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Incorporating Land-Use Requirements and Environmental Constraints in Low-Carbon Electricity Planning for California

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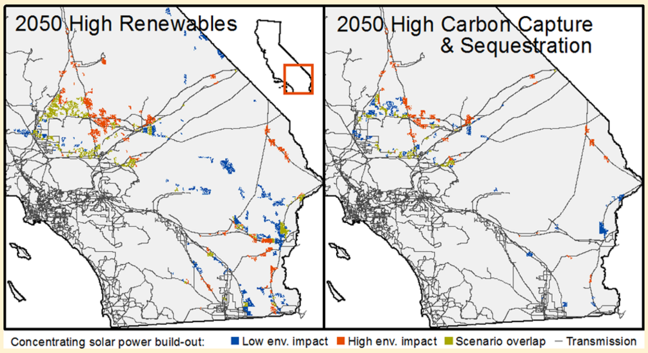
Ⓢ *Supporting Information*

ABSTRACT: The land-use implications of deep decarbonization of the electricity sector (e.g., 80% below 1990 emissions) have not been well-characterized quantitatively or spatially. We assessed the operational-phase land-use requirements of different low-carbon scenarios for California in 2050 and found that most scenarios have comparable direct land footprints. While the per MWh footprint of renewable energy (RE) generation is initially higher, that of fossil and nuclear generation increases over time with continued fuel use. We built a spatially explicit model to understand the interactions between resource quality and environmental constraints in a high RE scenario (>70% of total generation). We found that there is sufficient land within California to meet the solar and geothermal targets, but areas with the highest quality wind and solar resources also tend to be those with high conservation value. Development of some land with lower conservation value results in lower average capacity factors, but also provides opportunity for colocation of different generation technologies, which could significantly improve land-use efficiency and reduce permitting, leasing, and transmission infrastructure costs. Basing siting decisions on environmentally-constrained long-term RE build-out requirements produces significantly different results, including better conservation outcomes, than implied by the current piecemeal approach to planning.



INTRODUCTION

Recent studies indicate that incorporating very high (>70%) penetrations of low-carbon generation into the electricity grid by 2050 is both necessary to achieve deep economy-wide greenhouse gas (GHG) reductions, and feasible from a technical and cost perspective.[1−6] However, these studies have not systematically explored the resource requirements and non-GHG environmental impacts of these scenarios, including land use.

1.1. Current Land-Use Planning for Electricity. Several energy resource potential and zoning studies have been conducted in the U.S. to anticipate and coordinate transmission expansion requirements in the next 10−15 years and also to increase the efficiency and speed of renewable energy (RE) development.[7−10] To facilitate "environmentally responsible" development on public land, several federal agencies have collectively produced a Solar Programmatic Environmental Impact Statement (Solar PEIS) for southwestern states.[10] For strategic resource and load centers, efforts have recently been focused on higher resolution, regional studies, such as the landmark Desert Renewable Energy Conservation Plan (DRECP), a joint initiative charged with overseeing the siting of 22 GW-worth of RE projects in Southern California.[11] Stoms et al. (2013) developed an energy "compatibility index" metric based on degree of habitat degradation as a proxy for identifying valuable ecological resources.[12] Although these and other studies[12−14] have advanced integrated energy planning, their short-to-medium term planning horizon is a significant limitation in light of more recent, long-term deep-decarbonization goals. With few associated physical constraints, 5−15 year implementation plans have historically been the norm in the electricity sector.

Low-carbon studies of California point to the electrification of many uses, especially in transportation, such that even with unprecedented energy efficiency, total electricity demand could increase by 50−100%.[2,15] For example, if this electricity demand is met with mostly RE, installed capacity of utility-scale photovoltaic (PV) and thermal concentrating solar power (CSP) could be 30−35 GW and 20−90 GW by 2050, respectively.[2,3] Based on published ranges for solar land-use factors,[16−18] or the installed capacity per unit area, this would call for the conversion of 1400 to 3570 km^2 of land. Given the potential land-use impacts of solar and wind generation,[19−21] the

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integration of such large quantities of new generation into the landscape, combined with competing demands for residential and agricultural land plus the conservation imperative for diverse and unique ecosystems, poses a challenge for ecologically sensitive land-use and electricity planning.[22,23] Having one of the most ambitious RE targets in the U.S., California must be able to anticipate long-term land-use challenges and the dynamics of scaling up generation technologies to identify robust solutions. Policy and siting strategies that address potential conflicts in advance could expedite low-carbon development and reduce environmental impacts.

Given that deep-decarbonization goals will require sector-wide transformation, it is crucial that analyses treat the electricity sector as part of an integrated system, which calls for spatially incorporating multiple generation technologies, other electricity infrastructure, and conservation priorities into a single model. Previous publications on land-use impacts have treated technologies in isolation.[24,25] In contrast, an integrated, scenario-based approach would allow evaluation of alternative build-outs—reflecting not only trade-offs and complementarity among technologies, but also different conservation valuation and land-use prioritization of stakeholders.

1.2. Objectives. The goal of this paper is to develop an integrated assessment of the land-use requirements for deep-decarbonization electricity scenarios and anticipate the land-use implementation challenges and opportunities of a high RE build-out in a spatially explicit manner. We apply this approach to address three questions that have broad technical and policy relevance for any region that is planning high RE integration. California is used as the case study because of data availability and the policy imperative.

First, how much land is required to meet different low-carbon generation scenarios, and can California's goals be met primarily by RE without developing on environmentally sensitive lands? To understand the extent to which land could be a constraining factor, we estimate electricity land-use using operational-phase land-use factors and compare them with land availabilities modeled under different environmental constraint scenarios using a multicriteria geographic information system (GIS) approach.

Second, how spatially distinct are RE development areas selected based on economic versus environmental criteria? Using resource quality and transmission distance as an indicator for economic costs, we assess the degree to which conservation and cost-effective development goals may conflict by characterizing differences in environmental constraint scenarios and the spatial relationship between resource quality, environmental sensitivity, and transmission and road connectivity. This analysis determines whether meeting conservation goals could warrant more proactive planning or if additional land may be needed for development.

Third, to what extent do suitable development areas for different technologies overlap under various sets of environmental constraints? We explore if and where areas can support deployment of multiple technologies, which could inform the choice of generation technology or motivate innovative strategies such as colocation of technologies to produce hybrid wind-solar power plants.

2. MATERIALS AND METHODS

2.1. Operational Land-Use Requirements. We selected one recent study with which to examine probable electricity build-out scenarios for California in 2050.[2] The study estimates generation and installed capacity using aggressive learning curves for the following corner scenarios: baseline, mixed, high nuclear, high renewables (RE), and high carbon capture and sequestration (CCS). All low-carbon scenarios achieve 80% CO_2e reduction from 1990 levels (or a reduction to 85 Mt CO_2e from Baseline emissions of 875 Mt CO_2e) and are comparable in total generation, but produce at least an additional 120 TWh yr^{-1} of electricity over Baseline primarily due to the electrification of transportation.[2] Installed capacity is similar across the low-carbon scenarios, but is highest in the High RE scenario. See Supporting Information (SI) Figure S1 for estimates of generation and installed capacity.[2] SI Figure S2 provides a visual overview of the methods in the present study.

To estimate annual average, operational-phase land requirements of the nine largest electricity generation technologies (Figure 1), we used annual generation estimates under each build-out scenario[2] and empirical land transformation land-use factors for electricity generated (m^2 GWh^{-1}) assuming a 30-year plant lifetime (SI Table S1; highlighted in yellow).[26,16,27,28] All land-use factors represent operational-phase activities, which excludes indirect land impacts associated with energetic inputs or the production, manufacturing, or transportation of capital goods. Included are direct land use associated with the power plant; mining, drilling, and extraction of fuels; and the pipeline transport of the fuel. For nonbioenergy renewable technologies, the power plant's land use represents the entire operational-phase land use. All reported values in this present study represent "land transformation," or land that is "altered from a reference state" per unit of electricity generation (m^2 GWh^{-1}) or installed capacity (m^2 GW^{-1}).[26] We do not apply land occupation metrics, which account for the duration that the land is under use (e.g., m^2 y GWh^{-1}), due to the highly variable assumptions regarding recovery periods.[26]

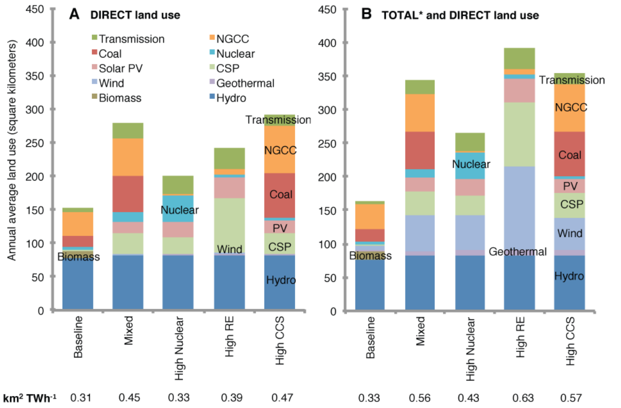


Figure 1. Annual average direct (A) and total (B) land use change for electricity generation necessary to meet the 2050 demand for 30 years (the assumed power plant lifetime) for each low-carbon scenario and its average land area (km^2) per unit generation (TWh) weighted across all technologies. Panel B shows total power plant land use (transformation) for only wind, PV, CSP, and geothermal technologies and direct land use for all other technologies since no total land-use factors could be confidently identified in the literature for conventional generation technologies. Land transformation land-use factors applied here do not account for duration of land recovery from uses associated with electricity generation, as is typically captured in land occupation metrics. Land occupation estimates are not reported in this present study.

The renewable technologies land-use literature distinguishes between "direct" and "total" land use, with the former being land

Table 1. Environmental Scoring Classification Scheme Based on the WECC Classification System for Transmission[30] and Environmental Constraint Scenarios

scoring scheme		environmental constraint scenarios			
score	description	Least Stringent	3rd Most	2nd Most	Most Stringent
4	legal exclusions: areas with legal restrictions against energy development, regardless of GAP status. This score strictly follows exclusions from previous planning studies.[7,8,30,31]	Ex[a]	Ex	Ex	Ex
3.5	high biodiversity risk: all remaining GAP status 1 or 2 areas not included under score 4 (private or public).		Ex	Ex	Ex
3	high environmental risk: areas with some restrictions on energy development in order to maintain natural characteristics, areas of important cultural or historical value (mixed natural and human landscapes), and prime agricultural land. This score includes some GAP statuses 3 and 4 areas, and all "avoid" and "Category 2" areas identified in WREZ[8] and RETI[7] studies, respectively.			Ex	Ex
2	medium environmental risk: lands not listed as avoidance or Score 2 but have ecological or social value, including recreational areas, national forest land, other agricultural land, important bird areas (for wind only).				Ex
1	no known restrictions on energy development.				

[a] "Ex" indicates scores excluded from each scenario.

that is transformed from one state to another, and the latter being the entire area of the power plant. Available Life Cycle Assessment (LCA) literature provide estimates of "land transformation" for conventional generation, which suggests that these are estimates of "direct" land use.[26,28,29] Given this lack of specificity for natural gas, coal, and nuclear, conventional generation estimates are compared with *both* direct and total land use of renewable technologies (Figure 1B).

2.2. Generation Potential of Renewable Technologies. To estimate available land for RE development in California under various environmental constraints, we developed suitability models for geothermal, PV, CSP, and wind technologies using Python, ArcGIS 10.1, and the following types of data sets: physical (slope, elevation, water), socio-economic (population, military, airports), technical (resource), natural disasters (flood, earthquake, landslide), agricultural (cropland, prime farmland), environmental (ecological, cultural, historic areas) (SI Tables S2−S4). Using specifications for thresholds and buffer distances from previous studies (SI Tables S2, S3),[7,8,30,31] we applied GIS map algebra techniques to create binary maps of areas that meet the technical, socio-economic, and environmental criteria for energy development.

To construct environmental constraint scenarios, we assigned each land type one of four environmental impact scores (Table 1) based on its conservation interest, biodiversity management designations, and legal restrictions against energy development (SI Table S4). The scoring scheme is loosely based on risk categories in the Western Electricity Coordinating Council's (WECC) Environmental Recommendations for Transmission Planning (ERTP) report.[30] We modified the land area classifications in previous stakeholder-based studies using the U.S. Geological Survey's (USGS) National Gap Analysis Program (GAP) status code system that ranks the biodiversity management intention for protected areas, to serve as a proxy for areas with conservation interest that have legal recognition (Table 1, SI Table S4). Gap statuses 1 and 2 have legal protection against permanent natural land cover disturbance and also meet the definition of "protected" by the International Union for Conservation of Nature (SI S1). However, land areas with GAP statuses 3 or 4 may still have conservation interest and are scored based on previously reported stakeholder-agreed categories. See SI Table S4 for all land areas included in the analysis, their environmental scores, and classifications used in previous studies. The four environmental scenarios that result from this are Least Stringent, Second-Most Stringent, Third-Most Stringent, and Most Stringent (Table 1). The Third- and Most Stringent scenarios, in particular, represent different degrees of land conservation above and beyond legal and biodiversity management protections. See SI Figure S3A for locations of environmental scores across WECC for solar.

To refine the suitability maps (SI Figure S4), potential areas in each environmental scenario were divided to represent utility-scale "development areas" between 100 and 1−1.2 GW in capacity, which serve as a spatial unit of analysis consistent with sizes of potential RE zones (SI Table S2). The potential installed capacity of each development area was estimated using *total* operational-phase capacity-based land-use factors (MW km^{-2}) for the four RE technologies (SI Table S1; highlighted in blue). Our initial results from modeling nuclear, coal, and natural gas land availability revealed vast suitable areas to site power plants within California that greatly exceeded demand, which is consistent with a previous study.[32] However, the site suitability of conventional power plant does not represent its "potential capacity", as is the case for renewable energy (excluding biomass), because the land footprint of fuel is distinct from that of the power plant.[32] Although operational-stage land-use factors exist for extraction and mining,[26] we do not spatially model the potential of coal, natural gas, and nuclear because we lack sufficient information to estimate the energy extracted per unit of land with the degree of confidence comparable to estimates for wind and solar resources. The fuel cycles of these technologies also lie largely outside of the California study area. We have included geothermal in our analysis because it does not have upstream and geographically distinct fuel stages, and spatial data on "geothermal feasibility" were publically available (SI Table S3).

2.3. Multicriteria Selection. To select development areas that meet 2050 demand, we developed a multicriteria selection process that maximizes resource quality (e.g., insolation) and minimizes environmental impact of additional transmission and road connection, a process that minimizes km^2 MWh^{-1}. Using a transmission "cost surface" based on WECC's ERTP,[30] we calculated the optimal, least-environmental-cost path connecting each development area to the nearest road and transmission

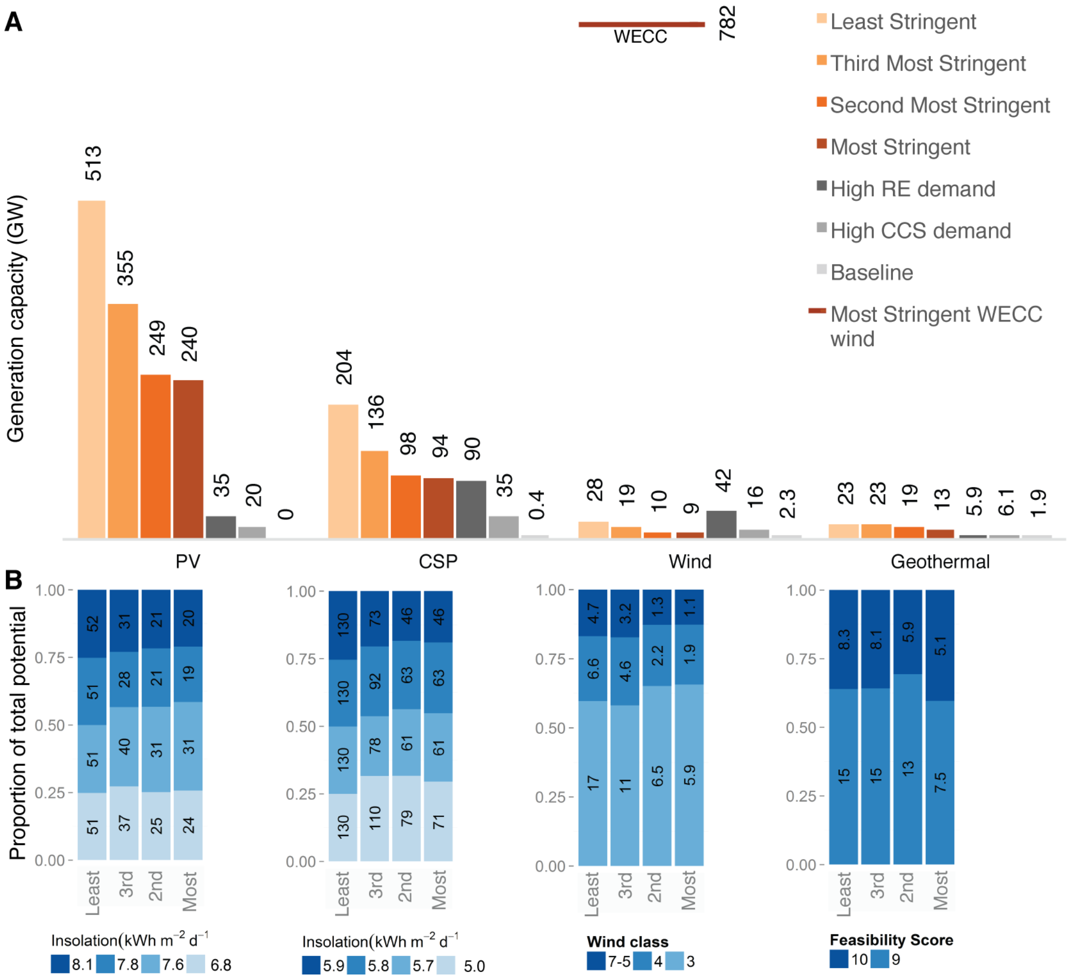


Figure 2. (A) Renewable electricity generation capacity potential (GW) under various environmental constraint scenarios (orange bars) compared with scenarios of California's technology-specific generation in 2050[2] (gray bars). The horizontal line shows the estimated potential of wind power capacity under the Most Stringent environmental scenario for the entire Western Electricity Coordinating Council (WECC) within the U.S. (B) Stacked blue bars show the relative proportion of renewable energy generation capacity that falls within each resource quality class (vertical axis) under each environmental constraint scenario (horizontal axis; Table 1). Values in each stacked bar indicate the potential in gigawatts (GW). For PV and CSP technologies, the class sizes follow quartiles of resource quality values under the Least Stringent environmental scenario. Due to the skewed distribution of wind classes, classes are approximate quartiles for wind capacity, and for geothermal, percentage of installed capacity is shown by the two highest geothermal feasibility scores (9, 10).

corridor (see SI Figure S3B for the transmission cost surface map and SI S3 for more details about transmission calculations). For each development area, we calculated the average annual electricity generation by multiplying the installed capacity (Section 2.2) by 8760 h and the capacity factor, which was calculated from the area-weighted average resource quality (equations in SI S2). We ranked each criterion (resource quality, environmental impacts of transmission, and road connection) and summed the individual ranks to calculate an equally weighted, multicriteria score with which to choose the best overall development areas that meet demand.

2.4. Spatial Interactions. To estimate the proportion of resource quality classes within each environmental constraint scenario, we sampled the resource quality value of each 500m cell and classified values into representative ranges. For solar, these ranges were based on quartiles of resource quality in the Least Stringent environmental scenario. We classified wind classes into the following bins: 3, 4−6, and 7. Since geothermal suitability assessment considered two classes, values were classified into feasibility scores of 9 and 10. For each class, we calculated the total area and the potential installed capacity.

To assess colocation potential and possible siting trade-offs between technologies, we quantified the pairwise overlapping area between technologies within each build-out and environmental constraint scenario. To assess the divergence of build-outs between environmental constraint scenarios, we calculated the overlapping area between scenarios for each technology.

3. RESULTS

3.1. Land-Use Requirements in Build-out Scenarios.

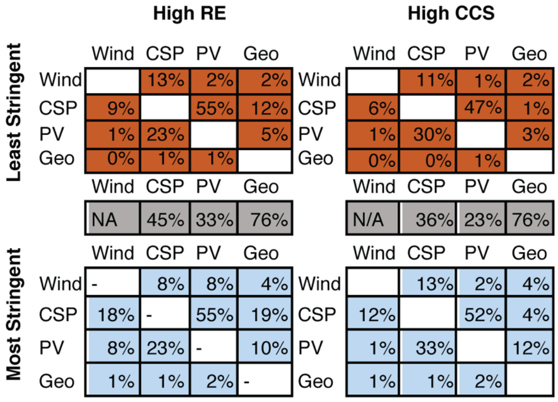
Direct land-use estimates are similar between high CCS and mixed scenarios, but high RE, high nuclear, and baseline scenarios require about 17%, 30%, and 50% less land, respectively (Figure 1A). The baseline scenario requires the least land because its total installed capacity is lowest due to the lack of transportation electricity demand, and the majority of capacity comprises of natural gas-combined cycle, which has high average land-use efficiency. The high nuclear scenario is the second-least land-intensive because of nuclear's higher land-use efficiency (140 m^2 GWh^{-1} vs ~400 m^2 GWh^{-1} for solar, NGCC−CCS, and coal). However, values reported here are for land transformation;

land occupation values for the operational phase of nuclear power is very high (~300, 000 m^2 y GWh^{-1}) because of the assumed recovery times of land from nuclear waste.[26] Due to the reliance on out-of-state deposits of coal, natural gas, and uranium—fuels that dominate the baseline and high nuclear scenarios—and since the land requirements for natural gas and coal dwarf those for power plants, the vast majority of the land requirements in the baseline and high nuclear scenarios would be outside California.[26] *Total* land use estimates are significantly greater than direct land use in the High RE build-out, primarily as a result of wind power (Figure 1B).

3.2. Renewable Generation Potential of Environmental Constraint Scenarios. We compared each technology's potential installed capacity with its expected capacity in 2050 (Figure 2) for different sets of environmental constraints. Although the amount of land available for development decreases with increasingly stringent environmental constraints, we found that generation potential within California is sufficient to meet 2050 demand under all build-out scenarios for PV and geothermal technologies. Wind development in California is constrained by the availability of suitable areas, using the current average total land-use factor assumed here (SI Table S1); higher land-use factors, which would generate enough in-state wind to meet high RE targets under the Least and third-most constrained scenarios, are theoretically achievable.[27] Figure 2A also shows the amount of wind potential in the WECC under the Most Stringent environmental constraint scenario, which vastly exceeds California's requirement for wind energy, though out-of-state resources would have greater transmission needs.

In these results, technologies are not required to have mutually exclusive areas of resource potential. If colocation cannot be achieved, these capacity estimates here would be lower. Notably, because wind and CSP suitable areas overlap, if all suitable areas for wind are developed exclusively for wind generation, the most stringent environmental constraints could preclude the development of approximately 10 GW of CSP, and wind development in California would still be insufficient to meet 2050 high RE scenario targets (Figure 2A).

3.3. Interactions between Conservation Value and Renewable Resource Quality. With increasing environmental constraints, the available land with the highest resource quality for all technologies decreases (Figure 2).This trend is stronger for wind and solar technologies because a disproportionate percentage of the reduction occurs in areas with the highest resource quality (Figure 2B). The covariance of resource and environmental quality is also reflected in the spatial distribution of modeled build-outs for solar. For CSP and PV development areas under the High RE build-out, there is 45% and 33% overlap, respectively, between the Least and Most Stringent environmental scenarios; thus, 55% and 67% of all development areas selected for high resource quality and low transmission and road impact are sited in different locations, depending on the stringency of environmental constraints (Figures 3 and 4). Under the Least Stringent scenario, CSP and PV are mostly concentrated in the Mojave Desert and east of the Sierra Nevada (Figure 4A), whereas under the Most Stringent scenario, relatively more development is located in the Southeast and Colorado Desert, where PEIS Solar Energy Zones have been identified (Figure 4B).[10] In the Most Stringent scenario and at high RE penetration, the average capacity factor will be notably lower for CSP and negligibly lower for PV, and diurnal generation profiles likely different compared with the Least Stringent scenario, but have large environmental impact benefits (Table 2).



High RE

	Wind	CSP	PV	Geo
Wind		13%	2%	2%
CSP	9%		55%	12%
PV	1%	23%		5%
Geo	0%	1%	1%	

Wind	CSP	PV	Geo
NA	45%	33%	76%

	Wind	CSP	PV	Geo
Wind	-	8%	8%	4%
CSP	18%	-	55%	19%
PV	8%	23%	-	10%
Geo	1%	1%	2%	-

High CCS

	Wind	CSP	PV	Geo
Wind		11%	1%	2%
CSP	6%		47%	1%
PV	1%	30%		3%
Geo	0%	0%	1%	

Wind	CSP	PV	Geo
N/A	36%	23%	76%

	Wind	CSP	PV	Geo
Wind		13%	2%	4%
CSP	12%		52%	4%
PV	1%	33%		12%
Geo	1%	1%	2%	

Figure 3. Percentage overlap of multicriteria, model-selected development areas between electricity generation technologies and environmental constraint scenarios for the High Renewable Energy (RE) and High CCS build-outs. Values indicate percentage overlap between generation technologies for development areas chosen under the Least (orange) and Most (blue) Stringent environmental scenarios. Columns indicate the technology used as totals in percentage calculations. For example, in the Least Stringent, High RE scenario, 13% of all CSP development areas overlap with selected wind development areas, and 9% of all wind development areas overlap with CSP development areas. Values in gray show percentage overlap between the two environmental exclusion scenarios for each technology. For example, there is 45% overlap in High RE CSP development areas between the Least and Most Stringent scenarios. Wind percentage overlaps are not provided because not enough wind potential exists within California to meet the demand in the build-out cases.

The overall generation area and transmission impacts for CSP differ between Least and Most Stringent scenarios. While the Most Stringent, High RE build-out requires only 112 km^2 (3% of total CSP area) more land than the Least Stringent scenario to generate the same amount of electricity due to exclusion of higher insolation areas, it has an order of magnitude greater transmission impact due to the need to develop some CSP in locations far from existing lines (Table 2).

3.4. Interactions between Technologies. In some cases, land is suitable for multiple generation technologies (Figure 4). As environmental stringency increases, the overlapping area between technologies increases, which demonstrates that developers and planners may be faced with trade-offs between technology options under increasingly constrained build-outs (Figure 3). In the Least Stringent, High RE build-out scenario, 420 km^2 of development areas overlap between wind and CSP and 770 km^2 between PV and CSP, significant portions of each technology's total area. In this scenario, overlap between wind and CSP account for 9% and 13% of each technology's total, and for PV and CSP overlap is 55% and 23%, respectively (Figure 3). CSP's 13% overlap with wind represents an area exceeding the additional CSP land (3% of all CSP) required under the Most Stringent, High RE build-out scenario (vs the Least Stringent). Thus, if colocation of wind and CSP is pursued for 3% of all installed CSP capacity, it would offset the additional land use requirements that arise under the Most Stringent scenario.

4. DISCUSSION

The recent suite of studies on low-carbon energy transitions at state, national, and international levels[33] has been complemented by renewable resource potential assessments, but there has not

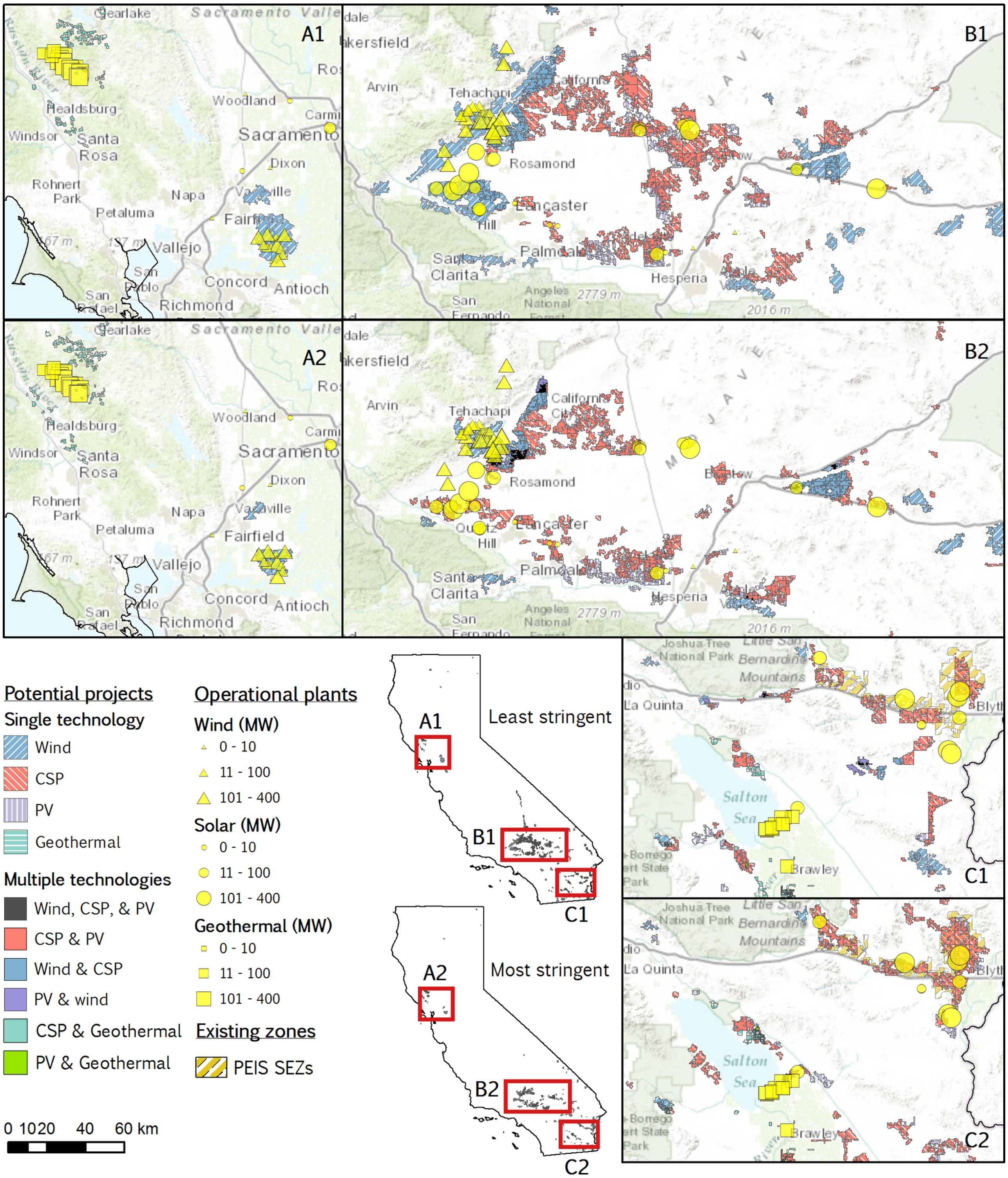


Figure 4. Potential renewable energy development areas under the Least (A1-C1) and Most Stringent (A2-C2) environmental scenarios for the High Renewable Energy (RE) build-out. Areas of overlap between technologies are shown in solid colors (quantified in Figure 3). Sites suitable for single technologies are shown in diagonal lines. Yellow symbols indicate locations of operational wind, solar, and geothermal power plants, with symbol size specifying online capacity in megawatts (Source: California Energy Commission).[46] The Department of Energy and Bureau of Land Management's Programmatic Environmental Impact Statement (PEIS) Solar Energy Zones (SEZs)[10] for California are shown in yellow diagonal lines. Percentage overlap by technology between maps (A1-C1) and (A2-C2) are provided within the gray boxes in Figure 3

been spatially explicit consideration of the land-use challenges as technologies are scaled up.[7,8,14,24,31,34−36] To inform policies that mitigate trade-offs between environmental and economic goals, our study investigates potential conflicts and opportunities by accounting for multiple land-use values, energy technologies, and generation scenarios.

4.1. Land Use in Low-Carbon Scenarios. Annual average direct land requirements for the four low-carbon scenarios of approximately 250 km^2 were not significantly different given the

Table 2. Characteristics of the Multi-Criteria Model-Selected Development Areas That Meet Demand in Three Electricity Build-out Cases and under the Least (L) and Most (M) Stringent Environmental Scenarios

		mean environmental impact[a]		mean resource quality[b]		total transmission environmental impact[c]		total road environmental impact		in-state generation area (km^2)	
		L	M	L	M	L	M	L	M	L	M
wind	baseline	1.70	1	5.25	4.51	0	0	0	0	248	272
	High CCS	2.35	1	3.88	3.60[d]	0	0	0	0	2403	1465[d]
	High RE[d]	2.29	1	3.67	3.60	565 500	365 300	6000	5000	4600	1465
CSP	baseline	3.05	1	8.58	8.39	0	0	0	0	13	13
	High CCS	2.34	1	8.22	8.04	2000	124 900	0	0	1253	1281
	High RE	2.09	1	8.08	7.81	358 900	4 827 200	0	0	3259	3371
PV	baseline										
	High CCS	2.63	1	5.93	5.90	0	0	0	0	797	802
	High RE	2.29	1	5.92	5.88	0	500	0	0	1399	1408
geo-thermal	baseline	1.36	1	10.00	10.00	0	2500	0	0	76	76
	High CCS	1.33	1	9.59	9.60	23 800	94 300	0	0	240	240
	High RE	1.34	1	9.61	9.62	23 800	93 300	0	0	233	233

[a]Environmental impact values were calculated using the scoring scheme detailed in Table 1. [b]Wind expressed in units of wind classes (1-lowest, 7-highest); CSP expressed in units of solar direct normal radiation (DNI), kWh m^{-2} day^{-1}; PV expressed in units of solar global horizontal radiation (GHI), kWh m^{-2} day^{-1}, geothermal expressed in units of geothermal feasibility score. [c]Transmission and road costs are in units of environmental impact score (Table 1) and area of land. The total impact reported constitutes the impact per grid cell of transmission (0.25 km^2) summed across all lengths of additional transmission required under each scenario following classifications in SI Table S4. [d]Demand exceeds supply; all criteria reported are for *all* potential sites in California (no project selection was performed) after applying environmental exclusions.

variability in published land-use factors and lack of consistent metrics for comparison of both direct and total land use. Wind had limited generation potential in California in our analysis, but it was based on current average assumptions about land-use efficiency and minimum resource requirements. With recent developments in wind technologies achieving higher performance at lower wind speeds and enabling installations at greater hub heights and on steeper slopes, innovation is increasing the generation achievable from the same land footprint as well as expanding areas suitable for wind development.[37] Even with innovation, some level of limitation on wind development by ecologically or recreationally valuable areas is likely to persist in CA, which may warrant importing wind energy.

Fair comparisons of renewable and nonrenewable technologies capture impacts over, at minimum, the lifetime of a power plant, often assumed to be 30 years in the LCA literature. The longer the time horizon examined, the more favorable renewable technologies' land-use efficiency becomes since total generation, which increases over time, is averaged over a consistent land footprint while nonrenewable technologies require a continuous fuel supply.[26,28] The type of land impacts also differs by generation technology. For example, landscape fragmentation due to natural gas pipelines and dispersed wellheads is greater than that due to solar electricity.[28] To improve overall land-use efficiency, policies can promote efficient, sustained use of land for RE development. For example, decommissioning policies could enforce removal of old equipment such that land can be released to other developers, and "re-powering" policies could encourage technical upgrades of (RE or conventional) power plants to increase installed capacity and capacity factors, and reduce environmental impacts.

4.2. Co-Location of Wind and Solar Technologies Could Address Multiple Siting Challenges. A notable proportion of low-environmental-impact land in California is suitable for multiple RE technologies. Most studies have evaluated siting for only one technology at a time; yet applying results of independent studies without reconciling overlap would overestimate the available land resource. Moreover, we find that higher RE penetration and/or environmental constraints increase the magnitude of the overestimate. Therefore, resource assessments will be more accurate, and planning and permitting more efficient, if land value of all suitable technologies is considered simultaneously when evaluating different technology options, including technology-specific natural resource impacts such as habitat degradation and water consumption.

At the same time, suitability overlap presents an opportunity for colocation and increased land-use efficiency. Although research quantifying the efficiency gains from colocation is in the nascent stages,[38] recent studies estimate that well-designed colocated wind-PV systems could double electricity generated on a given area, with shading from turbines resulting in a loss of only 1−2% of total PV production, and have better economies than single-technology plants.[39] Because transmission capacity and land can be shared, benefits include reduced transmission and substation footprint, reduced associated right-of-way challenges, and lower permitting costs and barriers per MWh produced.[40,41] Additionally, the seasonal and diurnal complementarity of wind and solar generation profiles would increase utilization of electricity infrastructure.[38,42] In fact, we find that if colocation were achieved in just half of the identified overlapping areas, it would be possible for California to avoid development on valuable conservation areas (i.e., apply strict environmental constraints) *and* develop less land—compared with a no colocation outcome that applies the least environmental constraints (i.e., gives the most flexibility in location). Thus, colocation reconciles the potential land conflict between resource quality and conservation value at high RE penetrations. Because retrofitting existing single-technology plants, especially solar, is more difficult than constructing new colocated plants, these opportunities are most cost-effective when implemented sooner.

4.3. The Need for Consistently Defined Environmental Exclusions. Inconsistencies among previous studies' designation of land area as restricting or allowing energy development, as well as in the definition of land types, create barriers to effective comparison across studies (SI Table S4).[7,8,30] We addressed existing discrepancies by (1) developing different levels of environmental constraints, (2) excluding areas with permanent legal protection, (3) using official management designations for biodiversity and landscape protection (GAP status) to inform what should be excluded from development but had not previously been excluded, and (4) applying environmental data sets that have been identified through stakeholder processes.[43] The DRECP represents a milestone in compiling and achieving consensus for biologically informed data sets in the desert region of Southern California.[11] Replicating such a much-needed initiative state-wide would require generation of similar stakeholder-accepted conservation and management-based data sets.

4.4. Synergistic Land-Use and Electricity Planning for High RE Penetration. Our findings are similar to other estimates of renewable generation potential on low-conservation-value land in California that report about 80 GW solar[12] and 6.2 GW wind.[13] These and other studies[14] have highlighted the feasibility of "win-win" strategies for climate and conservation that restrict development to disturbed lands. Ad hoc, market-driven development is more likely to result in environmental evaluation hurdles that increase expenses for developers, utilities, and ratepayers and have negative environmental impacts.

Our research reveals a trade-off between resource quality of energy and conservation interest for CSP, PV, and wind in a high RE penetration scenario. The low percentage of overlap between high and low environmental impact build-outs suggests that at some point (in time or in space), actions based on either conservation value or simple determinants of cost-effectiveness, (resource quality and transmission distance) could be at the cost of the other. This demonstrates that ecologically sensitive development must be actively pursued if California is to meet both its conservation and low-carbon goals, implying the need to encourage desired development patterns through coordinated energy and land-use planning. Analysis of economic and environmental spatial relationships could also help avoid conflict by identifying no-regret technology and siting choices, estimating the land and natural resource value of reallocation of generation capacity to distributed PV, or reducing demand through energy efficiency measures.[44] Additionally, current electricity planning processes sequentially site generation and transmission, yet potential generation-transmission land-use trade-offs suggest that transmission-focused environmental recommendations (e.g., WECC Regional Transmission Expansion Planning[30]) should be incorporated in the prioritization scheme in RE zoning studies.

4.5. Limitations. This study does not spatially model land use of conventional generation or bioenergy, nor does it estimate the indirect land use associated with renewable technologies. Other criteria for site selection, such as how generation profiles vary spatially or the economic cost of land, were beyond the scope of the study. Also, differences in economic cost of infrastructure requirements between scenarios were not estimated, but would be useful to better understand the cost impacts of conservation and economic trade-offs. Nonland resource requirements, particularly water, should also be considered for a fully comprehensive evaluation of resource constraints on low-carbon pathways.

4.6. Conclusion. With respect to the three objectives, we found that (1) California can meet high RE demands without the use of protected land, though wind energy may come from out-of-state. However, (2) because cost-effective development and conservation goals may conflict in some instances, we found that the most efficient and lower-impact build-out requires coordination of generation and transmission siting with conservation land-use priorities. (3) Because greater overlap between suitable areas for different RE technologies occurs with increasing environmental constraints, colocation of generation technologies could be an effective siting strategy to reduce conflicts between development and conservation. Spatially explicit, forward-looking land-use models of multiple technologies, like that presented here, can anticipate the challenges and opportunities of electricity planning under multiple land-use constraints and inform official planning tools and processes. Hence, Outka (2011) gives a timely call to action, that "early in the expansion of renewable energy, when most of the infrastructure remains to be built, is the time to begin working as well as we can with the tools we have," for the immediate conservation benefits and because "siting well may be the most effective way to streamline power projects."[45]

ASSOCIATED CONTENT

Supporting Information

Equations for calculating electricity generation, and additional tables, figures, and maps. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

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