaminated sites because such data is not absolutely spatially explicit, but instead, each site is modeled circularly, in known total area, outward from a centroid based on known latitude and longitude coordinates, which may not represent each site's actual boundaries. Overlap between contaminated sites and land classified as salt-affected may be the most unlikely as most actions at these sites focus on preventing human contact.⁴¹ Nonetheless, we did count 17 (189.5 km²), 3 (2.5 km²), and 740 (332.8 km²) contaminated sites that may potentially overlap with salt-affected land, reservoirs, and the built environment, respectively, but we did

Table 1. Contaminated Site Attributes across the Ten Most-Populated Cities Within the Central Valley, CA

city	city population	city area (km ²)	contaminated sites within city	contaminated sites within 10 km of city	contaminated site area within 10 km (km ²)
Fresno	494 665	112	38	58	21
Sacramento	466 488	98	83	140	47
Bakersfield	347 483	142	10	32	8
Stockton	291 707	62	53	95	35
Modesto	201 165	37	19	55	28
Elk Grove	153 015	42	27	71	52
Visalia	124 442	36	36	46	9
Concord	122 067	31	9	60	107
Roseville	118 788	5	8	60	75
Fairfield	105 321	37	10	26	34

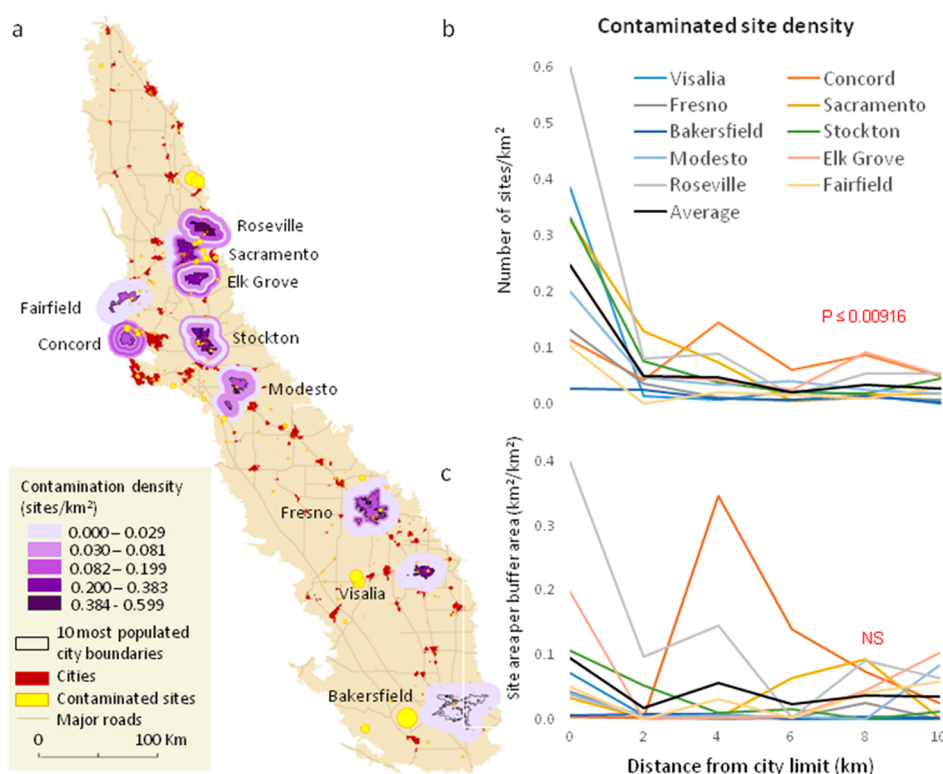


Figure 3. (a) Density of contaminated sites (circular points representing their total area but not shape; number of sites per square kilometer) within the Central Valley's (beige polygon) 10 most-populated cities: (1) within city limits (black line) and (2) across 0–2, 2–4, 4–6, 6–8, and 8–10 km buffers beyond city borders (purple buffers). Graphs show (b) the density of contaminated sites (sites per square kilometer) and (c) the total area of sites as a function of distance from city limits of the 10 most-populated cities in California's Central Valley. Land within each city boundary has a significantly greater number of contaminated sites based on total count (posthoc Tukey test, $P \leq 0.00916$) than buffer classes beyond the city perimeter (number of sites per square kilometer). No significant relationship exists between contamination site area and distance from urban cores. The map was made using ESRI ArcGIS Desktop (version 10.4) software.

not account for this overlap in the final values. We also enumerated spatial relationships between synergistic sites and other land-cover types throughout our analysis to determine the proximity of these opportunities to essential landscapes that may have otherwise been selected for energy siting and development.

Spatial Density and Proximity of Contaminated Lands to Human Populations. To elucidate relationships between attributes (number and size) of nearby contaminated sites potentially favorable for solar energy generation and urban development centers, we first identified the 10 most-populated cities within the Central Valley. We added 5 buffer distances around the perimeter of each city at 2 km increments up to 10 km (i.e., 2, 4, 6, 8, and 10 km). Within cities and each of these

buffered rings (e.g., area between 4 and 6 km beyond city limits), we calculated the area and divided the number and area of contaminated sites that fall within each buffer by its associated area (site km⁻² and site area [km²] km⁻²). We included any sites located outside of the CV within 10 km of the city analyzed. Contaminated sites that were in a 10 km radius of more than one of the 10 highly populated city were included in each density analysis. We used generalized linear models (GLMs) to test the effects of distance class on contaminated site metrics (i.e., count and area) and to observe if sites are generally located near, further away, or have no association with urban development centers, which serve as a proxy for electricity demand. Contaminated sites that were within a 10 km radius of multiple cities were observed

Table 2. Number of Times over PV and CSP Solar Energy Technologies Can Meet California's Projected Electricity Consumption Needs for 2025 (321 TWh) Based on Land-Sparing Opportunities within the Central Valley, CA: (1) Developed, (2) Salt-Affect Soil, (3) Reservoirs, and (4) Contaminated Sites^a

land-cover type ^b		PV				CSP	
		distributed and USSE		USSE only		USSE	
		capacity-based (times over)	generation-based (times over)	capacity-based (times over)	generation-based (times over)	capacity-based (times over)	generation-based (times over)
Central Valley		378.6	68.1–83.4	378.6	68.1	398.2	129.7
DNI ≥ 6 kWh m ⁻² day ⁻¹		–	–	–	–	135.4	46.9
developed	high intensity	2.8	0.5–0.60	1.5	0.3	–	–
	medium intensity	10.8	1.9–2.35	7.5	1.3–1.6	–	–
	low intensity	9.3	1.7–2.02	1.6	0.3–0.4	0.2	0.1
	open space	19.2	3.5–4.2	6.2	1.1–1.4	1.9	0.7
salt-affected soil	EC ≥ 4 and ≤ 8	0.6	0.1	0.6	0.1	0.2	0.1
	EC > 8 and ≤ 16	0.8	0.1–0.2	0.8	0.1–0.2	0.3	0.1
	EC > 16	0.1	0.0	0.1	0.0	0.0	0.0
	SAR ≥ 13	0.2	0.0	0.2	0.0	0.0	0.0
	overlap (EC ≥ 4 and SAR ≥ 13)	3.9	0.7–0.9	3.9	0.7–0.9	1.4	0.4
reservoirs		0.7	0.1–0.2	0.6	0.1	–	–
contaminated		7.1	1.3–1.6	7.0	1.3–1.6	3.0	1.0
total		55.4	9.9–12.1	30.1	5.4–6.6	7.0	2.4
overlapping areas		1.3	0.2–0.3	0.6	0.1	0.1	0.0
total (accounting for overlapping areas)		54.1	9.7–11.8	29.5	5.3–6.5	6.9	2.4

^aCapacity-based potential is representative of the full energy potential offered from the sun, whereas the generation-based potential estimates the energy potential given current technology capabilities including three PV system types (tilt, one-axis tracking, and two-axis tracking panels) and a CSP trough technology. ^bTotal energy potentials account for overlaps in land-cover types to avoid double-counting.

separately and therefore accounted for more than once. See the [Supplementary Methods](#) for further details.

RESULTS AND DISCUSSION

We found that 8415 km² (equivalent to over 1.5 million American football fields) and 979 km² (approximately 183 000 American football fields) of non-conventional surfaces may serve as land-sparing recipient environments for PV and CSP solar energy development, respectively, within the great CV and in places that do not conflict with important farmlands and protected areas for conservation ([Figure 1](#) and [Tables 1](#) and [Supplementary Table 1](#)). This could supply a generation-based solar energy potential of up to 4287 TWh year⁻¹ for PV and 762 TWh year⁻¹ for CSP, which represents 2.8 (CSP) – 14.4% (PV) of the CV area. We accounted for 203 km² of overlap across the built-environment, reservoirs, and salt-affected areas, the latter after eliminating land classified as protected areas (federal and state), critical and threatened habitats, and important farmlands from salt-affected soils.

In total, the CV encompasses 58 649 km² of CA, about 15% of the total land area in the state, and has a theoretical potential of 121 543 and 127 825 TWh annually for PV and CSP, respectively ([Table S1](#)). Considering areas with solar radiation high enough to economically sustain a CSP solar energy facility (locations with a DNI of 6 kWh m⁻² year⁻¹), less than one-third ($\sim 19\,000$ km²) of the CV is suitable for CSP deployment, and a capacity-based potential of about 44 000 TWh year⁻¹.

Among the potential solar energy TESs we studied, the built environment offers the largest land sparing potential in area with the highest solar energy potential for PV systems ([Figure 1a](#)), representing between 57% (USSE only) and 76% (small-scale to USSE) of the total energy potential for PV. If only USSE PV systems are considered for development, roughly half

of the total built environment is suitable, a constraint owing to areas not meeting minimum parcel requirements for a one MW installation (28 490 m² or greater). Specifically, installing PV systems across the built environment could provide a generation-based potential of 2413 TWh year⁻¹ utilizing fixed-tilt modules and up to 3336 TWh year⁻¹ for dual-axis modules ([Table S2](#)). Using CSP technology, both the low-intensity developed and the open spaces within the built environment could yield 242 TWh year⁻¹ of generation-based solar energy potential ([Table S1](#)). For CSP, the built environment represents 30% of all energy opportunity for the land-sparing solar energy TESs we studied.

Land with salt-affected soils, another potential land sparing solar energy TES, comprises 850 km² of the CV, excluding areas identified as important for agriculture and conservation ([Figure 2](#)). This remaining salt-affected land makes up 1.5% of the CV region. Generally, regions with high concentrations of salt also have unsuitable levels of sodium. Indeed, we found that 70% of sodic and saline soils overlap; occurring in the same place ([Table S2](#)). Geographically, most salt-affected land sparing opportunities suitable for solar energy development are within the interior region of the CV, away from the built environment ([Figure 1c](#)).

We found that 2% (1098 km²) of the CV is composed of contaminated lands with a generation-based potential of 407 and 335 TWh year⁻¹ for PV and CSP, respectively. A total of 60% of these sites are clustered within and near (<10 km) the 10 most-populated cities, a buffer area composed of 21% of the CV (inclusive of buffer areas of cities extending beyond the CV border; [Figure 3a](#) and [Table 1](#)). We found that across the top 10 most-populated cities, population was significantly positively related to the number of contamination sites (GLM, t value of 2.293, $P = 0.025916$). We also found that land within each city

boundary has a significantly greater number of contaminated sites based on total count (post-hoc Tukey test, $P \leq 0.00916$; Figures 3b and S2) than buffer classes beyond the city perimeter (number of sites per square kilometer; Figure 3b). We found no statistical relationship between contamination site area and distance from urban cores (Figure 3c). Note that in addition to the 953 contaminated sites quantified for solar energy potential, 51 more sites are included in the density analysis that reside outside of the CV boundary but are within 10 km of cities and 46 of the contaminated sites (Table 1) are accounted for multiple times because they are within the 10 km radius of multiple cities. Lastly, contaminated lands are particularly attractive for USSE projects, and indeed, 412 and 411 of the 953 contaminated sites from the EPA data set pass the minimum area requirement for supporting utility-scale PV and CSP technologies, respectively (Figure 3). Although our emphasis here was relationships between contaminated sites and urban development cores, more-robust analyses exploring spatial relationships between contaminated sites and population at the regional scale may be useful.

Reservoirs comprise 100 km² of available surface area for solar energy, just 0.2% of the total land area in the CV. The integration of fixed-tilt PV panels across all reservoir surface area would provide a generation-based energy potential of 39 TWh year⁻¹ (Table S1). There are roughly 4300 reservoirs within the CV, 2427 (56%) and 986 (23%) of which are classified as water storage and reservoirs, respectively (Figure S3). These water body types are the greatest targets for floatovoltaic development, and together, they make up roughly 66% of the total surface area of all reservoirs in the CV. While 66% of reservoirs identified in the CV are highest priority, the remaining 38% are treatment, disposal, and evaporator facilities, aquaculture, and unspecified reservoirs (Figure S3). In CA, farmers and water pump stations consume 19 TWh of electricity annually;⁷² based on estimated energy potential for floatovoltaics, reservoirs provide enough surface area to supply 2 times the electricity needs of farmers or water pump stations for CA (19 TWh).⁷²

California's projected annual electricity consumption needs for 2025, based on moderate assumptions, is 321 TWh.⁷³ The land-sparing solar energy TESs we explore in this study could meet CA's projected 2025 needs for electricity consumption between 10–13 times over with PV technologies and over two times over with CSP technologies (Table 2). In fact, each land-sparing TES individually can be used to meet the state's energy needs with the exception of reservoirs, which would provide enough surface area to produce electricity to meet 10–20% of CA's 2025 demands. However, reservoirs do offer enough surface area and potential to meet electricity needs within California's agriculture sector (i.e., 19 TWh annually).⁷² CSP systems are confined to limited areas within the CV and therefore offer relatively less energy potential than PV; yet still, contaminated lands alone offer adequate space for CSP technologies to meet projected electricity needs for 2025.

Our study found contaminated sites are clustered within or near highly populated cities, many with populations that are projected to rapidly expand owing to urban growth. Thus, contaminated sites may serve as increasingly desirable recipient environments for solar energy infrastructure within the CV of California and agricultural landscapes elsewhere. The mission of the Environmental Protection Agency's (EPA) RE-Powering initiative is to increase awareness of these contaminated sites by offering tools, guidance, and technical assistance to a diverse

community of stakeholders. Already, this program has facilitated development from 8 renewable energy projects in 2006 to nearly 200 today.⁴⁴ Across the United States alone, there are over 80 000 contaminated sites across 175 000 km² of land identified as having renewable energy potential, emphasizing the opportunity to repurpose under-utilized space. Given the globally widespread policy-based adoption of managing hazards in place, allowing for the less than complete remediation of environmental hazards on contaminated sites; the benefits of this TES must be weighed against risks assessed from indefinite oversight and monitoring.⁴¹

There are few studies or cost–benefit analyses on solar energy over functional water bodies that empirically and quantitatively assess the potential for synergistic outcomes related to water (e.g., water quality), energy, and land. Farmers frequently build water reservoirs to cope with limits on water allotment during drought periods,⁷⁴ offering opportunities for dual-use space for solar panels. Although floatovoltaics are increasing in popularity, particularly in Asia, where the largest floating solar installation exists,⁷⁵ more-comprehensive environmental impact assessments are needed to quantify beneficial outcomes (e.g., reductions in evaporative loss) and address risks. One concern is that avian species may perceive PV modules as water, known as the “lake effect,” leading to unintended collisions and possibly injury or mortality.

In 2015, installed capacity of solar energy technologies globally reached 220 GW driven by relatively high average annual growth rates for PV (45.5%, 1990–2015) and CSP (11.4%) compared with other renewable energy systems.^{76,77} At these rates, trade-offs between land for energy generation and food production in an era of looming land scarcity may be high⁹ when developed without consideration of impacts to land, including food and natural systems. For example, in the United States alone, an area greater than the state of Texas is projected to be impacted by energy development and sprawl, making energy the greatest driver of LULCC at a pace double the historic rate of residential and agricultural development by 2040.²⁸ California aims to derive half of its electricity generation (160 TWh) from renewable energy sources by 2030, and we show that the CV region can supply 100% of electricity needs from solar energy without compromising critical farmlands and protected habitats.

The extent to which agricultural landscapes can sustain increasing demand for agricultural products and transition to becoming a major solution to global change type threats instead of contributing to them depends on several factors; however, the manner in which land, energy, and water resources are managed within such landscapes is arguably the decisive factor.^{4,78} Our study reveals that the great CV of California could accommodate solar energy development on nonconventional surfaces in ways that may preclude loss of farmland and nearby natural habitats that also support agricultural activities by enhancing pollinator services (e.g., wild bees) and crop yields.^{79,80} Given the diffuse nature of solar energy, advances in battery storage would likely only enhance the economic and environmental appeal of the four solar energy TES we evaluated.^{81,82} The realization of this potential may also confer other techno-ecological synergistic outcomes (as characterized in Figure 1), and additional research could be conducted to improve the certainty and accuracy of these potential benefits. For example, the degree to which realization of solar energy potential in agricultural landscapes on nonconventional surfaces contributes to food system resilience⁸³ by alleviating competi-

tion of valuable land among farmers, raising property values, generating clean energy for local communities, enhancing air quality, and providing new job opportunities^{14,62} remains largely unexplored.

Other factors impacting the sustainability of agricultural landscapes include the level of funding to support research and development, collaboration across public and private sectors to advance technology and innovation, and policies that bolster decisions and action leading to appropriate renewable energy siting. Research efforts have increasingly focused on identifying where and how renewable energy systems can be sustainably integrated into complex landscapes with environmentally vulnerable ecosystems,^{21,22,84–86} but less emphasis has been on decisions with agricultural landscapes^{19,78,84,85} despite its importance to food security and nutrition. In the US, the National Science Foundation is prioritizing the understanding of food, energy, and water interactions, identifying it as the most pressing problem of the millennium, but land has remained underemphasized in these programs.⁸⁷ Policies that result in cash payments to growers and solar energy developers for land sparing energy development could facilitate, indirectly, the conservation of important farmlands and natural areas. Federal policy could provide the financial support to state and local governments to protect natural and agriculturally critical areas, and decisions can be tailored at these administrative levels to accommodate the land use and water rights unique to the region.

California's Great Central Valley is a vulnerable yet indispensable region for food production globally. Our analysis reveals model options for sustainable solar energy development via use of nonconventional surfaces, i.e., the built environment, salt-affected land, contaminated land, and water reservoirs, as floatovoltaics. These land sparing solar energy development pathways may be relevant to other agricultural landscapes threatened by trade-offs associated with renewable energy development and sprawl.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b05110.

Detailed information about methods and data used for analysis in this study. Figures showing the effect of distance from the 10 most-populated cities, water reservoirs in the Central Valley, theoretical solar radiation potential, and maps of land-sparing solar energy. Tables showing utility-scale solar energy potential and photovoltaic energy potential.(PDF)

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Notes

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