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Low-impact land use pathways to deep decarbonization of electricity

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Abstract

A growing number of jurisdictions are passing ambitious clean energy policies. Yet few studies have accounted for natural and agricultural land impacts of low-carbon pathways and how environmental siting constraints affect electricity costs and technology choices. To address this gap, we developed an integrated land-energy planning framework to examine the land use trade-offs of renewable energy development required to achieve ambitious clean energy goals, using the state of California as a case study. Using high-resolution ecological and agricultural datasets for 11 Western U.S. states, we modeled environmentally-constrained onshore wind, solar photovoltaic, and geothermal potential and used an electricity capacity expansion model to build generation portfolios for 2050. Here we show that California can meet its targets, but the technology mix, spatial build-out, and system costs are sensitive to land protections and availability of out-of-state renewable resources. Results suggest that failure to consider land availability in energy planning could increase uncertainties, environmental impacts, and risks in meeting subnational climate targets.

1. Introduction

Clean energy transitions are underway globally, propelled by rapidly declining renewable technology costs [1] and sparked by policies mandating significant greenhouse gas (GHG) reductions and high shares of carbon-free electricity [2–4]. Recent energy planning studies charting possible pathways to achieve these ambitious mandates have laid out the technology choices, estimated the scale of technology adoption, and compared system costs [5–7]. Despite the growing prominence and promise of wind and solar technologies in these deeply decarbonized electricity systems and the possible natural resource impacts and large land area requirements of utility-scale development [8–12], few studies have assessed the land use constraints and impacts of wind and solar infrastructure required in low-carbon pathways [13–16].

Addressing this gap requires integrating land conservation values into the energy planning process and evaluating both the environmental and system cost implications of electricity procurement choices. A key challenge in this integration is tackling a mismatch of spatial scales between regional energy policy adoption and local infrastructure development. Strategic spatial planning can help bridge this gap between policy and implementation by also bridging this divide in spatial scales [17]. Currently, analyses and models supporting energy planning are too spatially coarse to be able to capture or assess impacts on ecologically sensitive areas where development is likely to trigger environmental or social conflicts [18, 19].

We address these gaps by developing an approach to support policy and regulatory design that achieves multiple objectives—protection of natural and working (agricultural and rangelands) lands and renewable energy development, using the state of California as a case study. California is currently ranked second in annual electricity demand in the U.S. and is the second state to adopt a target of 100% renewable and zero-carbon electricity (Senate Bill
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explicit models [ural and working lands impacted using spatially-
transmission corridors and estimate the area of nat-
each portfolio's spatial build-out of power plants and
least 100% zero-carbon electricity by 2050; 3) model
of 80% below 1990 levels by 2050 and deliver at
California's goal of economy-wide GHG reductions
portfolios using RESOLVE that are consistent with
including California; 2) create optimal generation
levels of land use protections in 11 Western states,
solar, and geothermal energy potential under four
estimate the quantity and quality of onshore wind,
electricity demand by 2050.

The steps in the framework are as follows: 1) estimate the quantity and quality of onshore wind, solar, and geothermal energy potential under four levels of land use protections in 11 Western states, including California; 2) create optimal generation portfolios using RESOLVE that are consistent with California's goal of economy-wide GHG reductions of 80% below 1990 levels by 2050 and deliver at least 100% zero-carbon electricity by 2050; 3) model each portfolio's spatial build-out of power plants and transmission corridors and estimate the area of nat-
ural and working lands impacted using spatially-
explicit models [13, 22]. This framework can be adap-
ted for any regional or national scale energy planning process using an appropriate energy investment model (e.g. the Regional Energy Deployment System for the U.S. [23]).

We examine two main cases—varying levels of land use protections and varying levels of access to other Western states' renewable resources. We also examine sensitivities that assume lower battery costs and higher behind-the-meter solar PV. In terms of electricity demand, we selected an economy-wide 'high-electrification pathway' which assumes widespread electrification of the transportation sector except for 4.3 billion gallons of advanced biofuels sourced from both in-state and out-of-state sustain-
able agriculture and forestry residues, including from wildfire forest management, which is enough to meet 46% of gasoline, diesel, jet fuel and other non-
electric energy demand in 2050 [21]. Due to Cal-
ifornia agency concerns over sustainability and indir-
ect land use change, the 'high-electrification path-
way' is a more likely and lower-risk pathway com-
pared to a 'high-biomass' pathway that uses purpose-
grown bioenergy feedstocks [21]. Bio-electricity is an available technology option in RESOLVE, and relies on agricultural residues, forest residues, and urban wood waste for feedstocks [24]. However, optimal portfolios are predominantly comprised of wind, solar photovoltaic (PV), and storage technolo-
gies due to these technologies' lower costs and high potential. Thus, this study is focused on solar and wind technologies. If the proposed electricity planning framework were to be applied to other geograph-
ies where bio-electricity is being considered more prominently, steps 1 and 3 could include land use constraints on and impacts of bio-electricity. Lastly, the demand pathway used in this study also assumes highly aggressive energy efficiency and energy conser-
vation targets [21].

2. Results

2.1. Renewable resource availability

Using the Optimal Renewable Energy (ORB) [13] and MapRE [22] models, we identified onshore wind, solar, and geothermal potential under four environmental Siting Levels (SL)—representing the least protective (SL1) to the most protect-
ive levels (SL4; figure 1). Results show signific-
ant solar PV potential, with the highest quantity and quality in the southwestern states (figure 1; Supplementary Materials (SM) figures S3A, S4A [stacks.iop.org/ERL/15/074044/mmedia]). Onshore wind resources are distributed throughout the West-
ern U.S., with few remaining undeveloped resources in California and large concentrations of high-quality resources in New Mexico, Wyoming, Oregon, and Washington (figure 1, SM figures S3B, S4B).

We identified resource potential for all areas within non-California states (Unconstrained case) as well as only within RESOLVE Zones, which is cur-
cently used by California planning agencies for repre-
senting resource areas (Constrained case). We treat the Unconstrained assumptions as the main case because the RESOLVE Zone construct may be altered in the future by state planning authorities since it artificially restricts resource availability.

Although we modeled suitable sites for geo-
thermal, the amount of geothermal potential was sig-
nificantly lower compared to wind and solar (SM figures S3B, S4B). Offshore wind was not included to maintain consistency with assumptions in exist-
ing California planning agency versions of RESOLVE. Also, at the time the study was conducted, publicly available potential and cost data for offshore wind along the California coast had not yet been well char-
acterized or vetted in stakeholder processes. Based on technology costs in RESOLVE supply curve, estim-
ated levelized costs of floating wind turbines would be high enough that the model would not have selec-
ted offshore wind over solar PV (with battery storage) or out-of-state onshore wind [25].

2.2. Technology mix and total resource cost of portfolios

Using supply curves created from the resource poten-
tial estimates, RESOLVE created a generation port-
folio for each Siting Level and Geographic case by minimizing the total system costs. The In-State
Figure 1. Renewable resource availability maps showing candidate project areas of solar PV and wind for Siting Levels 1 through 4. Black outlines indicate states that were used to build supply curves for RESOLVE capacity expansion modeling. Total resource potential in gigawatts (GW) is labeled within each subfigure; the top value is the total resource potential across all states; the bottom value in bold is the resource potential within RESOLVE states (within black outlines). Cat 1–4 excluded from each Siting Level refer to Environmental Exclusion Category 1 (‘Legally Protected’), Category 2 (‘Administratively Protected’), Category 3 (‘High Conservation Value’), and Category 4 (‘Landscape Intactness’). See SM table S9–S12 for datasets and SM Methods for Category definitions. About 30 GW and 20 GW of wind potential were identified in Montana and 5.8 GW and 3 GW of wind potential were identified in Colorado under SL 3 and 4, respectively. However, these two states were not included in RESOLVE.

Geographic case restricts development to within California; the Part-West case expands resource availability to Arizona, New Mexico, Nevada, Oregon, and Washington states; and the Full-West case further expands availability to Idaho, Utah, and Wyoming (figure 4; SM figure S2; SM table S2). We also explored the sensitivity to more behind-the-meter solar (High Distributed Energy Resources or High DER case; SM table S3), lower battery costs (Low Battery Cost case; SM table S4), and spatial restrictions on resource availability (i.e. within RESOLVE Zones) combined with limitations on maximum area for solar (Constrained case; SM figure S2). We produced a total of 61 portfolios or scenarios for 2050, all compliant with economy-wide emissions reductions of 80% below 1990 levels and all generating 102%–110% renewable and zero-carbon electricity by 2050 based on retail sales. Cost results are presented in terms of the annual levelized cost of serving electricity load. Reported numbers reflect the costs of the portfolio, as well as the fixed costs of distribution (including utilization cost for behind-the-meter PV), transmission (including utilization cost for distributed energy resources), demand-side management, existing generation expected to remain in service in 2050, and resources already reflected in utility plans. These existing and contracted resources total to $64.5 billion USD and are referred to as ‘unmodeled’ costs because they do not vary between scenarios.

2.2.1.1. Effects of environmental siting levels
Siting Level constraints also affect the generation mix and the total generation capacity. The amount of (available and selected) wind capacity declines with more land protections in the Part-West and Full-West Geographies. Selected utility-scale solar capacity increases with more land protections from SL2 to SL4 for all Geographic cases (figure 2(A)). By reducing wind availability and requiring more solar capacity, more land protections also increase the need for battery storage by about 14% (In-State), 20% (Part-West), and 230% (Full-West) between SL1 and SL4 vs. 130–162 GW in In-State; figures 2(A), 4). Lower total capacity and significantly greater wind capacity is selected in the Part-West and Full-West Geographies. Grid storage—primarily 4-hr battery—decreases dramatically with increasing Geography (from 55 GW to 8.4 GW in SL1; and 64 GW to 27 GW in SL4). A portfolio with more wind will need less storage (figure 2(D)). By allowing more wind resources to be selected, increasing geographic availability reduces solar capacity by 30%–33% for Part-West and by 40%–62% for Full-West (range spans Siting Levels; SM figure S5).

Across all scenarios, total annual costs ranged from $95 to $114 billion USD in 2050 (figure 2(B)), or an average retail rate of $0.24–$0.28 per kilowatt-hour (in 2016 USD; California’s average rate in 2017 was about $0.16 per kWh). Access to out-of-state renewable energy significantly reduces cost. For SL3, expanding geography from In-State to Full-West reduces costs from $113 to $99 billion USD, or 12% (figure 2(B)).

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Figure 2. Selected new capacity of distributed resources, geothermal, solar, and wind by 2050 across all RESOLVE Zones (A), total resource cost in 2050 (B), generation tie-line (gen-tie) and planned bulk transmission land area requirements (C), and new pumped and battery storage capacity requirements (D) for the three Geographies (In-State, Part-West, and Full-West), four Siting Levels (1–4). As a comparison with the business-as-usual capacity and annual costs, the dotted horizontal line across all three Geography panel plots indicates the value of In-State SL.

(Sitting 2(D)). Siting Level constraints affect the geographic distribution of selected capacity across states. For example, reduced wind capacity in New Mexico and Wyoming is replaced by increased solar in California, Arizona, Nevada, and Utah in SL3 and SL4 in Full-West (SM figure S5).
Siting Levels are also a key determinant of total costs. All else equal, more land conservation increases the total resource cost. For In-State cases, costs increase 7.5% between SL1 and SL4 (figure 3(A)), or from $106 to $114 billion (figure 2(B)). The marginal impact of each successive Siting Level can vary widely. For example, in the In-State cases, SL2 has a modest incremental cost increase over SL1 ($1.4 billion, or 1.3%), while the impacts of SL3 and SL4 are more significant ($6.2 and $8 billion, or 5.6% and 7.5%, respectively; figures 2(B) and 3(A)).

2.2.1.2. The interaction of Geography and Siting Levels
While increasing siting protections increases total costs, expanding geography reduces total costs. These two trends can be combined to produce portfolios that satisfy both land use and cost objectives, achieving siting protections at low cost. Generally, procuring renewable electricity from more states can offset the cost increase associated with increasing land protections. SL1 In-State incurs nearly the same cost as SL3 in Part-West and is actually 6.5% more expensive than SL3 in Full-West (figure 3(B)). Thus, it is more cost effective to achieve SL3 in the out-of-state scenarios than to achieve SL1 In-State. Total costs are nearly the same for the most protective case (SL4) in Full-West and the least protective case (SL1) in the In-State Geography (figure 3(B)).

2.2.1.3. Effects of lower battery cost and high behind-the-meter PV adoption
Overall, sensitivity analyses increasing behind-the-meter PV (High DER case) and reducing battery storage costs (Low Battery Cost case; SM figure S2) do not significantly alter the generation mix, the distribution of selected capacity between states (SM figure S9–S12), or the total costs (figure 3).

Lowering battery costs decreases the overall cost of portfolios, particularly for In-State scenarios (figure 3), but does not change the relative cost-effectiveness across scenarios, does not shift the technology mix, and does not significantly change the quantity of batteries selected (SM figures S9–S12). This indicates that the quantity of batteries selected is determined more by the mix of other available resources rather than cost. Perhaps the most significant effect of lower battery costs is that no additional pumped hydro storage is selected (SM figure S11).

Increasing residential and commercial BTM solar resources by about 35% by 2050 (SM table S3) has the effect of reducing selected utility-scale solar capacity by 3–5.5% in SL3, primarily in California (SM figures S9A–S12A), but had only minor or negligible impacts on the geographic distribution of selected resources (SM figures S9B–S12B). While costs to utilities are lower in the High DER cases, the total cost (including $2.2 billion USD of rooftop PV borne by homeowners and businesses) goes up.

Transmission requirements
Transmission area and length requirements generally increase as land use protections increase and Geography expands—for both absolute area (figure 2(C)) and percentage of total (generation and transmission) infrastructure area (SM table S17). However, the trend is not consistent for Siting Levels since SL3 has the greatest transmission area needs for all Geographies. The land area from the seven planned bulk inter-state transmission lines (SM table S7) exceed the area of total modeled gen-tie lines in the Part-West and Full-West cases (figure 2(C)).

As expected, In-State requires the least transmission corridor area, while Full-West requires the most (figure 2(C)). In the Part-West and Full-West Geographies, wind dominates total transmission area requirements despite comprising a lower fraction of overall generation capacity, while the large capacity of selected solar for the same Siting Levels require very little additional transmission area. These regional Geography scenarios with more wind capacity have larger interconnection requirements since wind is typically more heterogeneous in quality (more dispersed) and has lower total land use efficiencies compared to solar PV.

2.3. Geographic distribution of selected wind and solar project areas
In order to assess the environmental impacts of each portfolio, we selected potential wind and solar project areas to satisfy each portfolio’s technology-specific generation requirements. This step is necessary for evaluating land use trade-offs and impacts as these can vary significantly by location, and power plants have specific siting requirements that make them more likely to be sited in some areas over others.

Results show that for the In-State Geography, increasing land protections causes solar development to shift from Southern to Northern California (figure 4). In Part-West, wind expands to New Mexico and the Oregon-Washington border. With increasing land protections, solar continues to shift northward in California, and wind shifts from New Mexico to the Pacific Northwest. In the Full-West scenarios, with increasing land protections, Wyoming and New Mexico wind selection reduces and is replaced by wind in the Pacific Northwest and Idaho.

2.4. Strategic environmental assessment of generation infrastructure
After selecting project areas, we used least-cost-path analysis to spatially model interconnection (gen-tie) transmission corridors required to interconnect selected areas to the existing network. With these spatially-explicit infrastructure build-outs, we assessed each portfolio’s impact on natural and working lands through a ‘Strategic Environmental Assessment’.
Environmental Exclusion Categories that were used to identify resource potential under each Siting Level were also used as general environmental metrics to explore overall impacts to natural and working lands. Without land protections, new solar and wind projects are likely to have sizable land impacts. Results show significant overlap (> 50%) between selected project areas and Categories 2, 3, and 4 (figure 5(A); see SM Methods and SM tables S9–S12 for datasets). Results suggest that applying these Environmental Exclusions could significantly shape the build-out of wind and solar power plants and that the lack of protections beyond legally protected areas (SL1) leaves open the potential to considerably impact natural lands.

The overlap of selected project areas in SL1 scenarios with Category 2 lands (‘Administratively Protected’) is considerable: one-third of In-State solar, one-third of Part-West wind, and half of Full-West wind (figure 5(A)). Overlap with Category 3 lands (‘High Conservation Value’ including prime agricultural land) is greater: one-fourth of solar in all Geographies and half to three-fourths of wind in all Geographies under SL1 and SL2 (figure 5(A)). For Category 4 (areas with ‘Landscape Intactness’), the overlap is also significant for SL1–SL3 scenarios: one-third of In-State and Part-West solar and half of wind in all Geographies (figure 5(A)). Generally, impacts are higher for SL1 and SL2 in the out-of-state Geographies.

Specific ecological metrics were chosen to explore focal species or habitats emphasized in public energy planning. Impacts to these specific ecological criteria—Critical Habitat, Important Bird Areas, Eagle Habitat, Sage Grouse Habitat, Big Game Habitat, Wetlands, and Wildlife Linkages—are considerably lower than the general Environmental Exclusion Categories (figure 5(A)). This suggests that ecological

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**Figure 3.** Percentage total resource cost differences of the main Unconstrained scenarios relative to the RESOLVE Base case within each Geographic case (A) and relative to In-state Base case (B) for each Siting Level (x-axis). Percentages are calculated using the total resource cost, including the $65 billion in un-modeled costs. Sensitivity analyses were only run for SL3 In-state and Full-West. For percentage calculations using only modeled costs and for Constrained results, see SM Fig S7.
Figure 4. Selected Project Areas for wind and solar PV for each Siting level (columns) and Geographic case (rows). Text in each panel shows total installed capacity of wind, solar PV, and geothermal, with wind (W) and solar PV (S) capacity shown individually within parentheses.

siting considerations are likely to be dominated by other factors, such as sensitive grassland birds and The Nature Conservancy portfolio areas (SM tables S9–S12), and may be emerging causes of land use conflicts. Impacts to these ecological impact metrics are greater in the Part-West and Full-West Geographies (figure 5(A)).

2.4.1. Agricultural impacts of generation infrastructure
Agricultural lands are a significant proportion of the land cover types for selected project areas. For SL1 and SL2 in all Geographies, one-third to one-half of selected solar project areas could be located on prime farmland, mostly in California (SM figure S18). Percentage of solar in non-prime agricultural lands increases under SL3 and SL4 (no impacts are allowed on prime farmland in SL3 and SL4; figure 5(A); SM tables S9–S12). Wind project overlap with agricultural lands is lower than that of solar, with up to half of wind selected project areas in Pacific Northwest under SL4 and one-third of areas in New Mexico under SL1 and SL2. Impacts to rangelands, which are characterized by grass or shrub-like vegetation suitable for grazing or browsing by livestock and provide important ecosystem services [26], are important for solar development, with approximately half of all solar in California and nearly all solar in Arizona and Nevada sited on rangelands (SM figure S18). Large fractions of selected wind projects are also sited on rangelands—nearly half of wind sites in Pacific Northwest and nearly all sites in New Mexico and Wyoming (SM figures S18, S19).

2.4.2. Strategic environmental assessment of transmission infrastructure
Proportional impacts of transmission gen-tie on general environmental metrics are similar to that of generation, while proportional impacts on specific ecological metrics are slightly greater (figure 5(B)). Bulk transmission impacts are proportionally greater than gen-tie impacts (figure 5(B)). Unlike for generation, little agricultural land is impacted by transmission. Large percentages of gen-tie and almost all bulk transmission corridors are located on rangelands.

3. Discussion and conclusions

3.1. Renewable energy required for California to achieve deep decarbonization in 2050 can be sited to limit environmental impacts
However, we find that technology choices, resource costs, and the spatial build-out to achieve California’s climate targets by 2050 are highly sensitive to the level of environmental siting protections and the availability of western regional resources. Importantly, we
Figure 5. Strategic Environmental Assessment for generation (A) and modeled gen-tie and planned bulk transmission corridors (B) summed across all regions for the Unconstrained assumptions case. Cat 1–4 refer to datasets in the Environmental Exclusion Categories created for the site suitability analysis. No impacts are expected for Siting Level (SL) scenarios equal to or greater than the Category (e.g. no Category 3 and 4 environmental exclusion impacts should exist for Siting Level 3 scenarios).

also find that the spatially-explicit portfolios have different impacts on natural and working lands. These results are broadly consistent with previous studies examining land use siting constraints on renewable energy development that found system cost increases of 2.3%–13% [15, 19] and that land availability is one of the most significant determinants of system cost increases [15].

3.2. Possible ecological impacts due to wind and solar siting are significant but can be avoided.
The large overlap of selected project areas in SL1 and SL2 with Environmental Exclusion Categories suggests that developers may face siting challenges for a sizable majority of projects because a large percentage of desirable sites also have environmental and social value. However, impacts can be largely avoided in SL3 and SL4. These findings underscore the importance of integrated land use and energy planning and effective screening tools early in the project development cycle.

3.3. Working lands impacts are significant in all scenarios.
Between 35% to 50% of selected solar project areas in the In-State scenarios are sited on existing agricultural lands, with the majority being prime farmland in SL1 and SL2. One-third to half of all selected wind and solar is sited on rangelands. Thus, agrivoltaics [27,
28], or land uses that integrate agriculture and solar PV generation, have the potential to not only reduce conflicts between farmland and solar development, but actually promote synergistic, higher land-use-efficiency landscapes. This is because agrivoltaic systems, particularly in arid and semi-arid ecosystems, can increase both crop productivity as well as electricity generation due to micro-climate effects [28]. Wind farms are inherently well suited for integration in agricultural landscapes. Wind-friendly farming and ranching practices and wildlife-friendly wind farm design and operations on rangelands will be important in reducing or avoiding siting conflicts.

3.4. Compared to solar, siting options for wind are more geographically and environmentally constrained, which drives the prevailing trends in cost and generation mix.

The low cost and relative abundance of solar enable large shares to be selected across all scenarios. However, in the absence of dispatchable generation, solar electricity must be complemented by wind or balanced by storage. Wind resources tend to be higher value in a high-variable-renewables system and are preferred over solar combined with batteries even in the low-battery cost sensitivity scenarios. However, compared to solar, wind is more limited in the more protective scenarios because of the relative rarity of low-conflict sites with high wind speeds. Wind resources are generally more spatially heterogeneous, while also having lower land use efficiencies when considering turbine spacing, making it more sensitive to land use restrictions. Thus, in wind-limited scenarios, additional selected solar capacity requires battery storage, driving up costs.

Although further research is required, results suggest that enough low-impact onshore wind and solar resources are available to meet the increased clean energy demand of all Western states. After accounting for the 41 GW of wind capacity in California’s portfolio, 59 GW of wind potential remains in the eight Western states in SL3, and 89 GW if Montana and Colorado are included. The total load in these remaining seven states is currently roughly equal to California’s. Assuming other states adopt a similar zero-carbon electricity target and pursue electrification, the technology mix and capacity requirements could closely resemble California’s. Thus, a rough estimate of the wind and solar resource needed to achieve ambitious targets in all nine states would be double the requirements presented here for California, and still within estimates of remaining resource availability under SL3.

3.5. Access to regional renewable resources can achieve lower environmental impacts at lower costs.

Increasing geographic availability of renewable resources can offset the cost increases due to lower impact siting within California. When California has access to out-of-state resources, we find that protecting areas with ‘High Conservation Value’ (SL3) and high ‘Landscape Intactness’ (SL4) can be achieved at a 2%–8% cost savings compared to avoiding just ‘Legally Protected’ (SL1) areas when development is limited to within California.

3.6. Environmental impacts are greater outside of California under the business-as-usual scenarios in which only legally and administratively protections are enforced.

This suggests that if California increases renewable resource sharing or allows significant out-of-state procurement, standards for permitting regional projects will be critical to ensure that greater land protections in California do not lead to leakage of ecological impacts. Impacts to Wildlife Linkages under SL3 remain, which points to the importance of design and operational practices that can minimize unavoidable impacts to wildlife.

3.7. Out-of-state development significantly increase gen-tie and planned bulk transmission requirements, presenting an important trade-off for an otherwise synergistic result that inter-state energy trade can reduce costs and avoid land use impacts.

Although gen-tie and bulk transmission land requirements are a small fraction of the total (< 5%), transmission projects are known to have disproportionate siting impacts due to landscape fragmentation [29], have long lead times for permitting and construction [30], and suffer from interstate permitting and cost allocation uncertainties [31–33].

3.8. High rooftop solar adoption can play an important role in reducing solar land use, but large quantities of utility-scale capacity are still needed in the scenarios examined.

In High DER scenarios, 12%–14% of California’s 2050 demand can be met with rooftop solar. These scenarios still require 100–145 GW of utility-scale capacity in SL3 across all Geographies, or 5,180–8,740 km² of land, which would double the recent historical rate of urbanization in California [34]. Nonetheless, these scenarios are limited in assuming development of 25% of technical rooftop PV potential in California [35] and do not include other land-sparing systems (e.g. floatovoltaics).

3.9. Policy changes and technology evolution could alter this balance of trade-offs and co-benefits, but land use trade-offs are likely to persist.

As other states pursue equally ambitious climate goals, increased competition for the best sites may change resource availability and introduce more land competition and conflict, leading to inefficiencies if not adequately coordinated. For example, compared
to states independently pursuing bilateral contracts within or outside of the state, a regional electricity market could lower transaction costs and help develop the best renewable energy sites across the region that serves the demand of the whole region [36]. Coordinated interstate transmission planning could expedite the lengthy process of transmission development. Offshore wind resources can enable access to much needed wind generation in In-State or most land protective (SL4) cases.

For jurisdictions planning to use bio-electricity, the source of feedstocks creates additional land concerns that could be similarly anticipated through a planning framework such as the one proposed in the present study. Bioenergy may also play a synergistic role in future deep decarbonization pathways. As jurisdictions pursue economy-wide climate goals, they may look towards ‘Natural Climate Solutions’ (NCS) for avoiding avoided or negative emissions [37, 38]. Some of these NCS are also sources of sustainable biomass feedstock (e.g. forest thinning for wildfire management [39]). A bioenergy market for these feedstocks could create a positive feedback cycle for sustaining NCS activities.

3.10. Achieving lower-impact electricity pathways.

In the U.S., many exclusions in SL2 have been incorporated through local, state, and federal land use policy specific to renewable energy. Regulatory mechanisms for achieving SL3-4 could include a combination of land use policy or zoning changes. Non-regulatory mechanisms can include adopting the framework laid out in this study—incorporating environmental spatial data into long-term energy and transmission planning to send market signals to prioritize low-impact development.

4. Methods

The methodological workflow is comprised of five key steps (figure 6). Step 1 consists of spatial environmental data gathering (representing ecological, agricultural, cultural, and other natural resource values). We classified datasets into four Categories of Environmental Exclusions to design four levels of renewable energy siting protections (SM figure 2, SM tables S9–S12).

The second step uses the Categories of Environmental Exclusions, along with spatial data on socio-economic and technical siting criteria for renewable energy (SM table S5), to identify suitable sites for development of each technology. The purpose of Step 2 is to identify potential locations of future wind, solar, and geothermal power plants and use these locations to construct a supply curve, which is an important input for the capacity expansion model. The supply curve is comprised of renewable energy resources and their attributes including location, size (MW), capacity factor, and estimated annual energy production. For this second step, we applied the Optimal Renewable Energy Build-out (ORB) framework [14], which is a suite of spatial modeling tools that perform site suitability and site selection analyses for planning the spatial build-out new wind, solar, and geothermal technologies. The ORB framework includes the Renewable Energy Zoning Tools developed under the MapRE (Multicriteria Analysis and Planning for Renewable Energy) Initiative [22], which were used in this study to create maps of suitable areas and subdivide them into smaller, utility-scale project-sized areas. We refer to these project-sized areas as Candidate Project Areas. After removing existing renewable energy power plants from the identified Candidate Project Areas, we created wind and solar supply curves by aggregating the amount of generation capacity and spatially-averaging the capacity factor (CF) per RESOLVE Zone. A RESOLVE Zone is the spatial unit with which the capacity expansion model, RESOLVE, aggregates the generation supply characteristics, including cost, generation potential, generation temporal profiles, and transmission availability.

In Step 3, we modified the supply curve and assumptions for RESOLVE, an electricity sector capacity expansion model used by California for energy planning that meets California’s electricity demand using generation resources within and out of state, depending on what is available. From the environmentally constrained supply curve, RESOLVE selected certain quantities of candidate resources to create generation portfolios. These differ in their input assumptions, but all satisfy the GHG emissions reduction target of 80% below 1990 levels by 2050. By varying assumptions in ORB (Step 2) and RESOLVE (Step 3), we explored the outcomes of 1) applying different Categories of Environmental Exclusions on resource availability (Siting Levels 1, 2, 3, and 4); 2) expanding geographic availability of renewable resources in the Western U.S. (In-State, Part-West, and Full-West Geographic cases); 3) relaxing existing constraints on renewable resource assumptions in RESOLVE (Constrained and Unconstrained Resource Assumption cases); 4) reducing battery costs (Low Battery Cost case); and 5) increasing behind-the-meter PV adoption (High DER case; see SM figure S2 for cases and sensitivities overview). By varying these input assumptions, we created 61 generation portfolios.

In Step 4, the ORB model then takes the portfolios of the RESOLVE model and determines optimal siting locations, or Selected Project Areas (SPA) in contiguous development areas of 1–10 km², for utility-scale renewable power plants that will collectively generate the amount of electricity specified in each portfolio. The site selection process is based on maximizing resource quality and minimizing distance to existing and planned transmission corridors. In step 5, we performed a ‘strategic environmental assessment’ on
each portfolio using these selected sites by calculating the area of overlap between SPAs and sets of general and specific environmental metrics. These metrics include the Environmental Exclusion Categories used in the site suitability analysis in Step 2, as well as 10 ecological metrics (e.g., Important Bird Areas, Wetlands, Eagle Habitat) capturing focal species and habitat in recent power plant siting cases, and agricultural lands and rangelands.

See the SI for detailed description of methods and data access.

Data availability

The data that support the findings of this study are openly available. Code and data tables listed in the SI are available to download on https://github.com/grace-cc-wu/LandUsePathwaysTo100. The Renewable Resource Areas and Environmental Exclusion spatial data can be downloaded in shapefile (https://tnc.app.box.com/s/votra7kgbme192z6q1rja7rg4cslflb) or geodatabase format (https://tnc.app.box.com/s/xyyiu8fp6sqcvmkayqz25ibxik7mh). The data are also presented in an online map (https://tnc.maps.arcgis.com/apps/webappviewer/index.html?id=71b0605e44bf475ea55f0d369e668b2c). You can also visit the paper’s website (https://www.scienceforconservation.org/products/power-of-place-ca) for up-to-date data downloads. Please see the first section of the Supporting Materials (Access to data, code, and results) for more details on how to access data and models.

Author contributions

G C W, E L, D R C, E B, D A designed research; G C W, E L, D A, O S, B C performed research; G C W, E L, D A, O S, B C, D R C analyzed data; G C W, E L, D A, O S, D R C, B C collected data; all authors contributed to writing the paper.

Competing interests

The authors declare no competing interests.

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