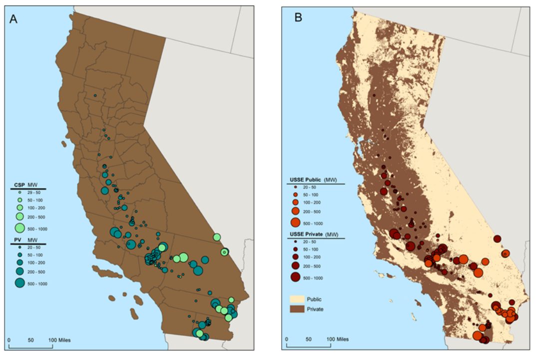
Environmental Science & Technology
Article
pubs.acs.org/est

Land-Use Efficiency of Big Solar

Rebecca R. Hernandez,[†,§,*] Madison K. Hoffacker,[‡] and Christopher B. Field[†,§]

[†]Department of Environmental Earth System Science, Stanford University, Stanford, California 94305, United States
[§]Department of Global Ecology, Carnegie Institution for Science, Stanford, California 94305, United States
[‡]Schmid College of Science and Technology, Chapman University, Chapman, California 92866, United States



ABSTRACT: As utility-scale solar energy (USSE) systems increase in size and numbers globally, there is a growing interest in understanding environmental interactions between solar energy development and land-use decisions. Maximizing the efficient use of land for USSE is one of the major challenges in realizing the full potential of solar energy; however, the land-use efficiency (LUE; Wm^{-2}) of USSE remains ambiguous. We quantified the capacity-based LUE of 183 USSE installations (>20 MW; planned, under construction, and operating) using California as a case study. In California, USSE installations are concentrated in the Central Valley and interior regions of southern California and have a LUE of 35.0 Wm^{-2}. The installations occupy approximately 86 000 ha and more land is allocated for photovoltaic schemes (72 294 ha) than for concentrating solar power (13 604 ha). Photovoltaic installations are greater in abundance (93%) than concentrating solar power, but technology type and nameplate capacity has no impact on capacity-based LUE. More USSE installations are on private land (80%) and have a significantly greater LUE (35.8 Wm^{-2}) than installations on public land (25.4 Wm^{-2}). Our findings can be used to better understand and improve the LUE of USSE, thereby maximizing economic, energetic, and environmental returns on investments.

INTRODUCTION

In the past decade, the capacity of photovoltaic (PV) and concentrating solar power (CSP) energy has risen exponentially and globally; notably in Germany, Spain, Japan, Italy, and the United States[1] (Figure 1). The expansion of solar energy development, particularly for utility-scale solar energy (USSE)—solar energy systems that exceed one megawatt (MW) in capacity—has increased interest in understanding ecological interactions with solar energy development, and how impacts may augment, reduce, or interact with drivers of global environmental change,[2−4] including land-use change.[2,3,5−9] Like cost and generation intermittency, maximizing the efficient use of land for USSE projects is one of the major challenges in realizing the full potential of solar energy development.[5,10,11]

All solar energy systems can be classified as either distributed or utility-scale, with the distinction determined by a project's size and location. Although this distinction can be tenuous, distributed systems are typically sized to meet a small, localized energy demand and may function independent of the grid (Figure 1a). These systems usually require little to no ancillary facilities, often utilizing pre-existing infrastructure within the built environment[11,12] (e.g., residential, governmental, and commercial rooftop photovoltaic systems; solar water heating systems; portable battlefield and tent shield devices). In contrast, USSE installations are large, centralized enterprises with large economies of scale. As such, they necessitate large swaths of flat space, creating trade-offs in places where development may compromise the sustainability of natural resources and reduce the provision of ecosystem services (Figure 1b). Such trade-offs can reduce or negate the overall return on investment, if one integrates across economic, energetic, and environmental returns.[2,5] Utility-scale solar energy systems that exceed 20 MW are becoming increasingly common and very large-scale installations, one gigawatt in size or greater, have been proposed.[13]

Within an installation site, the footprint of a solar energy system includes all areas directly transformed or impacted by the installation during its life-cycle from construction to decommission. Areas that are indirectly affected by solar energy systems (e.g., extraction or mining of raw materials offsite) are separate from this life-cycle analysis. Fthenakis and Kim[14] reported that the total land area that is indirectly transformed for multi-, mono-, and ribbon-Si systems (over a 30 year period using an insolation of 1800 KWh m^{-2} $year^{-1}$) is minor compared to direct land-use at 18.4, 18, and 15 m^2 GWh^{-1}, respectively. Photovoltaic panels and CSP mirrors are distributed uniformly across space—typically double the panel area[15]—and in rows, to preclude self-shading and allow for easy access and service (often by vehicles), but increasing the footprint. For example, PV arrays are not arranged flat, but are typically installed on tilted (fixed-tilt) or moving (e.g., single-axis or dual-axis tracking) frames to increase solar interception up to 50% more than flat arrays, but creating a

Received: July 11, 2013
Revised: December 5, 2013
Accepted: December 18, 2013
Published: December 18, 2013

dx.doi.org/10.1021/es4043726 | *Environ. Sci. Technol.* 2014, 48, 1315−1323

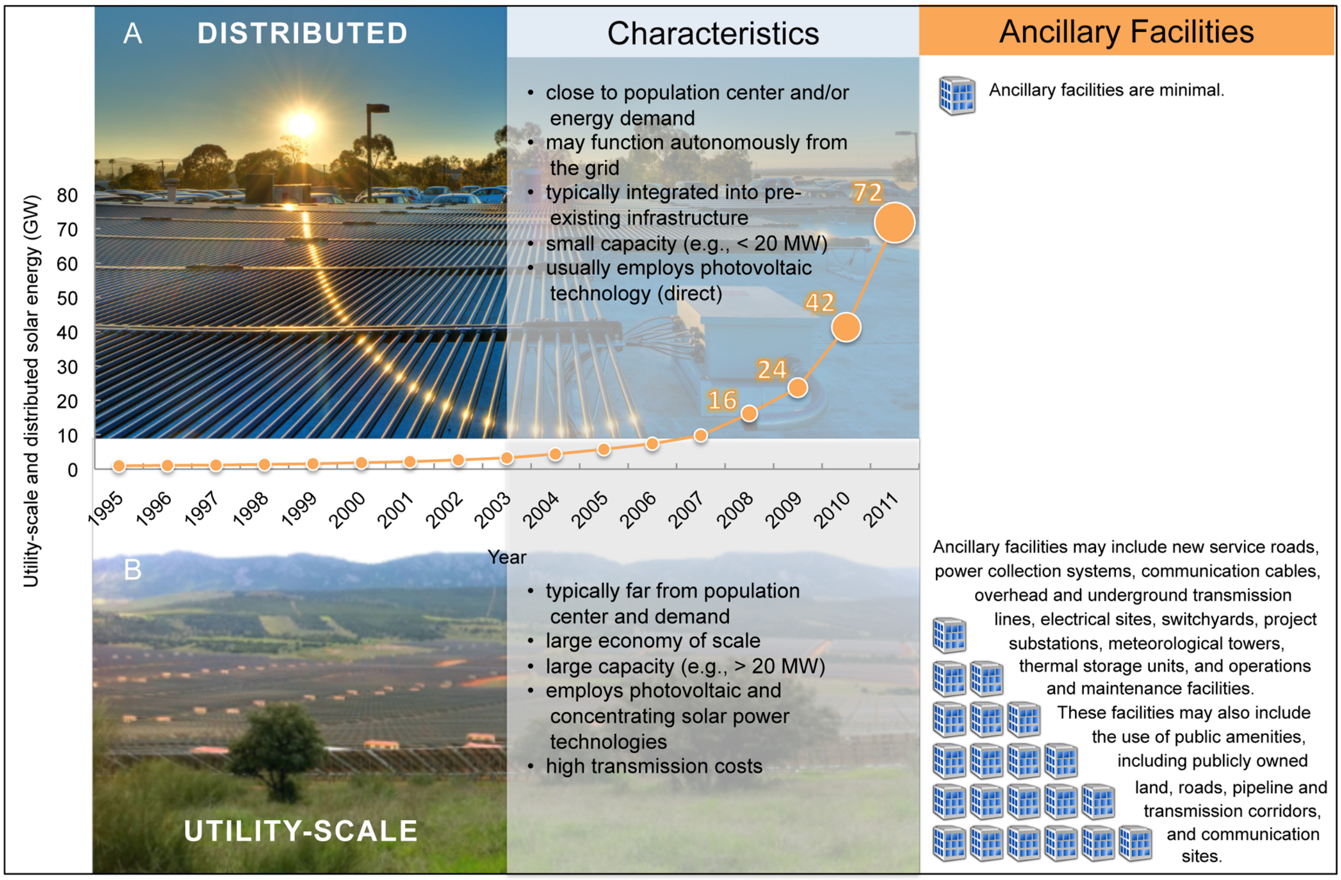


Figure 1. Graph shows utility-scale and distributed solar energy global installed capacity in gigawatts (GW) over time. Characteristics and ancillary facilities required of distributed (A) and utility-scale (B) solar energy systems. Photo credits: (top) Doug Kop; (bottom) Rebecca R. Hernandez.

trade-off between the cost of land and maximizing energetic yield.[6] The use of ancillary facilities adds to the land area required (see Figure 1 for complete list) and when appropriate may include publicly owned roads, pipelines, transmission corridors, and communication sites.

Consequently, maximizing the capacity and land-use efficiency (LUE) of USSE installations globally may serve to mitigate atmospheric CO_2 levels by reducing both direct and indirect emissions. Indirect emissions may be reduced by (1) reductions in land-use change, and (2) where solar energy substitutes for existing energy infrastructure, such land may transition into uses that increase carbon uptake (e.g., afforestation). Incorporating sustainable practices and conservation-compatibility into USSE development can further mitigate or obviate adverse environmental effects beyond those related to land-use impacts.[5,9,11,16]

The capacity-based (or nominal) LUE is the USSE installation's power by area (e.g., $\mathrm{Wm^{-2}}$) and is therefore a function of the project's spatial design and nameplate capacity. Capacity-based LUE data are useful for estimating land and cost requirements, and such data are useful as efficiency targets for new projects.[8] When realized generation data are available, some studies have reported generation-based LUE (e.g., $\mathrm{m^2\ GWh^{-1}}$), which is a function of a plant's location (e.g., climatic conditions and solar resources), technological efficiency, and thermal energy storage, the latter enabling the instantaneous capacity to exceed the nameplate (turbine) capacity.[8,17] Generation-based LUE data provides the greatest accuracy for more detailed comparisons, such as those between subtechnology types, and technology and storage options, despite the fact that generation may vary from one year to the next. Studies vary in the type of LUE they report, the data and methods they use to derive it, and the units they use to report their findings (e.g., $\mathrm{m^2\ GWh^{-1}}$,$\mathrm{(m^2{-}year)\ MWh^{-1}}$), which adds some confusion across studies (see Horner and Clark 2013)[18] and difficulty in deriving synthetic and comparative conclusions.

To date, studies quantifying LUE using specifications of more than one installation,[7,19] exploring the effects of land tenure, and using official records and documents[8] are few and the results, overall, are ambiguous.[18] However, quantifying the relationship between solar energy and land use is critical for understanding: (1) how USSE power plant configuration and design impact LUE; (2) effects on radiative forcing and the atmospheric boundary layer resulting from changes in surface roughness and albedo caused by USSE infrastructure;[20] (3) ecological consequences of the construction, operation, and decommissioning of USSE power plants; and (4) USSE power plant configuration and design necessary to integrate/colocate different energy systems for efficient use of land and water resources.

In this study, our goal was to quantify the capacity-based LUE (i.e., watts in nameplate capacity, per meter squared) and spatial distribution of USSE installations using California as a case study. We also report how LUE of USSE in California interacts with technology type, capacity, and land ownership (publicly or privately owned), as well as the implications of this land ownership type for land-use change. Lastly, we discuss mechanisms for increasing LUE and return on investment of

USSE development, including examples that integrate environmental cobenefits.

MATERIALS AND METHODS

California As a Case Study. We use California as a case study for assessing the land-use properties of USSE. California is interesting not only because it has been a leader in adoption of renewable energy systems and adaptation strategies,[21] but also for its increasing population, unique constraints on land availability, immense energy demand,[22] and vulnerability to climate change.[23,24] California has been at the vanguard of global USSE deployment since the early 1980s and a center of focus over solar energy-related land use decisions.[3,25] For example, California:

- is the site of the largest concentrating solar power plant in the world[26] (the 354 MW Solar Energy Generating Systems);
- is the site of the first multimegawatt concentrating solar power plant[26] (the 14 MW SolarOne power tower plant);
- is where 25 000 ha of USSE projects are required in the Desert Renewable Energy Conservation Plan area to meet 2040 greenhouse gas reduction goals;[27]
- if a country, would rank seventh for PV and includes over 2500 MW of installed solar energy capacity;[28] and
- leads the total installed capacity for U.S. military installations with over 47 MW.[12]

California includes, in part, the Mojave, Sonoran, Great Basin, and San Joaquin Deserts[29]—areas notable for high levels of solar resources and biodiversity—and approximately 90% of the California Floristic Province, a biodiversity hotspot known for high levels of species richness and endemism threatened by environmental change.[30] Energy demand in California may exceed 67 GW by 2016,[31] while energy reliability may be adversely impacted by climate change-related events, such as extreme heat waves.[22] Despite land conservation priorities and energy demands, spatially strategic penetration of USSE into the grid can be employed to meet both conservation and energy-related goals. For example, Cameron et al.[5] found 200 000 ha of low conservation value land within the Mojave Desert Ecoregion that could meet California's renewable energy goals 1.8 times over. These characteristics render the understanding of USSE and its associated land-use in California instructive, especially for other global regions that share similar resource demands and limitations.

Land-Use Efficiency of Big Solar and Technology. To derive an empirical estimate of USSE footprint and LUE, we collected data on 200 USSE installations in California, ranging in capacity from 20 to 1000 MW. Data were synthesized exclusively from official government documents (e.g., public county documents, the Bureau of Land Management records, environmental impact reports or statements).[32−34] Press and news releases, project fact sheets, developer Web sites, news articles, and other secondary sources were not used. For each installation, we recorded several characteristics including nominal capacity (generation under ideal conditions in MW), land footprint (km^2), technology type, location (latitude, longitude), and land ownership (i.e., public or private).

In our data sources, authors used various terms to describe the total footprint of an installation (e.g., "total acreage", "area impacted", "footprint", and "land needed"). In accordance, we define the land footprint as the land encompassing the entire power plant facility excluding land required for raw material acquisition and the generation of energy necessary for manufacturing. Other studies have explicated the raw material and manufacturing life-cycle stages (e.g., Fthenakis and Kim 2009; Burkhardt et al., 2012; Hsu et al., 2012; Kim et al., 2012) and this is beyond the scope of this study.[14−37] The footprint was delineated in our sources—sources that were paired with a respective environmental impact report or statement—and therefore can also be defined as the area where most, if not all, direct impacts from construction, operation, and decommissioning occur. As mentioned above, panels and heliostats do not cover the entire footprint, but direct impacts from development are likely not restricted exclusively to the land under panels and heliostats. For example, we anecdotally observed that developers often modify a large fraction, if not all, of the installation's footprint through the implementation of various activities, including vegetation removal, herbicide application, surface grading, gravel application, concrete production, and road and facility construction. Existing transmission corridors were not included in the site's footprint. To the best of our knowledge, compulsory or voluntary environmental set-asides (i.e., land for conservation typically equal to the area of land disturbed) were not included in the footprint, as such areas were explicitly and separately defined from the total footprint when described in our sources.

Data on technology subtype for PV (e.g., flat, fixed-tilt, single-axis, dual-axis) and CSP (e.g., solar power tower, parabolic trough, dish Stirling, Fresnel reflectors) were not typically described in our data sources. Additionally, subtypes specified for planned installations are highly subject to change due to market price fluctuations, reducing confidence in derived statistics. For CSP schemes, we used the reported capacity of the installation, as details regarding the presence and use of thermal energy storage were not provided. The effect of thermal energy storage on the LUE of CSP is beyond the scope of this paper, but see Sioshansi and Denholm.[17] Any installation that showed a range of values for capacity or area was deemed premature and was excluded ($n = 17$) from analyses, for a total of 183 power plants. We standardized all reported energy-area data to units of watts (W) per meter squared (m^2) and calculated the mean LUE, including the mean LUE by technology type (i.e., CSP and PV). We did not calculate capacity-based LUE for PV or CSP technology subtypes, but this may be feasible—and certainly informative for both capacity- and generation-based LUE—in the future as more installations become operational.

Land-Use Efficiency of Big Solar and Land Tenure. To explore how land ownership may influence capacity-based LUE, we mapped our geo-referenced data set in ArcGIS (10.x; Redlands, CA) and layered it with a land ownership data set.[23] Any installation that showed a discrepancy in land ownership type between public records and the location of the point in accordance with the NLCD was excluded ($n = 23$) from the land ownership analysis. We then calculated descriptive statistics on USSE projects by technology and land ownership type, and conducted a Wilcoxon rank-sum test (nonparametric) to determine significant differences between types. We used a linear model to test for a relationship between nameplate capacity and capacity-based LUE, however, no significant relationship was found. Nonetheless, we report the proportion and LUE of unique size classes (i.e., 20, 21−50, 51−100, 101−500, and 501−1000 MW); however, we caution that these classes are arbitrarily defined. All data processing and statistics

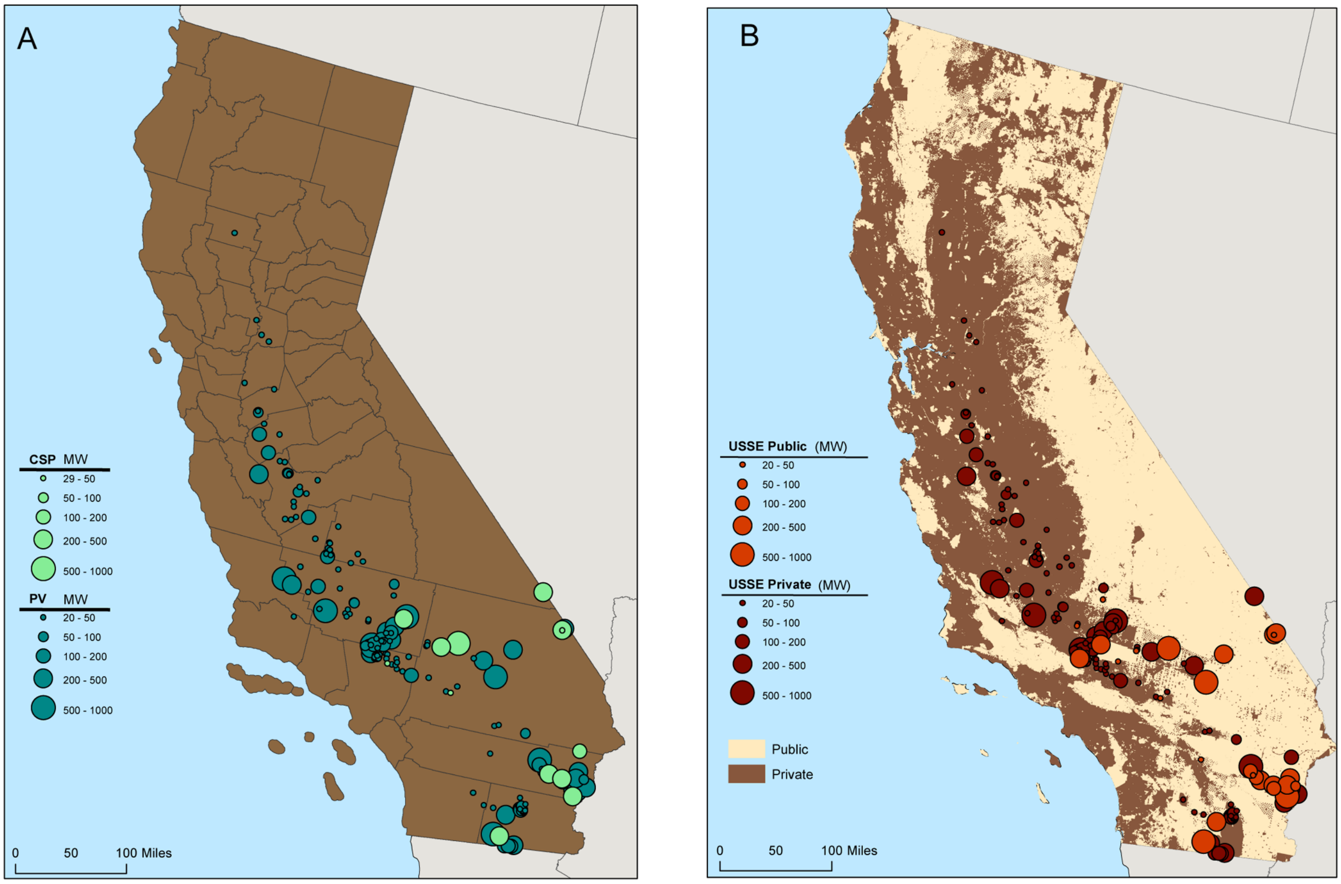


Figure 2. (A) The distribution of utility-scale solar energy installations in California (operating, under construction, and planned) by technology type: concentrating solar power (CSP) and photovoltaic (PV) with county lines shown. (B) The distribution of utility-scale solar energy installations in California by location: public or privately owned land. Larger capacity installations (in megawatts, [MW]) have relatively greater point size.

were performed in R (R: A Language and Environment for Statistical Computing). We mapped each USSE power plant as a function of technology and land ownership type in ArcGIS (10.x; Redlands, CA). The installations we evaluated varied in development stage—from in planning to operating—and our data set may therefore incorporate some power plants that never become operational.

Data Quality and Comparative Analysis. To gain access to public sites and facilities, an environmental impact statement and ROW (right-of-way) application is required and is made publicly available. To verify that the reported footprint in public records included all land impacted by the power plant, including ROW on public land, we compared publicly available footprint records with values reported by each installation's environmental impact statement or grant record of decision. We did this for a subset ($n = 13$) of USSE power plants—eight were located on public land and five on private land—and performed a Pearson's correlation to quantify the consistency between these two data sets. Lastly, we searched the literature for studies and reports that estimated the LUE of USSE. In general, these estimates were either based on industry standards, single power plant specifications, or back-of-the-envelope approximations. Due to the paucity of available research, we included both peer-reviewed literature and technical reports.

■ RESULTS

On the basis of records from 183 installations, we found that USSE in California is concentrated particularly in the Central Valley and the interior of southern California and with a capacity-based LUE of 35.0 Wm^{-2} ± 2.2 (95% CI; Figure 2a and 3a). Of these installations, PV-type installations are the majority ($n = 171$) and have a LUE of 35.1 Wm^{-2} ± 2.3. The smaller fraction comprises CSP installations ($n = 12$) with a LUE of 33.9 Wm^{-2} ± 7.9, which is not significantly different from the LUE of PV installations (p-value =0.5237, W = 1139.5). Concentrating solar power plants are located exclusively in inland southern California (i.e., San Bernardino, Riverside, and Imperial counties). The total capacity for the 183 installations that are planned, under construction, and operating in California is 24 156 MW; of these, 20 237 MW is PV and 3919 MW is CSP.

Of the 184 USSE installations, 160 met our criteria for analyzing the relationship between land ownership type and capacity-based LUE. Installations on private land, which are the great majority ($n = 128$ versus $n = 32$ on public land), have a significantly greater LUE at 35.8 Wm^{-2} ± 2.7 (95% CI) than installations on public land (25.4 Wm^{-2} ± 3.5; p-value < 0.001, W = 1157.5; Figure 2b). We found that publicly available records of USSE footprints and footprint values as reported by environmental impact statements or grant records of decision, are in good accord, i.e., highly positively correlated (r = 0.996786, p-value < 0.0001, r^2 = 0.993 584).

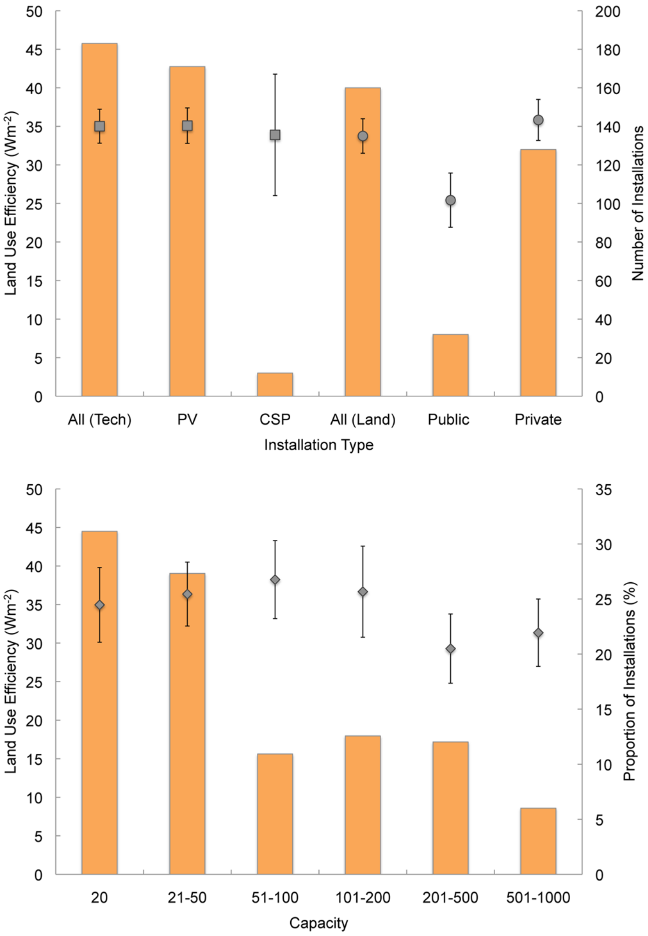


Figure 3. (A) The land-use efficiency (Wm^{-2}) of utility-scale solar energy (USSE) in California as a function of technology and land ownership type (points) and the number of installations in each category (bars),(B) The land-use efficiency (Wm^{-2}) of USSE in California as a function of capacity (MW; points) and the proportion of the total number of installations in each capacity range (bars). Error bars are 95% confidence intervals.

In California, USSE installations on private land are located particularly in the Central Valley and the Basin and Range province (Figure 2b). USSE installations on public lands are roughly confined to the Basin and Range province of southern California.

The total land area planned, under construction, and in use for USSE in California is 85 899 ha (Table 1; Figure 4). More land is allocated for PV (84.2%, 72,294 ha) than for CSP (15.8%, 13,604 ha). The amount of land allocated for USSE and PV is approximately equally divided between private (41 307 and 36 000 ha, respectively) and public (44 592 and 36 295 ha, respectively) land; however, approximately 22% more land for CSP is allocated on public land than privately owned land.

Table 1. Total Land Area (Hectares) Planned, Under Construction, And in Use for Utility-Scale Solar Energy (>20 MW) Power Plants, By Technology and Land-Ownership Type

type	all	private	public
all	85 899	41 307	44 592
PV	72 295	36 000	36 295
CSP	13 604	5 307	8297

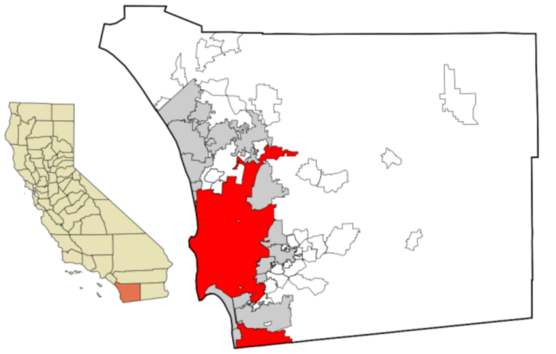


Figure 4. Map showing the city of San Diego (red, incorporated; gray/white, unincorporated; CA, U.S.). The city's area (84 220 ha) is approximately equal to the land planned, under construction, and in use for utility-scale solar energy (n = 160) in California.

The nominal capacity of installations included in our study ranges from 20 to 1000 MW. The plurality (n = 57, 31.1%) of these installations are 20 MW in capacity and average 35.0 Wm^{-2} ± 4.8 (95% CI) in capacity-based LUE (Figure 3b). Installations between 201−500 and 501−1000 MW have the lowest LUE at 29.3 Wm^{-2} ± 4.5 and 31.3 Wm^{-2} ± 4.4, respectively. Numerically, the greatest LUE (38.2 Wm^{-2} ± 5.1) was found for installations between 51−100 MW in capacity. Installations over 500 MW in capacity comprise a minor proportion (6.0%) of all power plants. Overall, there is no significant effect of nameplate capacity on capacity-based LUE (Multiple r-squared = 2.724, df = 181, p-value = 0.1006).

Estimations of capacity-based LUE as reported in 13 peer-reviewed studies and technical reports (Table 2) averaged 34.6 and 29.7 Wm^{-2}, for CSP and PV respectively. In total, estimates from these studies ranged over 2 orders of magnitude, from <1.0 Wm^{-2} to 74.8 Wm^{-2}, with a mean LUE of 31.3 Wm^{-2}. The LUE of individual USSE installations in our database showed a comparable range from 5.2 to 100.9 Wm^{-2}.

DISCUSSION

In this study, we found that capacity-based LUE is 35.0 Wm^{-2} based on actual footprints of over 180 USSE installations spanning the state of California. Prior to this study, the LUE of solar power plants were typically based on back-of-the envelope approximations, industry standards, data from uncertain sources, or data from a single facility, which has resulted in highly variable results (Table 2; also see Horner and Clark 2013).[18] For example, in a meta-analysis, Horner and Clark (2013) found that generation-based estimates varied by as much as 4 orders of magnitude (0.042−64 m^2/MWh) and by 2 orders of magnitude (5−55 m^2/MWh) after applying a harmonization.[18] Consequently, we provide greater accuracy for understanding capacity-based LUE and land-use characteristics of solar energy development in California, which is a consequence of the high number of installations analyzed and the high quality of data employed in this study.

The predicted rise in global energy demand and atmospheric CO_2 levels underscores the importance of understanding the nexus of energy, land, and the environment.[38] Understanding the efficient use of land for energy systems, particularly large-scale renewable energy systems, is critical to quantifying the complete energy conversion chain,[39] but studies quantifying

Table 2. Land Area (m^2) Required to Produce One Watt (W) of Energy Using Utility-Scale Solar Energy (USSE) Technologies, Including Photovoltaics (PV) and Concentrating Solar Power (CSP), as Reported in Primary Literature and Technical Reports[a–n]

N/means	type-subtype	authors	date	capacity (MW)	area (ha)	ha/MW	Wm^{-2}
1	CSP	Block et al.	2007	1	3	2.83	35.30076878
2	CSP	Dahle et al.	2008	1	2	2.02	49.42127685
3	CSP	DOE 2012	2012	1	3	3.00	33.33333333
4	CSP	Fluri	2009	1000	2800	2.80	35.71428571
5	CSP	Schillings et al.	2007	50	100	2.00	50
6	CSP	Simons and McCabe	2005	56	75	1.34	74.7995106
7	CS-tower	Bravo et al.	2007	324 300	42 762 315	131.86	0.758378026
8	CSP-trough	Bravo et al.	2007	2 739 000	43 433 293	15.86	6.30622232
9	CSP-trough	Pimentel et al.	2002	114	1100	9.64	10.37086843
10	CSP/PV	Allen and McHughen	2012	1000	2833	2.83	35.3007688
11	CSP/PV	Karstaedt et al.	2005	1	2	2.02	49.42127685
mean CSP						16.02	34.61
10	CSP/PV	Allen and McHughen	2012	1000	2833	2.83	35.3007688
11	CSP/PV	Karstaedt et al.	2005	1	2	2.02	49.42127685
12	PV	Copeland et al.	2011	31 689	1 000 000	31.56	3.168876464
13	PV	Pimentel et al.	2002	114	2800	24.54	4.074269739
14	PV	Webster and Potter	2010	5	12	2.43	41.18446522
15	PV-w/tracking	Bravo et al.	2007	708 400	45 656 533	64.45	1.551585197
16	PV-25°(fixed tilt)°	Denholm and Margolis	2007	na	na	na	65
17	PV-1-axis	Denholm and Margolis	2007	na	na	na	48
18	PV-2-axis	Denholm andMargolis	2007	na	na	na	20
mean PV						21.31	29.74
mean ALL						19.95	31.32

[a]Allen M and McHughen A. 2012. Solar Power in the Desert: Are the current large-scale solar developments really improving California's environment?. Riverside, CA: University of California Riverside, Desert Development Issues. [b]Block S, Cummer K, Gilton K, Hunsaker M, O'Connell R, Pletka R, Roush B, Stoddard L, Tilley S, and Woodward D. 2007. Arizona Renewable Energy Assessment. Overland. [c]Park, KS: Black and Veatch. [d]Bravo JD, Casals AG, and Pascua IP. 2007. GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. *Energy Policy* 35: 4879–4892. Copeland HE, Kiesecker JM, Pocewicz A. 2011. Geography of energy development in Western North America: Potential impacts to terrestrial ecosystems. Pages 7–22 in D. [e]Naugle editor "Energy development and wildlife conservation in Western North America" Island Press. [f]Dahle D, Elliott D, Heimiller D, Mehos M, Robichaud R, Schwartz M, Stafford B, and Walker A. 2008. Assessing the Potential for Renewable Energy Development on DOE Legacy Management Lands. Golden, CO: National Renewable Energy Laboratory. [g]Denholm P, Margolis R. 2007. The Regional Per-Capita Solar Electric Footprint for the United States. National Renewable Energy Laboratory. Technical Report: NREL/TP-670- [h]42463, Accessed: http://www.nrel.gov/docs/fy08osti/42463.pdf, Accessed on: 8 September 2013. [i]Fluri TP. 2009. The Potential of Concentrating Solar Power in South Africa. *Energy Policy* 37: 5075–5080. [j]Karsteadt R, Dahle D, Heimiller D, and Nealon T. 2005. Assessing the Potential for Renewable Energy on National Forest System Lands. National Renewable Energy Laboratory and USDA Forest Service. [k]Pimentel D, Herz M, Glickstein M, Zimmerman M, Allen R, Becker K, Evans J, Hussain B, Sarsfeld R, Grosfeld A, and Seidel T. 2002. Renewable Energy: Current and Potential. [l]Issues. *American Institute of Biological Sciences* 52:1111–1120. [m]Schillings C, Mannstein H, and Meyer R. 2004. Operational Method for Deriving High Resolution Direct Normal Irradiance from Satellite Data. *Solar Energy* 76: 475–484. Simons G, McCabe J. 2005. California Solar Resources. California Energy Commission. [n]Webster IA, Potter R. 2010. Solar Power on Brownfields Sites. Brea, CA: Project Navigator, Ltd.

such systems in this manner are few and ambiguous.[3,5,25,14,40,41] In a comprehensive life-cycle comparison of a wide range of energy systems, Fthenakis and Kim[14] used a nominal packing factor for various PV technology subtypes (based on a single footprint specifications) to determine the land transformation required by installations. Their estimates ranged between 229 and 552 m^2 GWh^{-1}. These values are comparable to our results—approximately 500 m^2 GWh^{-1} assuming a capacity factor of 13% for PV.

A few studies have compared the LUE of solar with other energy systems[7,25,14] and some use solar LUE data from individual power plants. Compared to other energy systems, Fthenakis and Kim (2009)[14] found that direct and indirect (i.e., energy for materials and energy use) generation-based LUE of PV and CSP was smaller relative to other renewable energy systems including wind, hydroelectric, and biomass and our results corroborate this finding. They also determined that ground-mounted PV systems in favorable locations have a higher generation-based LUE than the coal-fuel cycle coupled with surface mining. In the U.S., 70% of all coal is extracted at the surface, removing mountaintops and altering landscape topography.[42] McDonald et al. (2009)[7] found that CSP and PV had intermediate land-use efficiency—lower than natural gas, coal, geothermal, and nuclear power but greater than bioenergy, wind, hydropower, and petroleum. In regions where land is limited, these results and ours underscore the potential for solar energy systems, over other renewable schemes, to meet relatively greater energetic demands.

Total land-cover change as a result of USSE activities is likely smaller relative to other energy systems, owing to its recent deployment compared to long-standing activities of other energy systems, its inherent land-use efficiency, and the option to deploy installations in the built environment where no additional land-cover change occurs. For example, in the western United States, oil and gas energy systems have impacted approximately 2 orders of magnitude more land

(~21 million ha) than solar (~100 000 ha), but given the region's vast solar resources, solar energy development could impact up to 18.6 million hectares of land.[26] An accurate understanding of LUE is needed to determine net land-cover and land-use change impacts at large scales. Consequently, in this region and elsewhere, capacity- and generation-based LUE estimates such as ours can be used to determine if meeting renewable energy goals through solar energy development will necessitate relatively small or large land transformations.[7]

We found no significant difference in capacity-based LUE between different sized power plants or in plants employing PV or CSP technology (although CSP showed a rather large variance in LUE; Figure 3). Ong et al. (2013)[8] also found no relationship between capacity size and capacity-based LUE for PV and additionally found no relationship between capacity size and generation-based LUE. Given that certain geographic factors (e.g., slope, ambient temperature, water availability, and infrastructure cost) will render PV more favorable than CSP, or vice versa, our results suggest that a comparable level of capacity-based LUE may be achieved regardless of technology type. That is, differences in the capacity factor are more important in determining LUE than technology type.

Land-use efficiency is significantly different for USSE power plants located on publicly and privately owned plants. Installations located on private lands potentially generate over 10 more watts per m^{-2} more than those located on public lands. Possible reasons for this contrast include (1) public lands may be cheaper, conferring greater spatial lenience in the design of installations, whereas private USSE power plants are spatially maximized to be cost-effective; (2) public installations may be, on average, older in the development process and therefore may have lower nominal capacity due to technological lags; and (3) installations on public lands are impacted by their unique geographic attributes (e.g., installations are farther from existing transmission infrastructure and therefore require longer or new corridors). Future research should be conducted to identify the cause underlying this disparity.

If spatial elasticity in public installations contributes to a greater footprint, then there may be an opportunity to improve array design and layout such that the least amount of public land is utilized. Array design is a multifaceted problem that involves optimizing the nominal capacity, capacity factor, structural design, series/parallel circuit design, thermal and shading site characteristics, and ecological features of the land used. However, understanding of how USSE infrastructure impacts an ecosystem, especially impacts related to land-use, are still limited.[5,9] For example, do installations in previously undisturbed environments with lower LUE necessitate less environmental recovery upon their decommission than those with greater efficiency? Future research should be conducted to determine the effect of (1) LUE, (2) shape and layout properties of array design, and (3) different USSE infrastructure on ecological impacts and time to recovery from USSE activities.

By reducing the land used by USSE infrastructure, increasing the LUE can reduce environmental impacts of USSE development related to biodiversity,[3,5,43] water use and consumption,[41,44−46] and human health and air quality.[3,47−49] Improving LUE (i.e., for nameplate capacity) will require (1) maximizing the number of panels, mirrors, or heliostats in the space available for solar capture; (2) minimizing the size and/or number of ancillary facilities; (3) maximizing the density of ancillary facilities; and (4) minimizing new transmission corridors, which can augment the footprint. For example, Denholm and Margolis (2008)[6] state that USSE installers often maximally space arrays to solely increase yield, but that actual shading impacts may not justify the large array spacing, given realized weather conditions and the lower value of off-peak time periods. More research should be done to understand the relationships among spacing, energetic efficiency, and LUE.

In addition to practices that maximize LUE, USSE power plants can maximize their return on investment by integrating ecological cobenefit opportunities. Such opportunities include brightfields—when brownfields are utilized for solar energy development, the colocation of solar and agriculture, hybrid energy systems, floatovoltaics (i.e., PV installed on top of bodies of water), photovoltaic noise barriers, rooftop solar, and the use of salt-contaminated, agricultural, and other degraded lands. Co-benefits include but are not limited to obviating land-use (m^2) and land occupation ($m^2 \times$ year); reducing land deficits for energy, food, and fiber production;[6] creating novel job opportunities; stabilizing degraded soil; enhanced electrical generation; and water conservation. Reducing adverse environmental impacts of USSE and incorporating cobenefit opportunities while concomitantly practicing energy conservation may reduce rates of global warming.[4,38]

Our results are based on nominal capacity and therefore realized LUE will be different for each power plant given its unique capacity factor (e.g., the technological efficiency of the power plant and site-specific weather conditions) and thermal energy storage facilities, where solar-derived energy is converted and stored as thermal energy in a heat-transfer medium for use later.[17,50] To illustrate, a capacity factor of 13% and 33% would engender a realized LUE of approximately 4.6 Wm^{-2} and 11.2 Wm^{-2} for PV and CSP, respectively. Sources providing real time data for the total number of USSE installations online in California are lacking making it difficult to estimate the percentage of planned, under construction, and operating installations in our data set. In 2012, the cumulative installed capacity of solar energy in California was 25 560 MW, where 49.6% of the total MW installed in 2012 were USSE enterprises.[28] Future studies should explore the generation-based LUE of PV and CSP technologies and technology subtypes of USSE using large data sets like ours, especially as more installations come online.

Our results can be employed as inputs for future studies such as those modeling ecological impacts resulting from USSE construction, operation, and decommissioning activities and those quantifying land-atmosphere interactions that integrate effects of USSE infrastructure. Several studies have attempted to project the future land-use impacts of USSE under specific renewable energy goals (e.g., Copeland et al. 2011, Margolis et al. 2012)[25,51] and our study may provide accurate land-related inputs into these projection models. Lastly, our findings provide a baseline against which developers may strive to improve and better understand the LUE of USSE. Overall, our study provides greater clarity to a broader understanding of big solar development, especially the impact of technology, capacity, and land ownership on land-use practices.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (650) 681-7457; fax: (650) 462-5968; e-mail: rebecca.hernandez@stanford.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The McGee Research Grant of the School of Earth Sciences of Stanford University, the William W. Orcutt Memorial Fellowship of the School of Earth Sciences of Stanford University, and the Department of Global Ecology at the Carnegie Institution for Science supported this research. We thank F. Maestre for comments that improved this manuscript and M. Tavassoli who contributed to the data collection and analysis.

■ REFERENCES

(1) Sawin, J. L.; Bhattacharya, S. C.; Galán, E. M.; McCrone, A.; Moomaw, W. R.; Sims, R.; Sonntag-O'Brian, V.; Sverrisson, F. REN21 Renewables Global Status Report; 2012.

(2) Hernandez, R. R.; Maestre, F. T.; Easter, S. B.; Allen, E. B.; Barrows, C. W.; Belnap, J.; Murphy-Mariscal, M. L.; Ochoa-Hueso, R.; Ravi, S.; Tavassoli, M.; Allen, M. F. Environmental impacts of utility-scale solar energy. *Renew. Sust. Energ. Rev.* **2014**, *29*, 766−779.

(3) Lovich, J. E.; Ennen, J. R. Wildlife conservation and solar energy development in the desert southwest, United States. *BioScience.* **2011**, *61* (12), 982−992, DOI: 10.1525/bio.2011.61.12.8.

(4) Abbasi, T. M.; Premalatha, M.; Abbasi, S. A. The return to renewables: Will it help in global warming control? *Renew. Sust. Energy Rev.* **2011**, *15* (1), 891−894.

(5) Cameron, R. D.; Cohen, B. S.; Morrison, S. A. An approach to enhance the conservation-compatibility of solar energy development. *PloS ONE* **2012**, *7* (6), e38437 DOI: 10.1371/journal.pone.0038437.

(6) Denholm, P.; Margolis, R. M. *Impacts of Array Configuration on Land-Use Requirements for Large-Scale Photovoltaic Deployment in the United States. Presented at SOLAR 2008*; American Solar Energy Society(ASES): San Diego, CA, May 3−8, 2008, NREL/CP-670−42971.

(7) McDonald, R. I.; Fargione, J.; Kiesecker, J.; Miller, W. M.; Powell, J. Energy sprawl or energy efficiency: Climate policy impacts on natural habitat for the United States of America. *PloS ONE* **2009**, *4* (8), e6802.

(8) Ong, S.; Campbell, C.; Denholm, P.; Margolis, R.; Heath, G. *Land-Use Requirement for Solar Power Plants in the United States*; National Renewable Energy Laboratory: Golden, CO, 2013.

(9) Stoms, D. M.; Dashielle, S. L.; Davis, F. W. Siting solar energy development to minimize biological impacts. *Renew. Energy* **2013**, *57*, 289−298.

(10) Bravo, J. D.; Casals, X. G.; Pascua, I. P. GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. *Energy Policy* **2007**, *35* (10), 4879−4892.

(11) Dale, V. H.; Efroymson, R. A.; Kline, K. L. The land use-climate change-energy nexus. *Landscape Ecol.* **2011**, *26* (6), 755−773, DOI: 10.1007/s10980-011-9696-2.

(12) Enlisting the sun: Powering the U.S. military with solar energy; www.seia.org/sites/default/files/Enlisting%20the%20Sun-Final-5.14.13-R6.pdf?key=55908056.

(13) Devabhaktuni, V.; Alam, M.; Depuru, S. S. S. R.; Green, R. C.; Nims, D.; Near, C. Solar energy: Trends and enabling technologies. *Renew. Sust. Energy Rev.* **2013**, *19*, 555−564.

(14) Fthenakis, V.; Kim, H. C. Land use and electricity generation: A life-cycle analysis. *Renew. Sust. Energy Rev.* **2009**, *13* (6), 1465−1474.

(15) Love, M.; Pitt, L.; Niet, T.; McLean, G. *Utility-Scale Renewable Energy Systems: Spatial and Storage Requirements*; Institute for Integrated Energy Systems, University of Victoria: Victoria, 2003.

(16) Schepper, E. D.; Passel, S. V.; Manca, J.; Thewys, T. Combing photovoltaics and sound barriers—A feasibility study. *Renew. Energ.* **2012**, *46*, 297−303.

(17) Sioshansi, R.; Denholm, P. *The Value of Concentrating Solar Power and Thermal Energy Storage*; National Renewable Energy Laboratory: Golden, CO, 2010.

(18) Horner, R. M.; Clark, C. E. Characterizing variability and reducing uncertainty in estimates of solar land use intensity. *Renew. Sust. Energy Rev.* **2013**, *23*, 129−137.

(19) Pocewicz, A.; Copeland, H. Potential impacts of energy development on shrublands in Western North America. *Nat. Resour. Environ. Issues* **2011**, *16*, 93−97.

(20) Millstein, D.; Menon, S. Regional consequences of large-scale cool roof and photovoltaic array deployment. *Environ. Res. Lett.* **2011**, *6*, 031002 DOI: 10.1088/1748-9326/6/3/034001.

(21) Vine, E. Adaptation of California's electricity sector to climate change. *Clim. Change* **2012**, *111* (1), 75−99.

(22) Miller, N. L.; Hayhoe, K.; Jin, J.; Auffhammer, M. Climate, extreme heat, and electricity demand in California. *J. Appl. Meteorol. Clim.* **2008**, *47* (6), 1834−1844.

(23) Loarie, S. R.; Carter, B. E.; Hayhoe, K.; McMahon, S.; Moe, R.; Knight, C. A.; Ackerly, D. D. Climate change and the future of California's endemic flora. *PloS ONE* **2008**, *3* (6), e2502.

(24) Hayhoe, K.; Cayan, D.; Field, C. B.; Frumhoff, P. C.; Maurer, E. P.; Miller, N. L.; Moser, S. C.; Schneider, S.; Cahill, K.; Cleland, E.; Dale, L.; Drapek, R.; Hanemann, R.; Kalkstein, L.; Lenihan, J.; Lunch, C.; Neilson, R.; Sheridan, S.; Verville, J. Emissions pathways, climate change, and impacts on California. *Proc. Natl. Acad. Sci., U.S.A.* **2004**, *101* (34), 12422−12427.

(25) Copeland, H. E.; Pocewicz, A.; Kiesecker, J. M. Geography of Energy Development in Western North America: Potential Impacts to Terrestrial Ecosystems. In *Energy Development and Wildlife Conservation in Western North America*; Naugle, D. E., Ed.; Island Press: Washington DC, 2011; pp 7−22.

(26) Pavlović, T. M.; Radonjić, I. S.; Milosavljević, D. D.; Pantić, L. S. A review of concentrating solar power plants in the world and their potential in Serbia. *Renew. Sust. Energy Rev.* **2012**, *16* (6), 3891−3902.

(27) Desert Renewable Energy Conservation Plan: Renewable Energy Acreage Calculator and the 2040 Revised Scenario'S Renewable Portfolio; California Energy Commission, revised July 27, 2012; http://www.drecp.org/documents/docs/DRECP_Acreage_Calculator_Documentation.pdf

(28) Sherwood, L. *U.S. Solar Market Trends.*: Interstate Renewable Energy Council, 2013; http://www.irecusa.org/wp-content/uploads/2013/07/Solar-Report-Final-July-2013-1.pdf.

(29) Germano, D. J.; Rathbun, G. B.; Saslaw, L. R.; Cypher, B. L.; Cypher, E. A.; Vredenburgh, L. M. The San Joaquin Desert of California: ecologically misunderstood and overlooked. *Nat. Area J.* **2011**, *31* (2), 138−147.

(30) Myers, N.; Mittermeier, R. A.; Mittermeier, C. G.; da Fonseca, G. A. B.; Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **2000**, *403* (6772), 853−858.

(31) Large solar energy projects; www.energy.ca.gov/siting/solar/.

(32) The California Energy Commission; http://www.energy.ca.gov.

(33) The County of Kern; http://www.co.kern.ca.us.

(34) The U.S. Department of Interior; http://www.doi.gov/index.cfm.

(35) Burkhardt, J. J.; Heath, G.; Cohen, E. Life cycle greenhouse gas emissions of trough and tower concentrating solar power electricity generation. *J. Ind. Ecol.* **2012**, *16* (s1), S93−S109.

(36) Hsu, D. D.; O'Donoughue, P.; Fthenakis, V.; Heath, G. A.; Kim, H. C.; Sawyer, P.; Choi, J.; Turney, D. E. Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation. *J. Ind. Ecol.* **2012**, *16* (s1), S122−S135.

(37) Kim, H. C.; Fthenakis, V.; Choi, J. K.; Turney, D. E. Life cycle greenhouse gas emissions of thin-film photovoltaic electricity generation. *J. Ind. Ecol.* **2012**, *16* (s1), S110−S121.

(38) Abbasi, T.; Abbasi, S. A. Is the use of renewable energy sources an answer to the problems of global warming? *Crit. Rev. Environ. Sci Technol.* **2012**, *42* (2), 99−154.

(39) Evans, R. L. *Fueling our Future: An Introduction to Sustainable Energy*; Cambridge University Press: Cambridge, 2007.

(40) Gill, A. B. Offshore renewable energy: Ecological implications of generating electricity in the coastal zone. *J. Appl. Ecol.* **2005**, *42* (4), 605−615.

(41) Holbert, K. E.; Haverkamp, C. J. *Impact of Solar Thermal Power Plants on Water Resources and Electricity Costs in the Southwest*; North American Power Symposium(NAPS): Starkville, MS, 2009.

(42) Energy Information Administration. *Annual Coal Report 2006*; Office of Coal, Nuclear, Electric, and Alternate Fuels, U.S. Department of Energy: Washington, DC, 2007; http://www.eia.doe.gov/cneaf/coal/acr/acr.pdf.

(43) McCrary, M. D.; McKernan, R. L.; Schreiber, R. L.; Wagner, W. D.; Sciarrotta, T. C. Avian mortality at a solar energy power plant. *J. Field Ornithol.* **1986**, *57* (2), 135−141.

(44) Carter, N. T.; Campbell, R. J. *Water Issues of Concentrating Solar Power(CSP) Electricity in the U.S. Southwest*; Congressional Research Service: Washington D.C., 2009.

(45) Mani, M.; Pillai, R. Impact of dust on solar photovoltaic(PV) performance: Research status, challenges and recommendations. *Renew. Sust. Energy Rev.* **2010**, *14* (9), 3124−3131.

(46) He, G.; Zhou, C.; Li, Z. Review of self-cleaning method for solar cell array. *Proc. Eng.* **2011**, *16*, 640−645.

(47) Baptista-Rosas, R. C.; Hinojosa, A.; Riquelme, M.. Ecological niche modeling of *Coccidioides* spp. in western North American deserts. *Ann. N.Y. Acad. Sci.* **2007**, *1111* (1), 35−46.

(48) Pepper, I. L.; Gerba, C. P.; Newby, D. T.; Rice, C. W. A public health threat or savior? *Crit. Rev. Environ. Sci. Technol.* **2009**, *39* (5), 416−432.

(49) Russell, A. G.; Brunekreef, B. A focus on particulate matter and health. *Environ. Sci. Technol.* **2009**, *43* (13), 4620−4625.

(50) Dincer, I.; Dost, S. A perspective on thermal energy storage systems for solar energy applications. *Int. J. Energy Res.* **1996**, *20* (6), 547−557.

(51) U.S. DOE. Solar power environmental impacts and siting challenges. In *SunShot Vision Study, Februrary*, 2012.

■ NOTE ADDED AFTER ASAP PUBLICATION

This paper posted ASAP on January 3, 2014. Installation data was changed in the Results section and the revised version was reposted on January 10, 2014.