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Efficient use of land to meet sustainable energy needs

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The deployment of renewable energy systems, such as solar energy, to achieve universal access to electricity, heat and transportation, and to mitigate climate change is arguably the most exigent challenge facing humans today[1–4]. However, the goal of rapidly developing solar energy systems is complicated by land and environmental constraints, increasing uncertainty about the future of the global energy landscape[5–7]. Here, we test the hypothesis that land, energy and environmental compatibility can be achieved with small- and utility-scale solar energy within existing developed areas in the state of California (USA), a global solar energy hotspot. We found that the quantity of accessible energy potentially produced from photovoltaic (PV) and concentrating solar power (CSP) within the built environment ('compatible') exceeds current statewide demand. We identify additional sites beyond the built environment ('potentially compatible') that further augment this potential. Areas for small- and utility-scale solar energy development within the built environment comprise 11,000–15,000 and 6,000 TWh yr^{-1} of PV and CSP generation-based potential, respectively, and could meet the state of California's energy consumptive demand three to five times over. Solar energy within the built environment may be an overlooked opportunity for meeting sustainable energy needs in places with land and environmental constraints.

Technology, economics and environmental values are decisive factors in identifying areas most compatible for renewable energy development, including solar energy systems. Environmental values are underlying determinants of attitudes, behaviours and beliefs about the environment[8,9]. These attitudes, behaviours and beliefs can, in turn, guide decisions concerning which ecosystems and human assets to protect. They can also inform the way that the emphasis on different kinds of impact changes with the scale of the solar energy deployment[10,11]. Solar energy systems integrated within the built environment have several advantages if protecting ecosystems and their services are priority values. They confer the lowest environmental and land-use and land-cover change impacts[6,12], reduce energetic losses from and load on transmission, and are co-located with the energy needs of a growing population expected to be concentrated entirely in urban areas (that is, 62% by 2035; refs 13,14). Such installations are modular in their capacity, ranging from small-scale (<1 MW) to utility-scale (≥ 1 MW), and can use existing infrastructure within the built environment (for example, residential rooftops, commercial rooftops).

Utility-scale solar energy (USSE) systems are uniquely advantageous with their large economy of scale, compatibility with a wide range of sites, and numerous environmental co-benefit opportunities[6]. With a land-use efficiency of 35 W m^{-2} at a capacity factor of 0.20, a single terawatt of USSE capacity scales to 142,857 km^2 (roughly the area of the state of New York)[12], providing challenges for the integration of potentially massive projects into complex and fragmented landscapes. Criteria for siting USSE can be diverse, emphasizing, for example, warehouse rooftops, degraded lands, deserts, or sites remote from human populations. However, resource constraint and opportunity modelling can be used to assess value-based trade-offs and technical potential at large spatial scales where energy development is needed[7,15–17].

The state of California (USA) has been a long-standing model system for understanding the land–energy–environment nexus owing to its early and aggressive adoption of renewable energy systems (predominately wind and geothermal), vast land area (larger than 189 countries, for example, Germany, the Philippines and Zimbabwe), large population (that is, 38 million) and economy (that is, the eighth largest in the world), vulnerability to climate change, and sensitive ecosystems[12,18,19]. Abundant solar resources and diverse storage technology options suggest that small- and USSE technologies within the built environment and in places that minimize environmental impacts may be underutilized within California's current resource mix. Here, we test the hypothesis that land, energy and environmental compatibility can be achieved with small-scale solar energy and USSE within landscapes that are already managed for human uses in the state of California (USA), a global solar energy hotspot[6,20–22].

To determine whether land, energy and environmental compatibility can be achieved within existing developed areas in the state of California, we developed the Carnegie Energy and Environmental Compatibility (CEEC) model (Supplementary Methods) to achieve four objectives. First, we seek to quantify the capacity-based technical potential (that is, satellite-based estimates of PV and CSP technologies operating at their full, nominal capacity over 0.1° surface cells). Second, we seek to quantify the (accessible) generation-based technical potential (that is, realized potential incorporating a satellite-based capacity factor model with $0.1 \times 0.1°$ surface resolution) for PV and CSP. Owing to California's limited water resources, we model dry-cooled CSP parabolic trough technology. Photovoltaic technologies included three subtypes: fixed tilt (TILT25), single-axis (AX1FLAT), dual-axis (AX2). Third, we seek to create a compatibility index (that is, 'compatible', 'potentially compatible' and 'incompatible' areas) to categorize and quantify land resources meeting land, energy and environmental compatibility for solar energy infrastructure. Last, we seek to determine to what extent energy and climate change goals can be met therein.

California has a total area of over 400,000 km^2 with a solar resource of 881,604 TWh yr^{-1} and 1,000,948 TWh yr^{-1} for PV

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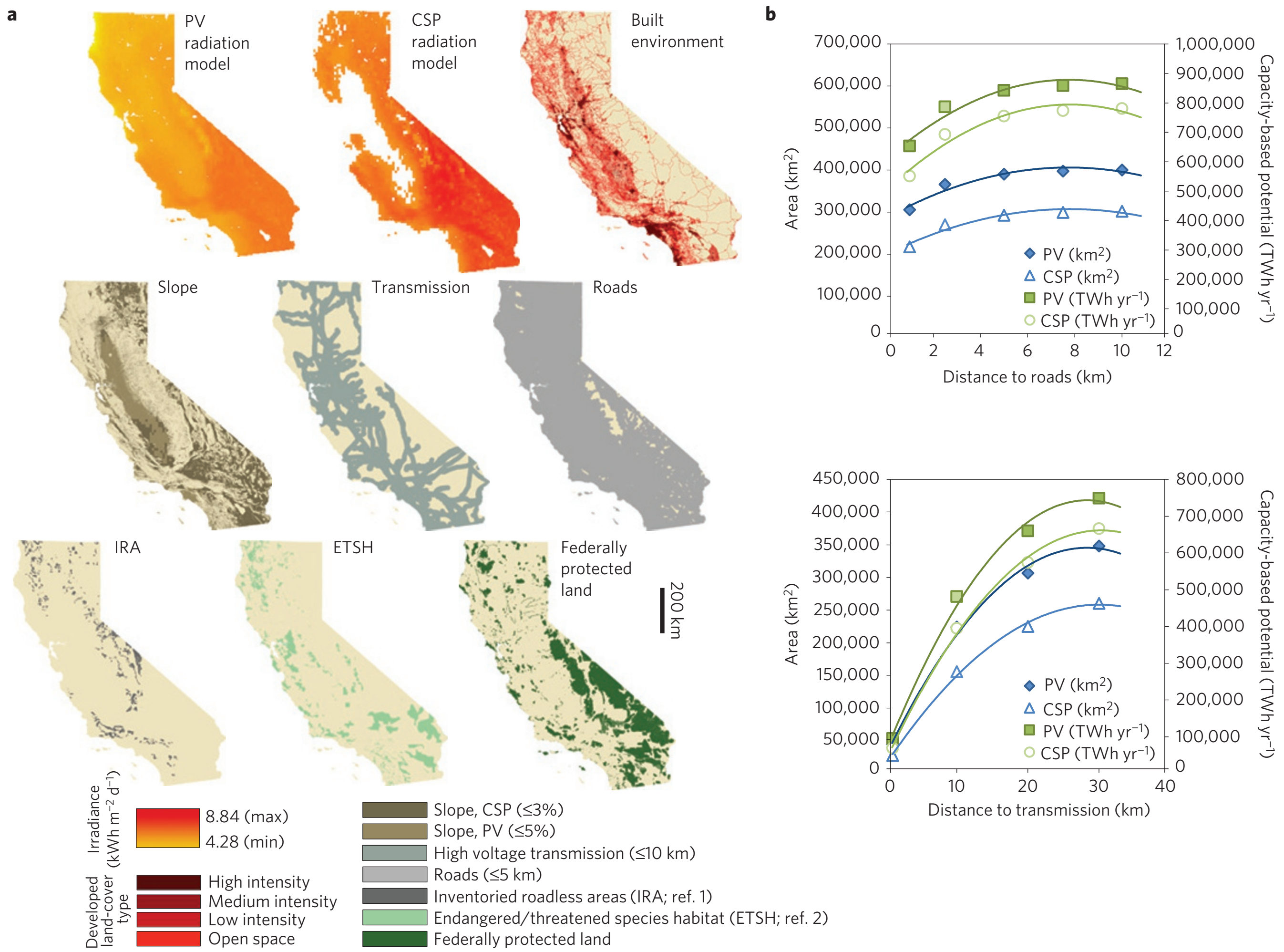

Figure 1 | Selected model inputs and sensitivity analyses. a, Maps showing resource opportunities (that is, PV and CSP radiation models, built environment land-cover types (high, medium, low intensity, and open space)) and resource constraints including slope, proximity to transmission, proximity to roads, inventoried roadless areas, endangered and threatened species habitat, and federally protected land (for greater detail, see Supplementary Section 2). **b**, Solar resource area (km^2) and technical potential (TWh yr^{-1}) as a function of distance to existing high-voltage transmission ($\geq$69 kV; 38,835 km total) and roads (700,914 km total). Trendlines are the best fit (polynomial), where the saturation point (slope = 0) is the mean distance between transmission corridors ($\mu \approx 30$ km) and between roads ($\mu \approx 8$ km). Technical potential increases with increasing distance from existing transmission corridors and road infrastructure up to approximately 30 km and 8 km, respectively ($r^2_{PV}=0.99714$; $r^2_{CSP}=0.99901$; $r^2_{PV}=0.98499$; $r^2_{CSP}=0.98768$). Last, incremental increases in capacity are greatest in the kilometre closest to existing transmission or roads and decrease as distance increases from these elements.

and CSP, respectively (Table 1 and Fig. 1a). However, CSP is economically maximized where direct normal irradiance (DNI) is 6 kWh m^{-2} d^{-1} or greater. California comprises approximately 310,000 km^2 of land where solar resources meet this criterion, conferring a theoretical capacity-based CSP potential of 795,973 TWh yr^{-1}. Although PV systems can be deployed on water, conferring reduced evaporation as a co-benefit (for example, floatovoltaics, Supplementary Table 1), we excluded open bodies of water and perennial ice and snow (Supplementary Section 1).

Collectively, 8.1% of all terrestrial surfaces in California, particularly along the west coast, have been modified by humans ('developed'; 32,675 km^2) and are classified as: high intensity, medium intensity, low intensity, and open space[23]. On the basis of our hypothesis about the adequacy of the areas modified by humans, we defined these developed areas as the 'compatible' opportunity space for solar energy generation (Fig. 1a and Supplementary Table 1). We excluded CSP potential from the built environment classified as high and medium density, because CSP schemes are, at this time, not deployed in such locations. More than a third of these developed areas (12,372 km^2) are urban open space, which is a matrix of vegetation with some constructed infrastructure (<20% impervious surfaces) as is commonly found in large-lot single-family residential units, parks, golf courses and vegetated landscape elements. Within the urban open space land-cover type, the total capacity-based PV (for example, ground or rooftop mounted) and CSP generation is 25,902 and 16,680 TWh yr^{-1}, respectively (Supplementary Table 1). Low- and medium-intensity environments are mostly single-family housing units and together encompass about as much land (13,336 km^2) as urban open space. The area of land potentially available for PV development is approximately equal in low- and medium-intensity built environments, and PV capacity-based generation (for example, ground or rooftop mounted) in these areas is comparable at 13,749 TWh yr^{-1} and 14,204 TWh yr^{-1}, respectively. PVs in high intensity developed land (for example, mostly rooftop modules) have a capacity-based generation potential of 3,244 TWh yr^{-1}. CSP in low-intensity developed land has a capacity-based generation potential of 7,268 TWh yr^{-1}, encompassing 2,942 km^2.

To identify 'potentially compatible' development opportunities beyond these 'compatible', developed areas, we identified

Table 1 | Technical potential of solar energy within environmentally compatible and potentially compatible land in California.

Land area, capacity-based potential and generation-based potential for PV and CSP development after integrating each parameter constraint (for example, slope).

CEEC model resource constraint or opportunity	PV					CSP		
	Total area (km^2)	Capacity-based potential (TWh yr^{-1})	Generation-based potential (TWh yr^{-1})			Total area (km^2)	Capacity-based potential (TWh yr^{-1})	Generation-based potential (TWh yr^{-1})
			TILT25§	AX1FLAT	AX2			
California	409,443	881,604	169,461	209,790	240,520	409,443	1,000,948	386,395
DNI $\geq$ 6 kWh m^{-2} d^{-1}	–	–	–	–	–	309,209	795,973	321,827
Open water and perennial ice/snow	404,062	870,242	167,288	207,088	237,420	305,454	786,715	318,223
Developed, high intensity*	–	–	–	–	–	305,257	786,248	318,052
Developed, medium intensity*	–	–	–	–	–	303,348	781,696	316,357
Developed, low intensity*	–	–	–	–	–	–	–	–
Developed, open space*	–	–	–	–	–	–	–	–
Slope*,†	142,056	310,423	59,735	73,790	84,454	70,102	183,912	75,451
Transmission line (10 km)*	101,765	220,202	41,873	51,575	58,869	46,469	120,364	48,594
Roads (5 km)*	101,527	219,640	41,757	51,431	58,702	46,333	119,988	48,432
Inventoried roadless areas*	101,044	218,648	41,572	51,201	58,436	45,974	119,147	48,110
ET species habitat*,‡	86,738	186,410	35,195	43,289	49,370	39,136	99,734	39,650
Federally protected areas*	81,334	174,148	32,756	40,260	45,889	35,917	91,048	35,999

Moving down columns, area and potential decrease as each constraint is integrated. Cells marked (–) indicate no change in area or potential from previous (above) constraint.

Land area, capacity-based potential and generation-based potential for all schemes (that is, small- and utility-scale) and for solely USSE (≥1 MW), according to the CEEC compatibility matrix.

CEEC model results	PV Total area (km^2)	PV Capacity-based potential (TWh yr^{-1})	TILT25§	AX1FLAT	AX2	CSP Total area (km^2)	CSP Capacity-based potential (TWh yr^{-1})	CSP Generation-based potential (TWh yr^{-1})
All schemes (small-scale + USSE)								
California (all)	409,443	881,604	169,461	209,790	240,520	409,443	1,000,948	386,394
Compatible areas	27,286	57,098	10,617	12,866	14,612			
Potentially compatible areas	54,048	117,050	22,139	27,394	31,277			
USSE only								
Compatible areas	22,028	46,080	8,565	10,349	11,744	6,274	15,400	5,947
Potentially compatible areas	55,733	120,460	22,751	28,139	32,119	27,215	69,551	27,650

USSE installations necessitate parcels large enough for a 1 MW power plant after ref. 12. CSP schemes are all utility-scale. *Reported area and solar potential do not include areas of open water, perennial ice and snow, and for CSP areas where DNI is <6 kWh m^{-2} d^{-1}. †Slope must be ≤5% and ≤3% for PV and CSP, respectively. ‡Endangered and threatened species habitat. §Fixed tilt (TILT25), single-axis (AX1FLAT), dual-axis (AX2).

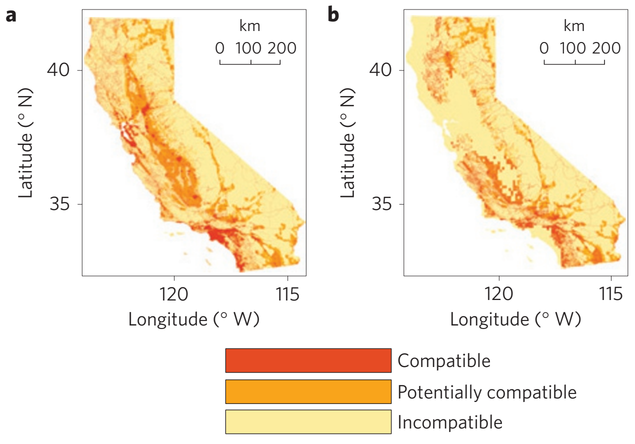

Figure 2 | Compatibility matrices for PV and CSP. a,b, Compatible (red polygons), potentially compatible (orange polygons), and incompatible (yellow polygons) areas for PV (**a**) and CSP (**b**) energy systems within the state of California. Compatible areas are restricted to areas within the built environment (that is, developed land-cover type).

topography most suitable for solar energy systems; where slopes are 3% and 5% or less, for CSP and PV installations, respectively. Next, we prioritized a 10 km development zone on each side of high-voltage (≥69 kV; 38,835 km total) transmission lines, and prioritized a 5 km development zone along each side of all roads of interest (700,914 km total). Last, we identified and excluded 20,193 km^2 of ecologically sensitive, federally protected habitat (Fig. 1a and Supplementary Table 1 and Supplementary Section 2). Such constraints, which are adjustable in the model, can be set to manage economic costs and environmental values associated with construction activities and materials (Methods and Supplementary Section 1.3). We qualify these areas as 'potentially compatible', recognizing that local-scale constraints and regulations beyond the scope of this study may render such areas 'incompatible'[20].

Slope and access to transmission had the greatest absolute effect on the compatibility of land and technical potential. For CSP, DNI was also an important constraint (Supplementary Table 2 and Supplementary Section 1.3). Owing to economic and environmental costs of high-voltage and long-distance transmission and road construction, we performed a sensitivity analysis to determine the effect of distance to transmission and roads on area and capacity-based technical potential for CSP and PV technologies, and to determine mean distance between transmission corridors and between

Table 2 | Potential to meet 33% renewable energy for all retail electricity by 2020 (California RPS, by scenario type) and total energy demand from PV and CSP technologies according to the CEEC compatibility matrix in California.

	PV				CSP	
Potential to meet 33% 2020 RPS	**Capacity-based* (times over)**	**Generation-based (times over)***			**Capacity-based (times over)**	**Generation-based (times over)**
		TILT25†	**AX1FLAT**	**AX2**		
High-demand scenario (47.0 TWh)						
Compatible areas	1,214.9	225.9	273.7	310.9	327.7	126.5
Potentially compatible areas	2,490.4	471.0	582.9	665.5	1,479.8	588.3
Medium-demand scenario (41.3 TWh)						
Compatible areas	1,382.5	257.1	311.5	353.8	372.9	144.0
Potentially compatible areas	2,834.2	536.0	663.3	757.3	1,684.0	669.5
Low-demand scenario (35.3 TWh)						
Compatible areas	1,617.5	300.8	364.5	413.9	436.3	168.5
Potentially compatible areas	3,315.9	627.1	776.0	886.1	1,970.2	783.3
Potential to meet total energy consumption‡	**Capacity-based (times over)**	**Generation-based (times over)**			**Capacity-based (times over)**	**Generation-based (times over)**
		TILT25	**AX1FLAT**	**AX2**		
All schemes						
Compatible areas	25.6	4.8	5.8	6.5	–	–
Potentially compatible areas	52.5	9.9	12.2	14.1	–	–
USSE only						
Compatible areas	20.7	3.8	4.6	5.3	6.9	2.7
Potentially compatible areas	53.9	10.2	12.7	14.4	31.2	12.4

*2020 RPS data for PVs represent potential for areas compatible for all schemes: small- and utility-scale. †Fixed tilt (TILT25), single-axis (AX1FLAT), dual-axis (AX2). ‡Total California state energy usage in 2011 was 2,291 TWh from, in order of increasing consumption: coal, other petroleum, nuclear electric power, distillate fuel oil, jet fuel, net interstate flow of electricity, motor gasoline, hydroelectric power, other renewables, biomass, natural gas, residual fuel, and liquefied petroleum gas. Source: Supplementary Table 4.

roads. Relationships between distance to infrastructure and area (or capacity-based potential) are nonlinear and best-fit equations are polynomial; that is, incremental increases in capacity are greatest in the kilometre closest to existing transmission or roads and decrease as distance increases from these elements. Technical potential increases with increasing distance from existing transmission corridors and road infrastructure up to approximately 30 km and 8 km, respectively ($r^2_{\mathrm{PV}} = 0.99714$; $r^2_{\mathrm{CSP}} = 0.99901$; $R^2_{\mathrm{PV}} = 0.98499$; $R^2_{\mathrm{CSP}} = 0.98768$; Fig. 1b).

In total, California has more than 27,286 km^2 and 6,274 km^2 of 'compatible' land for PV and CSP solar energy development, respectively (Table 1 and Fig. 2). Areas within California that are considered 'potentially compatible' amount to a total of 55,733 km^2 for PV systems and 27,215 km^2 for CSP technology. These areas constitute 174,148 TWh yr^{-1} of PV and 84,951 TWh yr^{-1} of CSP capacity-based potential. Utility-scale PV systems can be developed in 96% of these areas, that is, 77,761 km^2 in area and 166,540 TWh yr^{-1} of capacity-based potential. Next, we calculated realized generation-based solar energy potential for fixed tilt (TILT25), one-axis tracking (AX1FLAT), and two-axis tracking (AX2) PV installations and for parabolic trough CSP installations for all resource opportunities and constraints (Table 1). After integrating each resource opportunity and constraint (Supplementary Table 3), total realized generation-based potential in 'compatible' areas for development ranges from 10,617 to 14,612 TWh yr^{-1} for PV technologies and is 5,947 TWh yr^{-1} for CSP (Table 1). The generation-based potential for PV installations constructed at the utility-scale in 'compatible' areas ranges from 8,565 to 11,744 TWh yr^{-1}. 'Potentially compatible' areas have approximately three times the generation-based potential for PV and CSP technologies as 'compatible' areas.

California's dynamic renewable energy landscape is driven, in part, by legislation and renewable portfolio standards (RPS) that, for example, require renewables to serve 33% of retail electricity load by 2020—enacted as a 'floor' rather than 'ceiling'[22]—and greenhouse-gas emissions 80% below 1990 levels by 2050. In 2012, 22% of retail electricity sales were derived from renewable sources[24] and total energy consumption was 2,231 TWh where non-biomass, non-hydro renewable energy consumption comprises 6.7% (153.3 TWh; Supplementary Table 4). On the basis of the RPS and related legislation (for example, California Global Warming Solutions Act), California state and governmental agencies are directed by law to take all appropriate actions to facilitate the timely realization of RPS requirements including siting, permitting, procurement and transmission infrastructure needs[22].

Framing the realized, generation-based potential of solar energy technologies within the context of policy goals is a useful exercise for weighing its potential contribution to California's current renewable energy mix. We calculated the number of times over that PV (small- and utility-scale schemes) and CSP energy systems could meet the 2020 renewable net short (difference between current renewable energy production and target levels) for three different demand scenarios: low, medium and high. Total projected statewide retail sales demand is 292.6, 297.9 and 305.3 TWh. Net short demand is 35.3, 41.3 and 47.0 TWh for these respective scenarios[22,25]. Within 'compatible' areas, PV generation could meet the state of California's 33% renewable energy goal 301 (low demand), 257 (medium demand) and 226 (high demand) times over with fixed tilt (TILT25) modules. CSP generation in 'compatible' areas could meet the state's goal 436 (low demand), 373 (medium demand) and 328 (high demand) times over (Table 2).

Comparing the realized, generation-based potential of solar energy technologies to the state of California's total energy consumption further underscores the value of solar. The quantity of energy that could be produced solely within the built environment (that is, 'compatible'; conferring the least land-use or land-cover change) exceeds the energy needed to meet the state's total energy consumption (Table 2). Potential realized PV generation (small- and utility-scale) within 'compatible' areas is 4.8, 5.8 and 6.5 times greater than current demand using fixed tilt, single-axis and dual-axis modules. CSP generation within 'compatible' areas is 2.7 times greater than current total energy demand.

The built environment is conducive to high levels of solar energy development. The authors of ref. 26 estimate that 20–27% of all United States residential rooftop space and 60–65% of commercial rooftops are favourable for PV systems, depending on climate and accounting for roof material and structure, shading and orientation. For example, the 121 km^2 city of San Francisco has 23 MW of PV capacity producing an estimated 31,113 MW h yr^{-1} on residential and commercial rooftops and other features within the built environment[27]. At present, 11% and 44% of CSP installations are sited in 'compatible' and 'potentially compatible' areas, respectively, corroborating their feasibility within these land-cover types (R.R.H., unpublished data). Our model assumes that deployed CSP will use dry-cooling technology and therefore water resource constraints may pose unanticipated trade-offs for wet-cooled systems. Last, issues of cost, intermittency and storage, and local siting opposition can impact the scale of deployment in California and elsewhere.

Our study identified a diverse suite of sites in California that could be candidates for small- and USSE development, focusing on the generation potential of well-suited areas within the built environment and additional land that combines high-quality solar resources with proximity to existing roads and transmission lines. These areas provide options for minimizing environmental impacts associated with a large-scale transition to a renewable energy mix where solar energy technologies serve as a growing source alongside increasingly flexible, and optimized transmission integration[10,11,28,29]. California's energy stakeholders, developers and policymakers can use our results to inform development decisions, and the multiple-criteria model, CEEC, can be implemented in other regions.

Methods

Full details are in Supplementary Methods. The CEEC model is an adaptable multiple-criteria model that calculates technical solar energy potential for areas of interest, incorporating user-specified development opportunities and resource constraints. For this study, we applied the CEEC model for California (USA), integrating satellite-based solar radiation estimates with hydrologic, socioeconomic, topographic, energy infrastructure, and ecological opportunities and constraints (for data sources, see Supplementary Table 5). Model outputs include intermediate products of interest (for example, land area and technical potential) as well as a spatially explicit compatibility index ('compatible', 'potentially compatible', 'incompatible'). With a spatial resolution of $0.1 \times 0.1^\circ$, CEEC calculated capacity-based technical potential for PV and CSP (that is, energy output for systems operating at their full, nominal capacity), and generation-based technical potential (that is, realized potential incorporating a capacity factor model) for CSP (dry-cooled, parabolic trough) and for PV technology subtypes (that is, fixed tilt, single-axis, dual-axis).

Radiation estimates were from the National Renewable Energy Lab (NREL) Diffuse/Direct Normal Irradiation Model and the NREL Direct Normal Irradiation Model. These estimates incorporate geostationary weather satellite imagery, daily snow cover data, and monthly atmospheric water vapour, trace gas and aerosol data as well as ground measurement validation (1998–2005) to output annual average daily total solar energy at a spatial resolution of $0.1 \times 0.1^\circ$ ($\sim 10 \times 10$ km).

Capacity factors were from the NRELPV Watts model[30] for three PV system types: fixed tilt, south-facing with a 25° tilt (TILT25); one-axis tracking, rotating east–west with a ±45° maximum tracking angle (AX1FLAT); and two-axis tracking, rotating east–west and north–south of the sun across the horizon (AX2). We used five direct normal irradiance classes of capacity factors for a parabolic trough CSP system (Supplementary Table 6).

Features assessed with spatially explicit mapping included bodies of open water and perennial ice and snow; space within the built environment; topography suitable for solar energy systems, that is, where slopes are 3% and 5% or less for CSP and PV installations, respectively; 10-km-wide corridors on each side of high-voltage (≥69 kV) transmission lines; 5-km-wide corridors along each side of all roads; and ecologically sensitive and protected habitat (Supplementary Methods).

To better understand the amount of energy potential available within California and the CEEC Model Compatibility Matrix areas, we calculated the ratio of PV and CSP capacity and generation-based technical potential to the net short needed for meeting the state's RPS, defined as requiring renewables to serve 33% of retail electricity load by 2020 using the following equation:

potential to meet RPS goal (times over) = solar energy technical
potential / (net short = difference between current
renewable energy production and target levels)

Renewable net short is calculated for upper, mid-, and lower bound cases as:

net renewable net short (TWh) = ([projected retail electricity sales − energy efficiency programs − combined Heat & power customer services − self-generation additions − other demand reduction programs] × policy goal percentage) − generation from existing eligible renewable facilities likely to be generating in 2020.

Estimates of renewable net short depend on assumptions of future energy supply and demand and are, therefore, subject to change over time (for example, reductions in electricity retail sales will reduce renewable net short)[22].

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References

1. IPCC *Special Report: Renewable Energy Sources and Climate Change Mitigation* (Cambridge Univ. Press, 2011).
2. IPCC *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* (Cambridge Univ. Press, 2014).
3. Hoffert, M. I. *et al.* Advanced technology paths to global climate stability: Energy for a greenhouse planet. *Science* **298,** 981–987 (2002).
4. Barthelmie, R. J. & Pryor, S. C. Potential contribution of wind energy to climate change mitigation. *Nature Clim. Change* **2035,** 8–12 (2014).
5. Dale, V. H., Efroymson, R. A. & Kline, K. L. The land use–climate change–energy nexus. *Landsc. Ecol.* **26,** 755–773 (2011).
6. Hernandez, R. R. *et al.* Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* **29,** 766–779 (2014).
7. Cameron, D. R., Cohen, B. S. & Morrison, S. A. An approach to enhance the conservation-compatibility of solar energy development. *PLoS ONE* **7,** 1–12 (2012).
8. Ando, A., Camm, J., Polasky, S. & Solow, A. Species distributions, land values, and efficient conservation. *Science* **279,** 2126–2128 (1998).
9. Schultz, P. W. *et al.* Values and their relationship to environmental concern and conservation behavior. *J. Cross. Cult. Psychol.* **36,** 457–475 (2005).
10. Carbajales-Dale, M., Barnhart, C. J., Brandt, A. R. & Benson, S. M. A better currency for investing in a sustainable future. *Nature Clim. Change* **4,** 524–527 (2014).
11. Gaffin, S. R., Rosenzweig, C. & Kong, A. Y. Y. Adapting to climate change through urban green infrastructure. *Nature Clim. Change* **2,** 704 (2012).
12. Hernandez, R. R., Hoffacker, M. K. & Field, C. B. Land-use efficiency of big solar. *Environ. Sci. Technol.* **48,** 1315–1323 (2014).
13. International Energy Agency *World Energy Outlook 2013* 1–671 (International Energy Agency, 2013).
14. Van Vuuren, D. *et al.* An energy vision: the transformation towards sustainability—interconnected challenges and solutions. *Curr. Opin. Environ. Sustain.* **4,** 18–34 (2012).
15. Fluri, T. P. The potential of concentrating solar power in South Africa. *Energy Policy* **37,** 5075–5080 (2009).
16. Domínguez Bravo, J., García Casals, X. & Pinedo Pascua, I. GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. *Energy Policy* **35,** 4879–4892 (2007).
17. Stoms, D. M., Dashiell, S. L. & Davis, F. W. Siting solar energy development to minimize biological impacts. *Renew. Energy* **57,** 289–298 (2013).
18. Loarie, S. R. *et al.* The velocity of climate change. *Nature* **462,** 1052–1055 (2009).
19. Miller, N. L., Hayhoe, K., Jin, J. & Auffhammer, M. Climate, extreme heat, and electricity demand in California. *J. Appl. Meteorol. Climatol.* **47,** 1834–1844 (2008).
20. Allison, T. D., Root, T. L. & Frumhoff, P. C. Thinking globally and siting locally—renewable energy and biodiversity in a rapidly warming world. *Climatic Change* **126,** 1–6 (2014).
21. Armstrong, A., Waldron, S., Whitaker, J. & Ostle, N. J. Wind farm and solar park effects on plant-soil carbon cycling: Uncertain impacts of changes in ground-level microclimate. *Glob. Change Biol.* **20,** 1699–1706 (2014).

22. California Energy Commission *Renewable Power in California: Status and Issues* 1–282 (California Energy Commission, 2011); http://www.energy.ca.gov/2011publications/CEC-150-2011-002/CEC-150-2011-002.pdf
23. Fry, J. *et al.* Completion of the 2006 national land cover database for the conterminous US. *Photogramm. Eng. Remote Sens.* **77,** 858–864 (2006).
24. California Energy Commission *Tracking Progress: Renewable Energy–Overview* 1–18 (California Energy Commission, 2014); http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf
25. California Energy Commission *New Renewable Generation Needed to Comply with Policy Goals: Update for 2022 Planning* 1–25 (California Energy Commission, 2013).
26. Paidipati, J., Frantzis, L., Sawyer, H. & Kurrasch, A. *Rooftop Photovoltaics Market Penetration Scenarios* (National Renewable Energy Laboratory, 2008).
27. San Francisco, D. of the E. CH2M Hill. San Francisco Energy Map (2013).
28. Bazilian, M. *et al.* Re-considering the economics of photovoltaic power. *Renew. Energy* **53,** 329–338 (2013).
29. Cook, T. R. *et al.* Solar energy supply and storage for the legacy and nonlegacy worlds. *Chem. Rev.* **110,** 6474–6502 (2010).
30. Drury, E. & Lopez, A. Relative performance of tracking versus fixed tilt photovoltaic systems in the USA. *Prog. Photovolt.* **22,** 1302–1315 (2013).

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Author contributions

R.R.H. conceived the project, R.R.H. developed the model, R.R.H. and M.K.H. conducted analyses and model runs, and R.R.H., M.K.H. and C.B.F. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.R.H.

Competing financial interests

The authors declare no competing financial interests.