Power of Place

Land Conservation and Clean Energy Pathways for California

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This report has been prepared by E3 for The Nature Conservancy. This report is separate from and unrelated to any work E3 is doing for the California Public Utilities Commission. While E3 provided technical support to The Nature Conservancy in preparation of this report, E3 does not endorse any specific policy or regulatory measures as a result of this analysis. The California Public Utilities Commission did not participate in this project and does not endorse the conclusions presented in this report.

This study uses E3's California-wide RESOLVE model developed under California Energy Commission contract number EPC-14-069. Versions of this model have previously been used by E3 for projects completed on behalf of the California Energy Commission and the California Air Resources Board. These California state agencies did not participate in the project and do not endorse the conclusions presented in this report.

The RESOLVE model used for this project is distinct from the RESOLVE model developed for the CPUC's 2017-2018 Integrated Resource Planning proceeding (R.16-02-007). The following table summarizes the major differences in the RESOLVE model version used for this study and the version used in the CPUC's IRP proceeding.

Table 1: Key Differences in RESOLVE Input Assumptions as Compared to CPUC IRP Proceeding

Category	Assumption for This Study	CPUC IRP 2017-2018 Cycle Assumption
Geography	California Independent System Operator (CAISO) + Sacramento Municipal Utilities District (SMUD) + Los Angeles Department of Water and Power (LADWP)	California Independent System Operator (CAISO)
Demand forecast	Based on CEC EPIC PATHWAYS study forecast for a high electrification scenario, optimized for 2050.	Based on IEPR 2016/2017 forecast, optimized for 2030.
Carbon emissions trajectory	Developed to meet a 2050 target of 80% reduction relative to 1990 levels by 2050. An emissions target of about 8.8 MMT.	Developed to meet CARB's Scoping Plan Alternative 1 scenario for 2030.
Solar resource potential limitations	Reference case resource potential discounted to 267,076 MW in-state to accommodate the higher demand and deeper decarbonizations levels by 2050	Reference case resource potential discounted to 117,515 MW in-state.
Solar and Battery Storage Costs	Costs updated to be consistent with the 2017 National Renewable Energy Lab (NREL) Annual Technology Baseline (ATB), and Lazard Levelized Cost of Storage v3.0.	Renewable costs developed by Black & Veatch for RPS Calculator V6.3 Data Updates; Battery storage cost assumptions are derived from Lazard Levelized Cost of Storage v2.0 and DNV GL's Battery Energy Storage Study for the 2017 IRP.

Abstract

Despite the growing number of jurisdictions passing ambitious clean energy policies, including California's 100% zero-carbon electricity policy (Senate Bill 100), few studies have accounted for natural and working land impacts and how land constraints on energy availability affect infrastructure planning and the choices between technologies. To address this gap, we examine the environmental constraints and impacts of the new renewable energy development required to achieve California's goal of reducing greenhouse gas (GHG) emissions by 80% below 1990 levels by 2050. The scenarios in the study deliver 102-110% retail sales of renewable or zero-carbon electricity in 2050, which is consistent with Senate Bill 100 in 2050. Using detailed spatial datasets representing ecological, cultural, and agricultural siting criteria in 11 western states, we modeled onshore wind, solar, and geothermal energy availability under four levels of environmental land protections. We used these wind, solar, and geothermal energy estimates in a capacity expansion energy planning model, RESOLVE, to build several environmentally-constrained future electricity generation portfolios assuming both no access and access to out-of-state renewable resources. To assess each portfolio's environmental impact, we spatially modeled the locations of generation and transmission infrastructure using a site selection process and least cost path analysis, respectively. We find that California can decarbonize the electricity sector, but the balance between wind, solar PV, and storage capacity and resultant costs are sensitive to land protections and whether California has access to west-wide renewable energy. Land protections are highly effective in avoiding environmental impacts while achieving GHG targets, but can increase costs, primarily by reducing wind availability. However, higher costs can be more than offset by allowing access to out-of-state wind and solar resources, such that California can achieve both better cost and conservation outcomes by pursuing regional renewable resource development and trade. However, this path requires significantly more transmission infrastructure and can have greater land use impacts under scenarios with lower levels of environmental protections. Given the wide range of possible cost and technology mix outcomes due to renewable resource availability assumptions, energy planning studies aiming to capture drivers of model uncertainty should incorporate conservation data and siting constraints.

Keywords: land use, renewable energy, low-carbon, deep decarbonization, California, climate targets, 2050

Abbreviations and Acronyms

BLM	Bureau of Land Management
BTM	Behind-the-meter
CAISO	California Independent System Operator
Cat	Category (specifically in reference to Environmental Exclusion Categories)
CEC	California Energy Commission
CF	Capacity factor
CPA(s)	Candidate project area(s)
CPUC	California Public Utilities Commission
DER	Distributed Energy Resources
E3	Energy and Environmental Economics
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt-hour
HVDC	High-voltage direct current
IRP	Integrated Resource Planning
MW	Megawatt
MWh	Megawatt-hour
NGO	Non-governmental organization
NREL	National Renewable Energy Laboratory
ORB	Optimal Renewable Energy Build-out
PAD-US	Protected Areas Database of the U.S. (U.S. Geological Survey and Conservation Biology Institute)
PV	Photovoltaic
QRA(s)	Qualifying Resource Areas
RPS	Renewable Portfolio Standard
SI	Supporting Information
SL	Siting Level
SPA(s)	Selected project area(s)
TNC	The Nature Conservancy
USDA	U.S. Department of Agriculture
USWTD	U.S. Wind Turbine Database
WECC	Western Electricity Coordinating Council
WWWMP	West-wide Wind Mapping Program

Contents

1 Introduction

Clean energy transitions are underway globally, propelled by declining renewable technology costs [1] and sparked by policies mandating significant greenhouse gas (GHG) reductions and high shares of renewable electricity [2–4]. Recent studies charting possible pathways to achieve these ambitious mandates have laid out the technology choices, estimated the scale and rate of technology adoption, and compared system costs [5–7]. Yet few have accounted for natural resource constraints, barriers, impacts in implementing the pathways—and, in particular, where low-carbon infrastructure should be developed to avoid and minimize ecological and social impacts.

Ecological studies have begun to reveal the unintended impacts of large-scale solar and wind development [8, 9]. The media and scholars have noted the rise of "green vs. green" conflicts when siting renewable energy infrastructure in sensitive landscapes, such as the desert southwest in the United States [10]. To help alleviate these conflicts and potential trade-offs, studies are needed to assess the possible land use constraints and ecological impacts of energy infrastructure needed for a deeply decarbonized national or sub-national economy [11–14].

Addressing this gap requires integrating land conservation values into the energy planning process and evaluating both the environmental and system cost implications of siting policies and energy procurement standards. One of the key challenges in this integration is tackling a mismatch of spatial scales: energy policies are regional or national, but project implementation is local and must address local resource values. Planning can help bridge policy and implementation by also bridging this divide in spatial scales. Currently, renewable energy planning relies on electricity capacity expansion models, which simulate future investments in generation and transmission infrastructure given assumptions about energy demand, technology costs and performance, resource availability, and policies or regulations (e.g., GHG emissions targets). These capacity expansion models are highly spatially aggregated, but the renewable resource assumptions that serve as important inputs to these models must come from highly spatially-explicit analyses. These spatial analyses usually remove areas legally protected from development, but do not include the detailed spatial datasets that can account for many other ecologically sensitive areas where development is likely to trigger conflicts with resource management agencies, environmental organizations, and local communities [15, 16]. Other resource assumptions used in capacity expansion planning studies can also be overly conservative by applying uniform discounts on resource availability, with the unintended impact of underestimating low-impact and low-conflict siting options. In terms of evaluation and comparison of portfolios, capacity expansion model outputs are also typically too spatially coarse to provide information on possible siting impacts of portfolios.

We address these gaps and challenges by developing an approach to support policy and regulatory design that achieves multiple objectives—protection of natural and working (agricultural and rangelands) lands and decarbonization of the electricity sector for the state of California. California is the second state in the U.S. to pass legislation that sets a policy of supplying 100% of electricity from renewable energy and zero-carbon resources by 2045 (Senate Bill 100)—reinforcing and complementing an earlier goal to reduce GHG emissions by 80% below 1990s levels by 2050 (Executive Order S-3-05). To guide energy policy and regulations in support of climate commitments, utility regulators and energy planners use an electricity sector capacity expansion model, RESOLVE [17]. We develop a planning framework using RESOLVE that quantifies—using regionally-consistent, detailed, spatially-explicit datasets—how siting constraints to avoid impacts on natural and working lands in the Western United States are likely to affect technology choices, amount of generation and transmission capacity, system costs, and environmental impacts of pathways that achieve climate targets (Executive Order S-3-05). This study expands on related existing studies [11, 12] by examining the implications of the geographic availability of renewable resources in the Western Interconnection for import to California and examining pathways to achieving California's ambitious renewable and zero-carbon electricity policy by mid-century.

We first estimate the quantity and quality of onshore wind, solar, and geothermal energy potential under four levels of environmental siting considerations in 11 states in the Western United States. We use these environmentally-constrained resource estimates as inputs in RESOLVE. With these inputs, RESOLVE creates land-constrained optimal electricity generation portfolios that achieve the economy-wide GHG target of 80% below 1990 levels by 2050, and puts California on a path to meeting SB 100 as these scenarios deliver 102-110% renewable or zero-carbon electricity by 2050. We examine a high electrification pathway—a more likely and most cost-effective pathway for California—that relies predominantly on wind, solar PV, and storage technologies to meet most energy end uses [18]. In order to compare possible environmental impacts due to land conversion from infrastructure development, we use a geospatial site suitability model and a geospatial site selection model (ORB [11] and MapRE in conjunction with the RESOLVE model to identify each portfolio's spatial build-out of generation sites and transmission corridors and estimate the area of natural and working lands impacted. We examine how California's current resource availability assumptions, along with other variables such as lower battery costs, higher behind-the-meter solar photovoltaic (PV) adoption, and access to other states' renewable resources (states closest to California or all states in the Western Electricity Coordinating Council) affect outcomes such as California's generation portfolios' technology mix, the location and extent of environmental impacts, and system costs.

2 Methods

2.1 Methods overview

The methodological workflow is comprised of five key steps (Fig. 1). Step 1 (Section 2.2) consists of spatial environmental data gathering (representing ecological, agricultural, cultural, and other natural resource values). In this step, we constructed four Environmental Exclusion Categories and designed four different levels of siting protections for wind, solar, and geothermal power plants. The second step uses the Environmental Exclusion Categories, along with spatial data on socio-economic and technical siting criteria for renewable energy, to identify suitable sites for development of each technology (Section 2.3). The purpose of Step 2 is to identify potential locations of future wind, solar, and geothermal power plants and to construct a supply curve based on these locations. This forms the list of candidate supply-side power generation resources which will be available as inputs to the capacity expansion model. The supply curve is comprised of renewable energy resources and their associated 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 [12], which is a suite of spatial modeling tools that perform site suitability and site selection analyses for planning the spatial build-out of new wind, solar, and geothermal technologies. The ORB framework includes the Renewable Energy Zoning Tools developed under the MapRE (Multi-criteria Analysis Planning Renewable Energy) Initiative [19], 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.

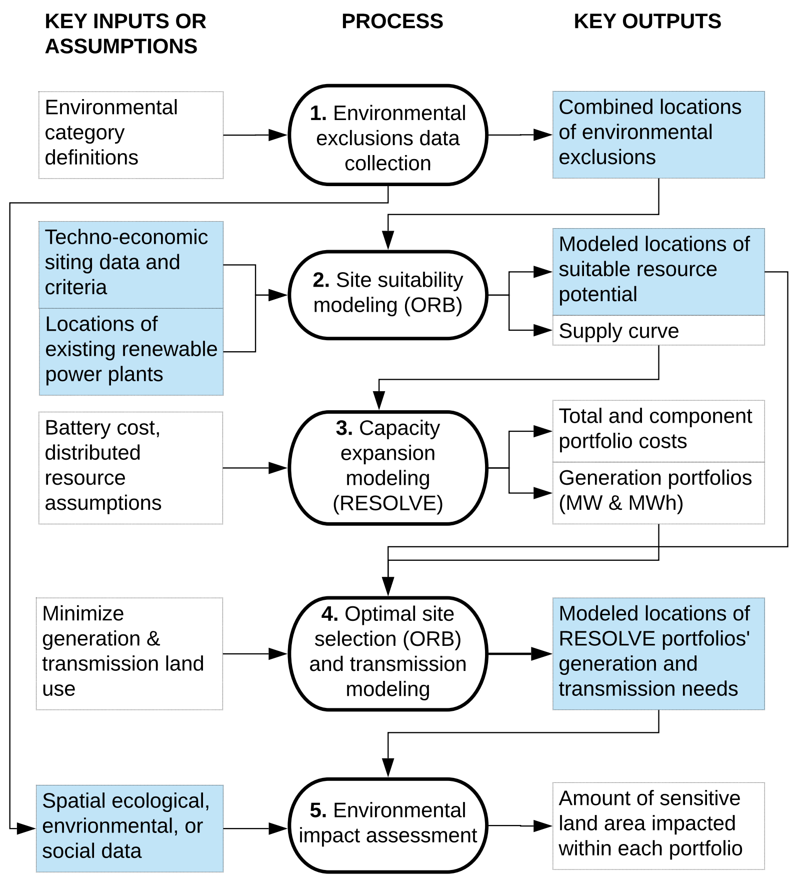


Figure 1: Flow diagram of key methodological inputs, processes, and outputs. Blue boxes indicate spatially-explicit inputs or outputs. RESOLVE and Optimal Renewable energy Build-out (ORB) are the two main models used in the study.

In Step 3, we modify the supply curve inputs and assumptions of RESOLVE, an electricity sector capacity expansion model used by the state of California for energy planning (Section 2.4). From the environmentally constrained supply curve, RESOLVE selects certain quantities of candidate resources to create generation portfolios. These differ in their input assumptions, but all satisfy the emissions reduction target of 80% reductions below 1990s levels by 2050. By varying assumptions in ORB (Step 2) and RESOLVE (Step 3), we explored the outcomes of 1) applying different Environmental Exclusion Categories to resource availability (Siting Levels 1, 2, 3, and 4, Section 2.5.1); 2) expanding geographic availability of renewable resources in the Western U.S.(*In-State*, *Part West*, and *Full West* Geographic cases; Section 2.5.2); 3) relaxing existing constraints on renewable resource assumptions in RESOLVE (*Constrained* and *Unconstrained* Resource Assumption cases, Section 2.5.3); 4) reducing battery costs (Battery cost sensitivity, section 2.5.4); and 5) increasing behind-the-meter PV adoption (Distributed Energy Resources sensitivity, section 2.5.4). By varying these input assumptions, RESOLVE generated 61 generation portfolios.

In Step 4, the ORB model then takes the output portfolios of the RESOLVE model and determines optimal siting locations, in contiguous development zones of 1 to 10 km^2, for utility-scale renewable power plants that will collectively generate the amount of electricity energy specified in each portfolio (Section 2.6). The site selection process is based on maximizing resource quality and minimizing distance proximity to existing and planned transmission corridors. The resulting modeled project locations are used to assess the overall environmental impacts of each portfolio in the fifth and final step of the analysis (Section 2.7). In step 5, we perform a "Strategic Environmental Assessment" by calculating the area of overlap between Selected Project Areas 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., Audubon Important Bird Areas, wetlands, eagle habitat) capturing focal species and habitat in recent power plant siting cases, and agricultural lands and rangelands.

2.2 Step 1. Environmental exclusions definitions and data collection

The gathering and compiling of environmental data for this study was informed by conventions established in prior work [12, 15, 20–26]. Following prior studies, we aggregated environmental data into four categories. These data types, which we refer to as Environmental Exclusion Categories, range from low to moderate and high levels of protection for lands with high conservation value and intactness. The definitions of the four Environmental Exclusion Categories are as follows (see Supporting Information [SI] Tables 10–13 and the full spreadsheet linked here for an exhaustive list of individual datasets in each Category):

- **Environmental Exclusion Category 1 (Legally protected)**: Areas with existing legal restrictions against energy development. (Examples: National Wildlife Refuge, National Parks)
- **Environmental Exclusion Category 2 (Administratively protected)**: Areas where the siting of energy requires consultation or triggers a review process to primarily protect ecological values, cultural values, or natural characteristics. This Category includes areas with existing administrative and legal designations by federal or state public agencies where state or federal law requires consultation or review. This Category includes tribal lands, as these areas are subject to the authority of Tribes, or nations, to determine if utility-scale renewable energy development is an appropriate or allowable use. Lands owned by non-governmental organizations (NGOs) that have conservation obligations also included in this Category. Multiple-use federal lands such as Forest Service lands without additional designations were not included in this Category, although in some prior studies they have been. (Examples: Critical Habitat for Threatened or Endangered Species, Sage Grouse Priority Habitat Management Areas, vernal pools and Wetlands, tribal lands)
- **Environmental Exclusion Category 3 (High conservation value)**: Areas with high conservation value as determined through multi-state or ecoregional analysis (e.g., state, federal, academic, NGO) primarily characterizing the ecological characteristics of a location. This category may also include lands that have social, economic, or cultural value. Prime

farmlands as determined by U.S. Department of Agriculture (USDA) are also included in this Category. Despite their conservation value, these lands typically do not have formal conservation protections. (Examples: Prime Farmland, Important Bird Areas, big game priority habitat, The Nature Conservancy Ecologically Core Areas)

- **Environmental Exclusion Category 4 (Landscape Intactness)**: Lands with potential conservation value based on their contribution to intact landscape structure. This Category includes lands that maintain habitat connectivity or have high landscape intactness (low habitat fragmentation). Again, despite their conservation value, these lands typically do not have formal conservation protections. (Examples: landscape intactness, wildlife corridors)

As a guiding principle for the environmental and land use data compilation, we strove for consistency with prior work. Where prior work included transparent peer review, public stakeholder processes, and agency adoption of the final work product, these products were prioritized for accurate incorporation into this study. However, there were many land use types that did not fit neatly into categories, where treatment varied in prior studies, and where discretionary judgment was applied. These areas are described briefly below, with further Supporting Information and a comparison of datasets included in other similar studies found in Supporting Information [SI] Tables 10–13.

Studies vary in their treatment of the following area types: protected areas identified in different versions of PAD-US (the Protected Areas Database of the U.S. created by the U.S. Geological Survey and Conservation Biology Institute), multiple-use public lands (e.g., state and national forests), critical habitat, big game habitat, and species-related information. This study fills gaps in prior studies (e.g., improving west-wide treatment of wetlands, important habitat for non-listed species, Audubon Important Bird Areas, tribal lands, agricultural lands, county zoning ordinances, landscape intactness). Although we considered including a least-conflict land category such as that identified in A Path Forward, and that identified in the TNC Site Wind Right study, we decided not to include such a layer, as the intent of this study is to conduct scenario analysis and not to provide direct siting guidance. We did, however, include data that were used to inform the identification of least conflict areas. See Supporting Information (Tables 10–13 and the full spreadsheet linked here) for more detailed descriptions of data, rationale for their categorization, and their sources.

The draft list of data layers and categorization decisions were subjected to several rounds of review, and comments were incorporated from the following: The Nature Conservancy (TNC) state chapters, the TNC Site Wind Right project team, and several peer NGOs. After review and refinement, we converged on a final list of more than 250 data layers for Categories 1, 2, 3, and 4 (SI Tables 10–13). For each Category, the constituent data layers were aggregated into a single layer. These aggregated layers were later applied in the site suitability analysis (Step 2, Section 2.3) and in the strategic environmental assessment (Step 5, Section 2.7).

2.3 Step 2. Renewable resource assessment (ORB)

2.3.1 Site suitability modeling

The purpose of site suitability modeling is to identify areas that would be suitable for large-scale terrestrial renewable energy development, based on several siting criteria. The result of site suitability modeling is a spatial dataset representing wind and solar resource potential areas in the form of vector polygons and associated attributes. Attributes include Candidate Project Area size (km^2), potential capacity (MW), and capacity factor (modeled from irradiance and wind speed). These attributes are necessary components for constructing a generation "supply curve," which is an important input for the capacity expansion model, RESOLVE.

Technical and economic data inputs For this study, site suitability modeling of wind and solar potential closely followed methods described in several previous studies [11, 12, 19]. To identify technically and economically suitable areas for renewable energy development, we used spatial datasets that capture technical (e.g., competitive wind resource locations), physical (e.g., slope, water bodies), and socio-economic or hazardous (e.g., densely populated areas, military zones, railways, airports, mines, flood zones) siting considerations. We used the National Renewable Energy Lab (NREL)'s WIND Toolkit metadata, which reports annual average capacity factor per point location, for the basis of economically and technically viable wind locations in the U.S. [27]. We did not apply a capacity factor threshold for solar PV suitability, but allowed RESOLVE to select solar capacity from each RESOLVE Zone based on capacity factors generated from NREL's System Advisor Model (SAM) [28]. A list of RESOLVE Zones can be found in the RESOLVE User Manual as Figure 7: In-state transmission zones in RESOLVE. A more complete list can be found in the RESOLVE "User interface" workbook, "REN_Candidate" sheet [17]. For feasible geothermal locations, we relied on the Western Renewable Energy Zone's study of resources in the Western U.S. [21], which is also the source for RESOLVE's current geothermal resource availability inputs. We modeled the geothermal facilities' footprint using the appropriate buffer radius assuming 25.5 MW km^{-2} and the capacity (MW) in the attribute table. See SI Table 6 for sources of all non-environmental input datasets. Although we modeled suitable sites for geothermal, the amount of geothermal potential in the RESOLVE Base case supply curve was significantly lower compared to potential estimates for wind and solar (SI Figs. 14B–15B). Thus, while we show geothermal findings in the results figures, we focus on discussion of wind and solar results.

We did not include offshore wind and concentrating solar power (CSP). Offshore wind resources were not included primarily to maintain consistency with assumptions in existing versions of the RESOLVE model, in which offshore wind has not yet been incorporated. Secondarily, the publicly available data for offshore wind along the Pacific Coast is not yet well enough characterized and vetted in stakeholder processes for incorporation at the time of the study. Although CSP is included in the supply curve for existing versions of RESOLVE, its estimated capital costs are too prohibitive for new capacity to be selected under any scenario.

Identification of suitable sites and Candidate Project Areas In order to create resource potential maps, we used Stage 1 of the MapRE (Multi-criteria Analysis for Planning Renewable Energy) Zoning Tool [19], which uses raster-based algebraic geoprocessing functions and siting assumptions specified for each dataset and technology (SI Table 6). MapRE Zone Tools are the graphical user interface version of the ORB tools and are part of the ORB suite of siting tools. We created a single 250 meter resolution raster of areas that satisfy techno-economic siting criteria for each technology (i.e., suitability map). For each technology, we removed the Environmental Exclusion Categories (section 2.2) from the techno-economic suitability map to create four Siting Levels (SL) of suitable areas that meet both techno-economic and environmental siting criteria (see Section 2.5.1 for a full description of Siting Levels). In order to simulate potential project locations within suitable areas identified, we used Stage 2 of the MapRE Zoning Tool, or the "project creation stage," to create Candidate Project Areas (CPAs) by subdividing suitable areas into smaller, utility-scale project-sized areas. Solar potential project areas ranged from 1 km^2 to 7 km^2 (or about 30–270 MW), with the vast majority of solar CPAs designed to be 4 km^2 or to accommodate approximately 120 MW of solar capacity. Wind CPAs ranged from 1 km^2 to 10 km^2 (or about 6.1–61 MW), with the vast majority of wind CPAs designed to be 9 km^2 or to accommodate approximately 55 MW of wind capacity. We eliminated CPAs less than 1 km^2, as these parcels would typically be considered too small for commercial utility-scale renewable energy development.

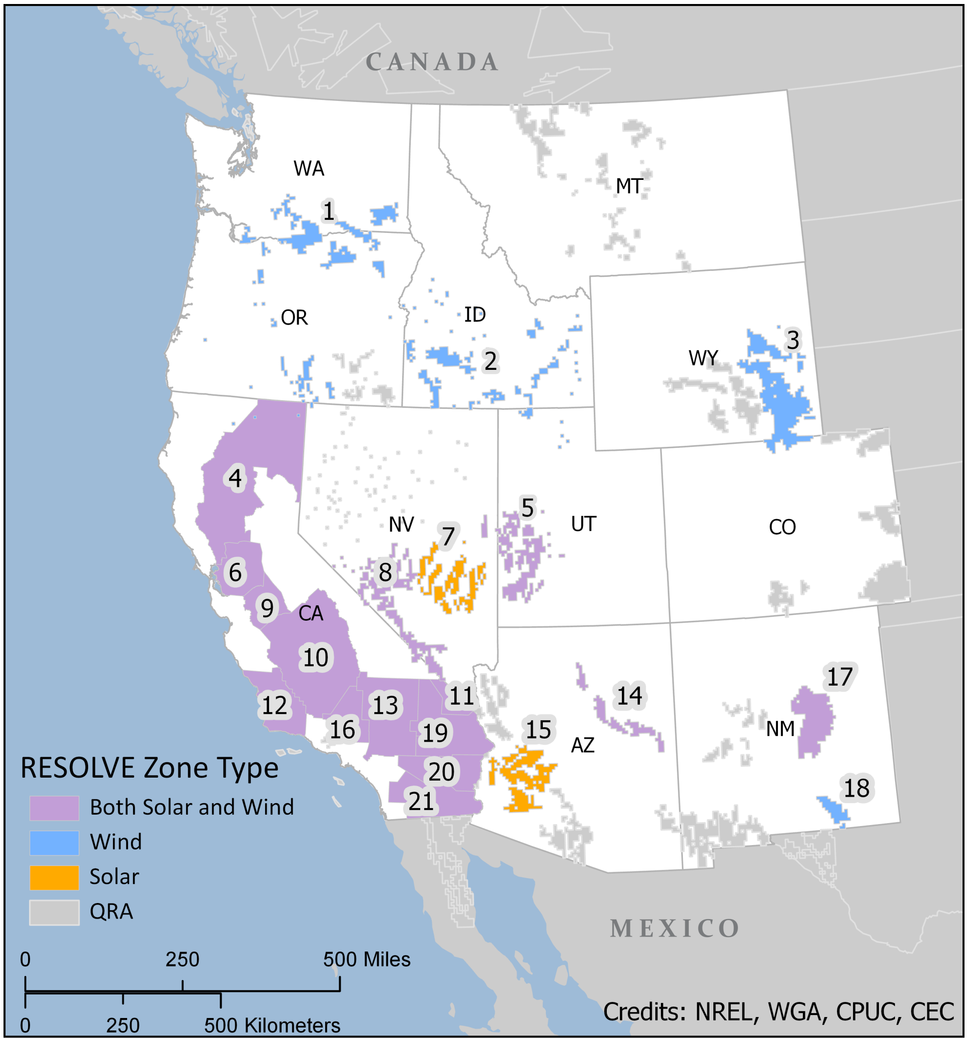
Creation of candidate supply curves for capacity expansion modeling To create supply curves for RESOLVE, we summarized site suitability results for each RESOLVE Zone. Each row in the supply curve table corresponds to an area within which resources and their attributes have been aggregated or averaged (i.e., RESOLVE Zones in this study). From this supply curve, RESOLVE selects certain quantities of candidate resources in a capacity expansion optimization. Within California, RESOLVE Zones are comprised of one or more Super Competitive Renewable Energy Zones, regions identified in previous California renewable energy planning processes and studies [20, 29] (Fig. 2). Outside of California and within the Western Electricity Coordinating Council (WECC) states, RESOLVE Zones are collections of various Qualifying Resource Areas (QRA) [21] specific to each technology (Fig. 2).

To generate these RESOLVE-specific supply curves, we spatially averaged capacity factors (CF) across all CPAs (CFs are from resource datasets listed in SI Table 6) and calculated the megawatts (MW) of potential generation capacity for each technology (assuming 6.1 MW km^{-2} for wind [30], 30 MW km^{-2} for solar PV [31], and 25.5 MW km^{-2} for geothermal [31]), for each RESOLVE Zone or state, and for each Siting Level (see Section 2.5.1 for explanation of Siting Levels). These Zone- and state-specific MW and CF values formed the basis for the supply curve inputs for RESOLVE. See SI Figures 14, 15 for plotted supply curves. We made modifications to the supply curve to account for wind capacity that can be accessed via existing transmission lines. RESOLVE assumes that 500 MW and 1500 MW of wind potential in New Mexico and Pacific Northwest RESOLVE Zones, respectively, can utilize existing transmission infrastructure (and thus have lower system costs). Because CPAs represent all suitable sites for energy development, in order to avoid over-estimating candidate wind resources, we subtracted these 500 MW and 1500 MW of "existing transmission" candidate resource capacity amounts from the total capacity in all wind Candidate Project Areas in the New Mexico and Pacific Northwest RESOLVE Zones. This meant that the sum of CPAs in New Mexico RESOLVE Zones and the "existing transmission" resources in New Mexico should equal the total available CPAs identified for New Mexico. The "existing transmission" resources in RESOLVE are additional, non-spatial resources, with no associated project footprint. As such, RESOLVE treats them as additional to the CPAs. When selected by RESOLVE, these resources must be assigned to a spatial footprint. This subtraction essentially completes this assignment.

Because the existing policy assumptions and the version of RESOLVE currently being used in California energy planning do not include Montana and Colorado, the supply curve inputs for the RESOLVE capacity expansion model and all subsequent steps do not include Montana and Colorado wind, solar, or geothermal resources.

2.3.2 Accounting for existing power plant footprints

The results of the above site suitability modeling steps include maps of possible locations for wind and solar development. For many of these possible locations, however, there are wind and solar power plants that have already been constructed. Existing power plants must be removed from



Map Label	RESOLVE Zone	Map Label	RESOLVE Zone	Map Label	RESOLVE Zone
1	Pacific Northwest Wind	8	Southern Nevada Wind and Solar	15	Arizona Solar
2	Idaho Wind	9	Central Valley North Los Banos	16	Tehachapi
3	Wyoming Wind	10	Westlands	17	New Mexico Wind and Solar
4	Northern California	11	Mountain Pass El Dorado	18	New Mexico Wind
5	Utah Wind and Solar	12	Greater Carrizo	19	Southern California Desert
6	Solano	13	Kramer Inyokern	20	Riverside East Palm Springs
7	Southern Nevada Solar	14	Arizona Wind and Solar	21	Greater Imperial

Figure 2: RESOLVE Zone names and locations for solar-only, wind-only, and both technologies. Other Qualifying Resource Areas (QRA) that were not used to create RESOLVE Zones are also shown in grey.

the CPAs and supply curve in order to ensure that the supply curve only contains undeveloped future candidate projects. By removing existing projects, we enable RESOLVE to optimize future capacity expansion investment decisions and avoid overestimating the resource potential.

For existing wind facilities, we used a combination of Ventyx/ABB wind farm boundaries and theU.S.Wind Turbine Database (USWTD) to fill in gaps in both datasets (SI 7). We selected only turbines greater than 1 MW (or with no MW data but built after the year 2000) for removal as existing projects. In order to account for re-powering potential, for older, smaller wind turbine models, we assumed that existing wind turbines smaller than 1 MW or with online dates prior to the year 2000 could be re-powered. This increased the candidate wind resource potential significantly in some areas with existing wind turbines (e.g., the Tehachapi region of California). The remaining

>1MW turbines were buffered using 1200 meters. This was the distance that best approximated the Ventyx wind farm boundaries in the locations where turbines and farm boundaries overlapped. Because substantially large regions of several Ventyx "wind farms" did not contain turbines (as verified by overlaying the USWTD points and visual inspection of recent satellite imagery), we clipped the Ventyx wind farm boundary feature classes to the buffered USWTD extent (creating the "corrected Ventyx boundaries" polygons), which effectively removes areas in the Ventyx dataset that do not have existing wind turbines. However, we also found that the Ventyx wind farm boundary did not encompass all existing wind turbines in the USWTD, so we isolated these turbines without wind boundaries and created wind farm boundaries for them using a 750-m buffer radius (creating the "additional USWTD boundaries" polygons). Finally, we merged the corrected Ventyx and additional USWTD polygons to have a gap-filled existing wind turbine footprint dataset. These areas with existing wind turbines were removed from the candidate wind project areas.

For solar resource potential, we used the TNC solar array footprint dataset for within California [32] and the USGS national solar array footprint datasets for all other states in the study [33] (SI Table 7). These existing solar projects were removed from the candidate solar project areas.

2.4 Step 3. Capacity expansion modeling (RESOLVE)

2.4.1 Overview of RESOLVE

The capacity expansion modeling was carried out using Energy and Environmental Economics' (E3) RESOLVE model, developed for the California Energy Commission (CEC) Deep Decarbonization in a High Renewables Future study [18]. The CEC study evaluates long-term scenarios that achieve a 40% reduction in economy-wide greenhouse gas (GHG) emissions by 2030 and an 80% reduction by 2050, relative to 1990 levels. The RESOLVE model determines the resource portfolios necessary for the electric sector to reliably serve loads without exceeding a sectoral carbon budget consistent with meeting these goals.

RESOLVE uses linear programming to identify optimal long-term generation and transmission investments in an electricity system, subject to reliability, technical, and policy constraints. Designed specifically to address the capacity expansion questions for systems seeking to integrate large quantities of variable renewable resources, RESOLVE layers capacity expansion logic on top of a production cost model to determine the least-cost investment plan, accounting for both the up-front capital costs of new resources and the variable costs to operate the grid reliably over time. In an environment in which most new investments in the electricity system have fixed costs significantly larger than their variable operating costs, this type of model provides a strong foundation to identify potential investment benefits associated with alternative scenarios.

RESOLVE's optimization capabilities enable it to select from among a wide range of potential new resources. For this study, the options for new investments are limited to those technologies that are commercially available today. This approach ensures that the GHG reduction portfolios developed in this study can be achieved without relying on assumed future technological breakthroughs. A more detailed description of the RESOLVE model structure and operations, along with a publicly available version of the model used in the state's Integrated Resource Plan (IRP) process, are available on the California Public Utilities Commission (CPUC) website [17]. Because this study was designed to look at the entire state of California's electricity demand on the 2050 timeframe, the CEC version of the model was the appropriate choice.

2.4.2 Key assumptions

The inputs and assumptions used in this analysis are generally consistent with those used in the CEC study, but certain parameters were updated to allow modeling of the specific scenarios for this study. In the case of renewable and storage costs, values were updated to include the latest available data on the costs of resources.

Electricity Demand The electricity demand forecast is consistent with the ”high electrification” scenario from the CEC Deep Decarbonization study, which achieves California’s long-term emission goals through extensive electrification of space and water heating loads in buildings and a heavily decarbonized electricity sector. The demand forecast from the CEC Deep Decarbonization study incorporates findings from recent studies regarding impacts of climate change on California’s electricity sector, including a lower average availability of hydroelectric generation available to meet California demand in 2050, and higher average temperatures, which result in lower heating demands in buildings and higher air-conditioning demands. After exploring ten “mitigation” scenarios, the Deep Decarbonization study identified the “high electrification” scenario as one of the lower-cost, lower-risk mitigation scenarios. The “high electrification” scenario assumes high levels of energy efficiency and conservation, renewable electricity, and electrification of buildings and transportation, with reliance on biomethane in the pipeline to serve mainly industrial end uses. It also assumes a transition of the state’s buildings from using natural gas to low-carbon electricity for heating demands. More details on the assumptions behind this scenario can be found in the CEC publication [7].

RESOLVE Base resource potential The RESOLVE model contains a list of candidate resources also referred to as the supply curve. The supply curve is a list of resource potentials identified in zones, often referred to simply as “resource potential.” The current versions of RESOLVE contain resource potential estimates, which are referred to here as the “RESOLVE Base” case [20, 21]. In most scenarios, the “RESOLVE Base” resource potential estimates only assume Categories 1 and 2 lands to be protected in California and west-wide; however, characterization of Category 2 lands outside of California is incomplete. All other lands (outside of the techno-economic-environmental screens) are assumed available for renewable energy development in the “RESOLVE Base” scenarios. However, there are differences in the Category definitions and their underlying datasets between the current study and the “RESOLVE Base.”

The resource potential values developed for the CPUC IRP RESOLVE model used only 5% of the total solar technical potential from the California RESOLVE zones, reflecting concerns about the level of conversion to industrial land use associated with developing the full potential in any given resource area. In the CEC study and this analysis, this assumption was expanded to 20% of the technical potential due to the increase in demand for clean electricity in 2050 relative to 2030. The estimated resource potential in the CEC study for all other supply-side resources is consistent with the amounts assumed in the CPUC RESOLVE model. For creating Siting Level portfolios constrained by the Environmental Exclusion Categories, these RESOLVE Base resource potential values were replaced by estimates derived from the site suitability analysis (Section 2.3.1).

The existing versions of the RESOLVE model currently being used by state agencies in California, do not include any wind or solar resource potential in Colorado or Montana. Colorado resources are not included because Colorado is not well electrically interconnected to export power to California. Montana resources were not included because the geographic scope was limited to what were considered the most economically attractive and feasible resources at the time. For this study, we addressed a broader geographic extent and longer timeframe than prior studies, and thus we did complete a site suitability analysis and resource potential assessment for Colorado and Montana. However, for consistency with existing RESOLVE model conventions in state energy planning forums, we did not incorporate Montana or Colorado zones into the supply curve. RESOLVE Zones are currently being used in California energy planning, and so we retain the RESOLVE Zone convention for consistency.

Existing or Baseline Resources In addition to candidate future resources, the RESOLVE model also includes a list of baseline resources (for all renewable and conventional technologies, including nuclear and hydropower; this is the list of contracts included in the RESOLVE model User Interface workbook, within the sheet called "REN_Existing Resources." This list represents commercial projects that are existing and under development—including projects with online dates in the past and in the future. This list of contracts was incorporated into the site selection process, and hence removed from the future candidate resource potential.

Resource Cost Assumptions Each candidate resource in the RESOLVE model supply curve has capital cost attributes. Capital costs for solar, wind, batteries, etc. are updated periodically. For this study, capital costs for solar, and battery storage resources were updated to reflect recent cost estimates from the National Renewable Energy Laboratory's (NREL) Annual Technology Baseline (ATB) [34] and Lazard's Levelized Cost of Storage studies [35]. Table 2 shows the capital cost differences among the three versions of the model.

Table 2: Capital cost assumption comparisons between different RESOLVE versions

Capital Cost Comparison (2016 $/kW)						
Technology	CPUC IRP 2020	CPUC IRP 2050	CEC Study 2020	CEC Study 2050	This Study 2020	This Study 2050
Solar PV – 1-axis Tracking	$1,862	$1,692	$1,862	$1,692	$2,108	$1,916
Li-Ion Battery (4 hr duration)	$2,135	$1,407	$2,427	$1,874	$1,013	$815

The solar PV costs in this study are higher than the costs assumed in the CPUC IRP and the CEC study because of differences in data sources used as the basis for the capital cost assumptions. Previous capital cost assumptions were based on 2016 estimates provided by Black & Veatch as part of the IRP process. The latest cost assumptions are based on estimates from NREL's ATB [34]. Forecasted battery costs for this study are lower than 2016 forecasts in the CPUC IRP and the CEC studies because of cost updates in the Lazard study used as the basis for the capital cost assumptions.

Transmission Assumptions For California zones, RESOLVE assumes a limited transmission capacity is available per zone. Beyond this available capacity, a cost is assumed for building additional transmission capacity. See Table 3 for resources able to be accommodated per transmission zone.

There are two forms of transmission costs associated with resources in the supply curve. First, for all resources (in-state and out-of-state), there is the $/kW-yr cost of transmission upgrades within CAISO once the Full Capacity Deliverability Status (FCDS) limit for the resource's associated transmission zone is exceeded (Table 24 of the RESOLVE Inputs and Assumptions [17]). Second, for the out-of-state resources, there are 2,000 MW of existing transmission capacity into California from the "Existing Northwest" (from the Pacific Northwest) and "Existing Southwest" (from New Mexico) transmission zones. Beyond this cost-free existing transmission capacity, there is a $/kW-yr cost for delivery to the California border (Table 25 of the RESOLVE Inputs and Assumptions document [17]). These transmission costs are in addition to the other costs associated with each resource, resulting in an all-in fixed $/kW-yr resource vintage cost. See RESOLVE model Inputs and Assumptions documentation for more information [17].

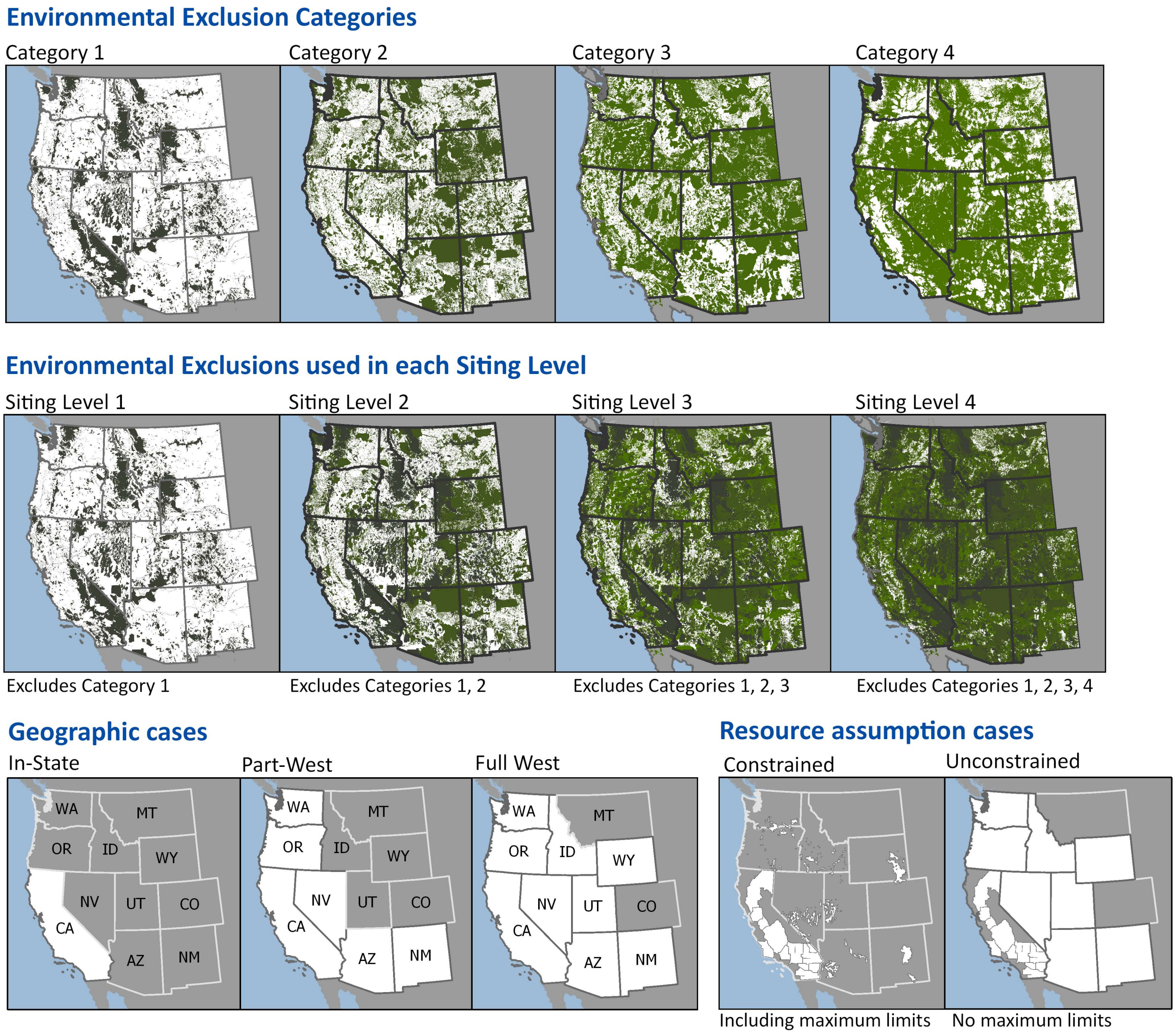
2.5 Description of cases and sensitivity assumptions

We developed several cases and modified sensitivity assumptions in order to understand the impact of the following changes: 1) applying different Environmental Exclusion Categories to resource availability (Siting Levels, Section 2.5.1); 2) expanding geographic availability of renewable resources in the Western U.S. (Geographic cases, Section 2.5.2); 3) relaxing existing constraints on renewable resource assumptions in RESOLVE (Resource Assumption cases, Section 2.5.3); 4) reducing battery costs (Battery cost sensitivity, Section 2.5.4); and 5) increasing behind-the-meter PV adoption (Distributed Energy Resources sensitivity, Section 2.5.4). See Fig. 3 for summary of cases and sensitivities examined. *Constrained* cases were identified as the core cases for this study because they are most closely aligned with existing models being used in California state planning. We refer to a case as a modification of a single assumption (e.g., Siting Level 1), whereas a scenario is a combination of cases or a set of assumptions that generate a specific result (e.g., Siting Level 1, *Full West* Geography, *Constrained* resource assumptions, base case DER, and battery cost assumptions; see sections below for an introduction and explanation of example case names).

2.5.1 Environmental Siting Levels for candidate resources

Using the Environmental Exclusion Categories (Section 2.2) and the technical and economically suitable areas (Section 2.3.1), we created four supply curves, which are referred to as Siting Levels (SL) 1, 2, 3, and 4 (Fig. 3). All Siting Levels use the same set of technical and economically suitable areas, but are additive in their use of the Environmental Exclusion Categories. That is, Siting Level 1 excludes only land area datasets in Category 1; Siting Level 2 excludes land area datasets in Categories 1 and 2; Siting Level 3 excludes land area datasets in Categories 1, 2, and 3; and Siting Level 4 excludes datasets in Categories 1, 2, 3, and 4. As such, as the Siting Level increases, more land is protected from development (Fig. 3). As described in Section 2.3.1, we created candidate resource supply curves for each of these Siting Levels using the land area in each RESOLVE Zone or state by converting km^2 to MW of capacity for each technology and calculating spatially-specific average capacity factors for each Siting Level. These supply curves were further modified to create *Constrained* and *Unconstrained* cases, as introduced and explained in Section 2.5.3 below. We compare these Siting Levels with the unmodified RESOLVE supply curve, which we refer to as the RESOLVE Base case (Section 2.4.2).

To ensure consistency with the representative RESOLVE resource temporal profiles for wind and solar generation, we adjusted the site suitability supply curve potential values using the average CF of the temporal profiles. The adjustments to capacity were necessary to ensure that the amount of energy generated by the resource (assuming load profiles and average capacity factors in RESOLVE) will match the expected energy based on the supply curve. To do this, we calculated the amount of generation (MWh) using the resource potential and the average CF for each RESOLVE Zone



Battery Cost sensitivity cases

	Cost in 2050 ($/kWh-yr)
Base battery cost	$29.89
Low battery cost	$22.67

Distributed Energy Resources sensitivity cases

	GWh	GW	% of technical potenal in CA
Base DER	49,207	24.7	19.2%
High DER	65,966	33.2	25.7%

Figure 3: Summary of assumptions for the following cases and sensitivities examined: Siting Levels, Geographic cases, Resource Assumption cases, Battery Cost and Distributed Energy Resources sensitivity cases. Siting Levels (row 2) use the Environmental Exclusion Categories (row 1) cumulatively as indicated by the corresponding color in the maps of the Categories. The three Geographic cases (row 3) include resources identified within states indicated in white in addition to 1.5 GW and 0.5 GW of wind resources in the Pacific Northwest and New Mexico, respectively (see Table 3 for more details regarding Geographic cases). The *Constrained* Resource Assumption cases restrict resource potential to within RESOLVE Zones and apply the RESOLVE Base as the maximum limit in each zone. The *Unconstrained* cases expand resources to the rest of the state and do not impose maximum limits except for New Mexico Wind in the Part West Geography.

estimated from the site suitability analysis. We then divided this value by 8760 hours and the RESOLVE temporal profiles' average CF for that zone to calculate an adjusted site suitability potential (MW). For example, if a 100 MW solar resource has a 25% capacity factor in the supply curve, but a 22% capacity factor based on the resource's generation profile, the associated capacity with that resource in RESOLVE becomes 113 MW (i.e. (25%)/(20%)*100 MW). See Figure 15 for the unadjusted supply curve values and Figure 14 for the adjusted values. For the most part, the adjustments did not result in significant changes to the original resource values.

2.5.2 Geographic cases

Three Geographic cases—also referred to as Geographies—were constructed for the analysis, representing different potential for imported out-of-state resources to meet California's need for clean electricity (Fig. 3). The *In-State* case restricts renewable resource availability to within California's borders while allowing up to 2,000 MW of out-of-state wind resources delivered to California using existing available transmission capacity (see Transmission Assumptions in Section 2.4.2). This allowance was made in order to most closely reflect existing market conditions. In the *Part West* case, RESOLVE has access to renewable resources in five other states with strong electrical ties to California. In this case, New Mexico wind resource is Constrained at 3,000 MW based on the capacity of an existing 500-kV dual-circuit HVDC transmission line. In the *Full West* case, RESOLVE has access to renewable resources across eight other states in the Western Interconnection. The *Part West* and *Full West* cases would require changes to markets and policies to allow for import of electricity at the quantities in the 2050 portfolios. Table 3 shows the zones and the maximum available resources allowed in each Geography.

Table 3: RESOLVE resources available by Geographic cases

Resource		Geographic cases	
Resource Zone	In-State	Part West	Full West
California Solar	X	X	X
California Wind	X	X	X
California Geothermal	X	X	X
Existing Northwest Transmission Wind	Constrained at 1500 MW	Constrained at 1500 MW	Constrained at 1500 MW
Existing Southwest Transmission Wind	Constrained at 500 MW	Constrained at 500 MW	Constrained at 500 MW
Utah Solar	-	-	X
Southern Nevada Solar	-	X	X
Arizona Solar	-	X	X
New Mexico Solar	-	-	X
Pacific Northwest Wind (new transmission)	-	-	X
Idaho Wind	-	-	X
Utah Wind	-	-	X
Wyoming Wind (new transmission)	-	-	X
Southern Nevada Wind	-	X	X
Arizona Wind	-	X	X
New Mexico Wind (new transmission)	-	Constrained at 3000 MW	X
Pacific Northwest Geothermal	-	X	X
Southern Nevada Geothermal	-	X	X

2.5.3 *Constrained* and *Unconstrained* sensitivity cases

The publicly-available RESOLVE model used in the California Public Utilities Commission's (CPUC) Integrated Resource Planning (IRP) process assumes that out-of-state development is limited to "Qualifying Resource Areas" (QRA) identified by Black and Veatch through the 2009 Western Renewable Energy Zones study [21]. This assumption stands as the current policy default. As explained in Section 2.3.1, these QRAs have been reclassified as "RESOLVE Zones". As previously explained (Section 2.4.2), the CPUC RESOLVE model "discounts" solar resources estimates within California by 95% and the CEC RESOLVE model discounts it by 80%. For example, if a resource assessment identified 100 GW of solar in a particular RESOLVE Zone, the CEC version of the RESOLVE model assumes 20 GW of that solar will be available for development, as reflected in the supply curve. For the *Constrained* assumptions case, we maintained these current (RESOLVE Zone and solar discount) resource assumptions. For the *Constrained* case, we also restricted non-California resource potential estimates to within these RESOLVE Zones for each Siting Level and used the lower of the two following values: the site suitability resource estimates within RESOLVE Zones and the default RESOLVE "discounted" Base case resource potential values (Figs. 2, 3).

To understand how these current resource assumptions affect cost and generation mix, we developed an *Unconstrained* sensitivity case in which the supply of out-of-state resources is not limited to RESOLVE zones, but rather is based on a "wall-to-wall" estimate of technical potential across the entire state for each of the Siting Levels (Fig. 3). Additionally, the *Unconstrained* case uses the site suitability resource potential estimates directly for all solar RESOLVE Zones, thus removing RESOLVE's "discounted" base case resource potential as the upper limit.

As an example of how the *Constrained* and *Unconstrained* cases were developed for the present study, consider the Westlands RESOLVE Zone in central California. Within the Westlands RESOLVE Zone, the default RESOLVE Base solar potential in the existing model is 28.1 GW. The site suitability analysis for this study identified a much greater solar resource potential—210 GW—under *Unconstrained* assumptions in Siting Level 3 (which assume no development on high conservation value lands). Thus, for Westlands, we assumed 28.1 GW of solar potential in the *Constrained* case and 210 GW of solar potential in the *Unconstrained* case for SL 3 (SI Fig. 14). Again, potential values are options for the capacity expansion model to select from in creating an optimal generation portfolio—not all candidate renewable resources may be chosen.

As an example of how the *Constrained* and *Unconstrained* assumptions differ for regions outside of California, consider that in Siting Level (SL) 1, the estimated amount of wind resource potential within the New Mexico RESOLVE Zone is 36.1 GW (SI Fig. 15B). Looking beyond the RESOLVE Zone, the amount in the entire state of New Mexico is 190 GW (SI Fig. 15B) while the default RESOLVE Base potential is 34.6 GW (SI Fig. 14B). Thus, for New Mexico, we assumed 34.6 GW of wind potential in the *Constrained* assumptions case and 190 GW of wind potential in the *Unconstrained* assumptions case (SI Fig. 14).

2.5.4 Battery cost and distributed energy sensitivity cases

Along with the cases considered above, we considered two additional sensitivities: high behind-the-meter PV distributed energy resource (High DER) and low battery cost.

High DER sensitivity A high behind-the-meter (BTM) PV adoption forecast was developed for the High DER sensitivity analysis, using the relationship between the High BTM PV and Mid BTM

PV forecasts from the 2016 CEC Integrated Energy Policy Report (IEPR) [36]. A capacity factor of 22.7% is assumed for the DER resource. Table 4 below shows the forecast for the Base and High DER cases.

There are several publicly available DER forecasts that were considered (LBNL technical potential, NREL technical potential, IEPR). The IEPR High DER forecast is widely considered a realistic optimistic forecast, assuming faster customer adoption rates and continued falling costs. It includes more residential solar tied to Title 24 (high penetration assumes 90% of new houses built after 2020 install rooftop solar). Other publicly available forecasts may include additional considerations such as major policy changes, new incentives, and technological disruption. Because we do not have control over policies or market forces, we chose to use the forecast that assumes fulfillment of current policy mandates with expected increased adoption rates and does not assume major disruptive changes.

The RESOLVE model treats BTM PV resources as a demand modifier, reducing the total demand that will be met by the optimized resource portfolio. Assuming a projected demand of 400 TWh year^{-1} in 2050, the high BTM PV sensitivity case reduces demand by about 5%. Using NREL's estimate for technical potential of rooftop PV in California of 128.9 GW [37], the High DER scenario assumes the installation of about 25.7% of technical potential and is about 35% greater than the Base BTM assumptions (Table 4). The NREL technical potential study does not consider limits such as how much rooftop solar the distribution system can accommodate before needing upgrades, nor does it consider load balancing costs. These and other integration challenges are why economic potential typically tends to be less than the technical potential for a resource, as is the case here.

For more detail about the High DER assumptions, see the IEPR California Energy Demand Updated Forecast 2016, and the independent 2018 Distribution Working Group Forecast Report by Itron, which confirms the robustness of the IEPR forecast. The amount of BTM PV assumed in the model is separate from, and additional to the 40 GW of distributed solar that is available for RESOLVE's optimization as a supply-side candidate resource. It should be noted that the supply-side distributed solar in RESOLVE is characterized with the cost and generation profiles of a typical parking lot and warehouse rooftop solar array.

Table 4: Behind-the-meter PV forecast generation (GWh) and capacity (GW) assumptions for the base case and high distributed energy (High DER) sensitivity

BTM PV	2020	2025	2030	2035	2040	2045	2050
Base DER (GWh)	11,578	19,084	30,499	35,071	39,782	44,562	49,207
Base DER (GW)	5.82	9.60	15.3	17.6	20.0	22.4	24.7
High DER (GWh)	12,432	22,770	38,440	45,391	52,332	59,268	65,966
High DER (GW)	6.25	11.5	19.3	22.8	26.3	29.8	33.2

Low Battery Cost sensitivity We also explored the effect of an optimistic battery cost forecast by assuming 25% reduction in the levelized cost of battery storage through the modeled period [35] (Table 5).

2.6 Step 4. Site selection and transmission modeling

Table 5: Battery cost assumptions: All-In Fixed Cost, 4 hr Li-Ion Battery

Cost (2016 $/kWh-yr)	2020	2025	2030	2035	2040	2045	2050
Base Battery Cost	$38.08	$31.21	$29.88	$29.88	$29.88	$29.88	$29.887
Low Battery Cost	$27.48	$23.53	$22.67	$22.67	$22.67	$22.67	$22.67

2.6.1 Generation site selection

The RESOLVE model selected an amount of generation from each spatially coarse RESOLVE Zones. In this step, we spatially disaggregated the generation and assigned each MWh to locations within each RESOLVE Zone by selecting CPAs to meet each portfolio's technology-specific generation requirements. This site selection step is necessary because impacts to natural and working lands vary significantly by location, and power plants have specific siting requirements that make them more likely to be sited in some areas over others. This approach models the possible build-out of infrastructure and enables a "strategic environmental assessment" of each portfolio, enabling comparison of portfolios by their modeled overall impact on natural and working lands (Section 2.3.1).

Attribute calculations We calculated the following set of attributes for each CPA, with details for specific calculations described in subsequent paragraphs: generation land area, Euclidean distance to the nearest existing or planned transmission line or the interconnection/gen-tie distance (i.e., transmission line to interconnect the new generator with the grid), gen-tie land area, adjusted gen-tie land area (see explanation below), total land area (generation and gen-tie), estimated generation capacity (MW), area-weighted average capacity factor (CF), area-weighted average CF adjusted using RESOLVE assumptions, annual average generation in MWh, the average total (generation and gen-tie) land use efficiency in MWh km^{-2}, and distance to the nearest "RPS executed" wind or solar power plant. We performed these attribute calculations for each CPA after removing other technologies' selected CPAs to account for changes in land area due to removal of previously selected CPAs. For example, if a CPA was selected as the site of a future wind project to fulfill the generation requirements of a portfolio, then that CPA was removed from the solar resource potential.

We then calculated gen-tie paths distances for each CPA. We assumed developers of selected CPAs would need to permit and develop interconnection corridors to the nearest existing transmission line >69 kV (data from the California Energy Commission and Ventyx/ABB) or an interstate planned transmission line in "advanced development" (SI Table 7). As in the ORB study [12], Euclidean distances from each CPA to the nearest transmission line were multiplied by a rule-of-thumb factor of 1.3 [12] in order to account for the additional length required due to topography and other environmental or social right-of-way constraints. Gen-tie Euclidean distances were then multiplied by an average transmission corridor width of 76 meters to estimate gen-tie land area. Since the sizes of CPAs span a large range and to avoid systematically reducing the total land use efficiency (MWh km^{-2}) of smaller CPAs as a result of a fixed interconnection area, we applied a correction factor to the gen-tie area using the ratio of the CPA area (as small as 1 km^2) to the largest possible CPA area (10 km^2 for wind and 7 km^2 for solar). This correction results in a fixed generation-to-interconnection area ratio for CPAs of different sizes that are the same distance from the nearest transmission line and have the same capacity factor. Note, however, that the least-cost gen-tie paths modeled after the generation site selection step (Section 2.6.2), not these adjusted

Euclidean distance gen-tie areas, are the areas that are finally reported in the results section as transmission land use requirements.

Wind and solar average CFs per RESOLVE Zone in the RESOLVE Base case differ from the area-weighted average CFs estimated from site suitability renewable resource CFs (see Section 2.4 for an explanation). Thus, to achieve consistency with existing RESOLVE CFs for both wind and solar, we scaled the average CF per CPA using an adjustment factor calculated as the ratio of the RESOLVE Base CF to the average site suitability CF of each RESOLVE Zone in Siting Level 1. This approach assumes that SL 1 resource assumptions are the most similar to the RESOLVE Base resource assumptions. We applied this RESOLVE Zone and technology-specific adjustment factor to each CPA across all Siting Levels, which maintains relative variation in CFs geographically and between Siting Levels.

Selection process Due to the relatively fewer areas of spatial overlap between CPAs of different technologies across the study region (primarily as a result of not including concentrating solar power and constraining resource areas to RESOLVE Zones outside of California) and the significantly lower availability of wind resources compared to solar resources, we did not perform site selection using an integer optimization program as per the approach in the ORB study [12]. Instead, we implemented a sequential selection approach that chooses CPAs based on their potential candidacy as a planned or commercial project (based on proximity) and total (generation and estimated transmission interconnection) land use efficiency (in MWh km^{-2}). By choosing based on total land use efficiency, we effectively select sites by prioritizing those with highest resource quality (highest capacity factor) and those closest to existing transmission infrastructure (reducing gen-tie costs), which are key siting criteria used by developers as they both lower development costs per unit of generation.

The sequence of steps were as follows for each case: 1) select geothermal CPAs, 2) remove selected geothermal CPAs from available wind CPAs, 3) select wind CPAs, 4) remove selected wind and geothermal CPAs from available solar CPAs, 5) select solar CPAs. The selection process for each technology simply involved ranking the CPAs by their total land use efficiency from highest to lowest, and selecting from this ranked "supply curve" the number of CPAs that would meet the expected amount of technology-specific generation as per the RESOLVE portfolio for each scenario or sensitivity case. Due to CPAs having discrete areas and sizes, CPAs selected at the margin will not meet the RESOLVE expected generation target exactly, but will exceed the target. That is, the decision to select a CPA is discrete—and marginal CPAs are not sized to precisely meet the RESOLVE generation target. Lastly, because the underlying spatially explicit site suitability dataset or Candidate Project Areas for out-of-state RESOLVE Zones used to create the RESOLVE Base supply curve do not exist in the public domain and the methods to replicate the process of creating the site suitability dataset are also not publicly available, we used Siting Level 1 CPAs to select project areas for all RESOLVE Base cases.

We made two exceptions to the CPA selection heuristic above—the first for allowing co-location of wind and solar resources in California, and the second to account for inadequate existing power plant footprint data in California. In the first exception, we did not remove selected wind CPAs from available solar CPAs before selecting solar CPAs—but only for the *Unconstrained* assumptions cases. This assumes that areas where selected wind and solar CPAs overlap, solar panels can be constructed between wind turbines. We made this exception in order to allow the maximum capacity to be selected in RESOLVE Zones where there is significant potential for both wind and solar energy—

specifically, in the Tehachapi RESOLVE Zone in California. Because the site suitability analysis and supply curve creation steps could not account for the overlap of wind and solar CPAs, if the capacity expansion optimization does select the maximum amount of resource capacity in RESOLVE Zones with significant enough technology overlap, there would be an insufficient number of CPAs to meet the RESOLVE generation target for solar (i.e., this zone would be over-subscribed or have too much development). While this condition was only true in the *Unconstrained* assumptions case in the Tehachapi RESOLVE Zone in Siting Levels 3 and 4, for consistency, we made this exception for all *Unconstrained* cases.

The second exception was to address the fact that despite using the most recent and best available wind farm and turbine and solar array footprint data, we found that these datasets did not entirely encompass the renewable energy projects in the CPUC's database of Renewable Portfolio Standard (RPS) executed projects, which are point locations (SI Table 7). To address this issue, we identified all "RPS executed" projects locations that do not overlap with existing power plant footprint data and then labeled all CPAs within 2.5 km of these project locations to prioritize them in the site selection process (i.e., select these labeled CPAs first, in order of their land use efficiency, before selecting non-labeled CPAs). This approach assumes that proximity to these executed project locations is an adequate proxy for whether the CPA has already been developed or should be considered for development potential. Since these additional RPS executed project locations meant that we did not adequately account for the spatial footprints of existing power plants in California, we calculated more representative "selected" generation to model. We did this by subtracting the MWh estimated from existing power plants with footprint data (using RESOLVE's CFs) from RESOLVE's "baseline" and "selected" resources for California, or the "total" resource portfolio, for wind and solar and modeled the spatial build-out using these "net" selected resources. For other states and RESOLVE Zones, we used RESOLVE's "selected" resources directly, without further modification.

2.6.2 Gen-tie corridor modeling

Through the selection process described above, wind and solar resources selected by RESOLVE (total MWh per Zone) were assigned spatial project footprints. The approach generally assigned new renewable capacity to sites that were simultaneously economically attractive (having high capacity factor and low capital cost) and land use efficient (low total land area for the amount of generation, including straight-line-distance estimated gen-tie area).

Once the new resources were assigned to spatially explicit locations, it was possible to more accurately model the gen-tie route for connecting the Selected Project Areas to the existing transmission system. This then allowed a more accurate estimate of gen-tie area requirements and enabled a footprint-based strategic environmental assessment for modeled transmission projects. We modeled future gen-tie paths by performing a least cost path analysis. This analysis requires the following three inputs, described in detail below: a cost surface, a source dataset, and a destination dataset.

Cost surface The cost surface is comprised of WECC environmental data and topographic slope information (SI Table 6). The WECC environmental data was used because these layers were intentionally designed for the siting of linear features such as transmission lines [22]. We used a weighted sum to combine the slope and environmental risk layers into a cost surface, assigning the following levels of influence to the two layers: 66% slope, 34% environmental risk, per methods described in the EPRI GTC paper [38]. We intentionally set WECC Environmental Risk Category

4 values to "null" so that no gen-tie paths would be modeled across areas where development is prohibited [22].

Source dataset The source dataset was a combination of the existing and planned transmission lines (Ventyx and CEC existing transmission, planned transmission lines in advanced stages of permitting; see SI Table 7 for existing and planned energy infrastructure data sources).

Destination dataset The destination dataset was composed of wind and solar project areas that had been selected in the prior step for being economically attractive and in close proximity to existing transmission (estimated using Euclidean distance).

The resulting least cost path dataset contains drawn gen-tie lines for each Candidate Project Area or group of Candidate Project Areas (Fig. 25). We enabled the "each-zone" option so that shared interconnection paths would be identified for groups of projects. The final least cost gen-tie paths were included with the Selected Project Areas in the later step, strategic environmental assessment. In this way, we were able to assess the total impact of a new wind or solar project including the interconnection line, beyond just the area impacted by wind turbines or solar panels.

It should be noted that terrain multiplier criteria (such as landcover type, rolling hills, mountains) identified in the WECC TEPPC Transmission Cost Report [39] were not included, nor were other layers such as weighted values for residential and non-residential building densities, utility corridors, open land, forest, roads, mines, and quarries (identified in EPRI-GTC transmission line siting methods 2006). These could be added in future analyses.

2.7 Step 5. Strategic environmental assessment

We conducted a land-area-based strategic environmental assessment using the modeled generation, gen-tie, and bulk transmission spatial build-out of portfolios created in Step 4 (Section 2.6). The purpose of the strategic environmental assessment is to anticipate the impact of energy development on lands with conservation value, and to examine whether siting protections can be effective in reducing development in areas with high conservation value. For bulk transmission lines with polyline spatial data, we approximated polygon corridor footprints using the average corridor width for each line reported in the BLM Record of Decision for each utility Right-of-Way Management Plan (see SI Table 8 for widths). For each infrastructure type (generation, gen-tie, bulk transmission) and each scenario, we calculated the amount of land area that overlaps with the four Environmental Exclusion Categories, 10 other environmental metrics, and the area-weighted average housing density. Ecological and landscape metrics included critical habitat for sensitive and listed species, sage grouse habitat, Important Bird Areas, wetlands, big game corridors, eagle habitat, and wildlife linkages [40]. Working lands metrics include all agricultural land (crop and pasture land), prime farmland, and rangelands [41]. For rangelands, we used the only known publicly available rangelands extent maps for the U.S. created by Reeves and Mitchell [41] and chose the map created using the National Resources Inventory (NRI) definition of rangelands mapped using the 2001 LANDFIRE landcover dataset. We use the rangelands definition adopted by the Natural Resources Conservation Service's NRI program, which states that rangelands are, "land on which the climax or potential plant cover is composed principally of native grasses, grass-like plants, forbs or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland" [41]. Several environmental metrics are comprised of datasets that are also used in Environmental Exclusion Categories 2-4. See SI Table 9 for the underlying datasets, sources for each metric, and whether a metric was also included in an Environmental Exclusion Category.

The metrics for the strategic environmental assessment were chosen to represent two types of impacts—specific and generalized. The specific metrics (e.g., sage grouse habitat and wildlife linkages) were intended to explore areas of focus in current public discourse in energy planning forums. Thus, several specific metrics were chosen to explore trends and implications to key species. In contrast, the generalized metrics (e.g., impacts to Environmental Exclusion Category 3 lands) are meant to explore overall impacts to natural and working lands for a given resource portfolio.

3 Results

3.1 Site suitability

Site suitability results show significant solar PV potential, with the highest quantity and quality in the southwestern states (Fig. 4, SI Figs. 14A–15A). Onshore wind resources are spread throughout the Western U.S., with few remaining undeveloped resources in California but large concentrations of high-quality resources in New Mexico and Wyoming as well as along the Oregon-Washington border (Fig. 4, SI Figs. 14B–15B). 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 Siting Levels 3 and 4, respectively. The resources for these two states were not included in the capacity expansion analysis.

In the *Constrained* scenarios, land protections appear to reduce resource potential, but significantly more resources are available when areas outside of the RESOLVE Zones are considered in the *Unconstrained* scenarios. Additionally, RESOLVE maximum limits in the *Constrained* scenarios were effective at reducing solar resource potential (SI Fig. 14A) in several of the Northern California RESOLVE Zones across all Siting Levels, several Southern California RESOLVE Zones for SL 1-2, and almost all other states' Zones for SL 1-4 (except Nevada under SL 4). For many states, wind and solar resources outside of RESOLVE Zones are several times greater than those within the Zones, and for states like Nevada, Arizona, and Utah, almost all wind resources are outside of RESOLVE Zones in Siting Levels 2-4 (SI Fig. 15B). This is notable for more protective scenarios, since expanding beyond the Zones can counteract the effect of land use exclusions in Siting Levels 3 and 4. Between SL 2 and 3, wind resources are reduced from 96 GW to 25 GW in the *Constrained* case and 328 GW to 95 GW in the *Unconstrained* case (SI Fig. 15), such that it is possible to develop the same amount of wind resources while achieving SL 3 if we include resources outside of RESOLVE Zones.

Although we modeled suitable sites for geothermal, the geothermal potential in the RESOLVE Base case supply curve and identified under Siting Levels 1-4 was significantly lower compared to potential estimates for wind and solar (SI Figs. 14B–15B). Thus, while we include geothermal findings in the figures, we focus on discussion of wind and solar results.

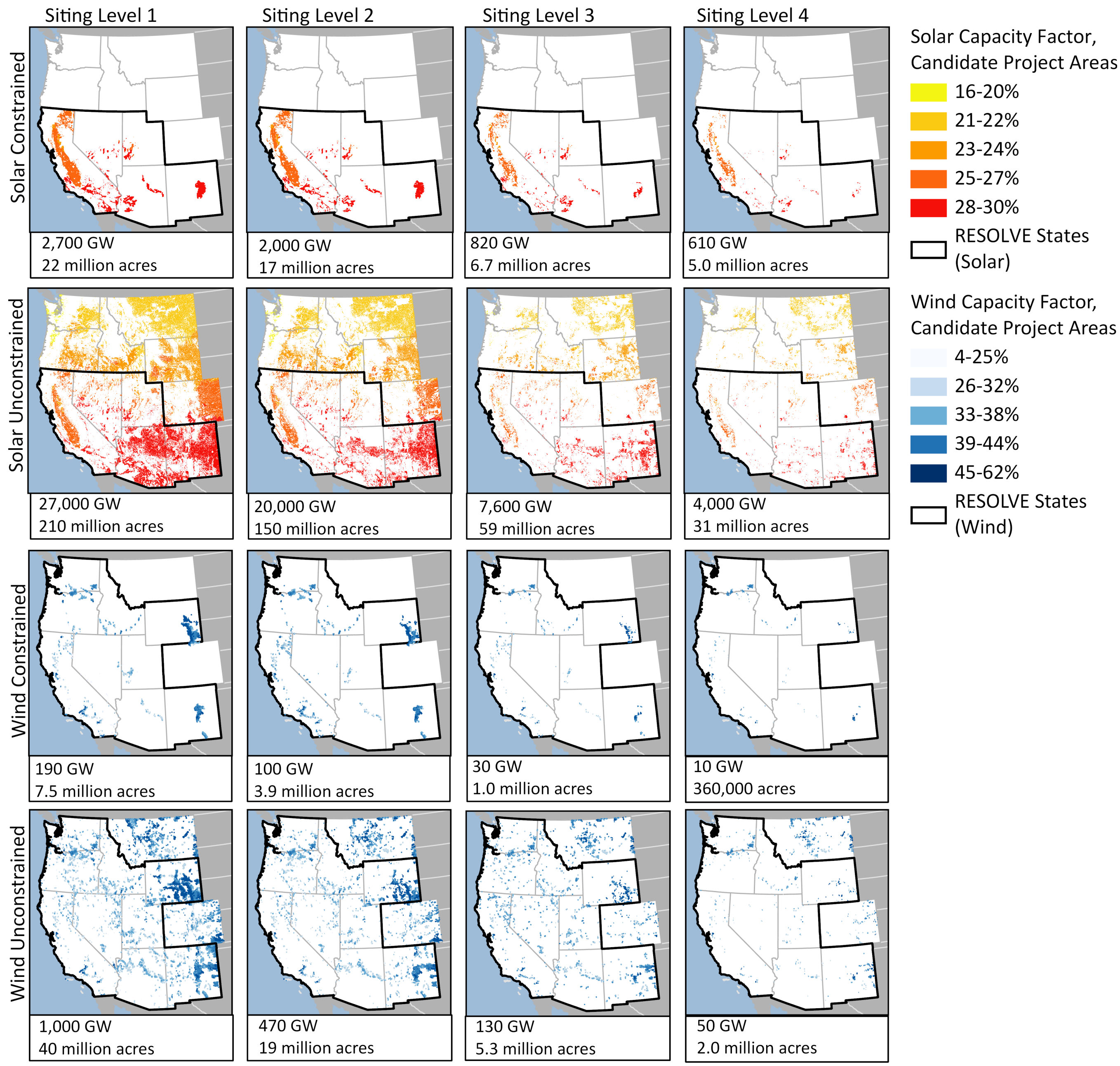


Figure 4: Site suitability maps showing solar and wind Candidate Project Areas for Siting Levels 1–4. Black outlines indicate states that were used to build supply curves for RESOLVE capacity expansion modeling. Total resource potential (summing all colored areas across all states) is indicated in text labels within each subfigure. (Note: RESOLVE supply curve potential is less than the total resource potential reported here for the state-wide maps due to some states not being included in RESOLVE. For RESOLVE supply curve potential, see Figs. 14 and 15). For context, any given 2050 portfolio typically requires no more than 180 GW of total capacity.

3.2 Selected capacity, economic costs, and spatial build-out

3.2.1 Technology mix and total resource cost of RESOLVE portfolios

We used the environmentally-constrained supply curves in the RESOLVE model to generate a resource portfolio (i.e., generation mix) for each Siting Level, as well as to explore the sensitivity of the results to higher levels of distributed energy resources (DERs) in the form of rooftop solar, lower battery costs, and removal of the spatial (i.e., RESOLVE Zone) and solar discount constraints on resource availability. In total, we produced a total of 61 different resource portfolios or scenarios, all compliant with GHG emissions reductions of 80% below 1990 levels and that generate 102%–110% renewable and zero-carbon electricity by 2050 based on retail sales.

RESOLVE optimizes the generation mix to minimize the total cost of each portfolios. We present the results in terms of the annual levelized cost of serving load in California. These cost numbers reflect not only the costs of the portfolio selected by RESOLVE, but also the continuing costs of existing resources expected to remain in service in 2050 and resources already reflected in utility plans. As an input to the model, existing and planned resource costs (totaling $64.5 billion) are not subject to cost-optimization and do not vary across scenarios. We refer to these as "unmodeled" costs. They are included in the final annual cost estimates to provide a sense of scale for the modeled costs that result from RESOLVE's optimization.

Effects of Geography Geographic availability of resources affects not only the generation mix, but also the total generation capacity required from wind, solar, and geothermal sources (102–145 GW in *Full West* vs. 135–181 GW in *In-State*; Fig. 5A). Less overall capacity and significantly greater wind capacity is selected in the *Part* and *Full West* Geographies. Grid storage decreases dramatically with increasing geographic availability of resources (declining from 50 GW to 9 GW of storage in the RESOLVE Base case, and 67 GW to 45 GW in Siting Level 4). As more wind is available, less battery storage is required (Fig. 5D). By allowing more wind resources to be selected, increasing geographic availability reduces solar capacity in California by 30%–60% for *Part West* and by 50%–70% for *Full West* (range spans resource assumption cases and Siting Levels; Fig. 6).

Across all scenarios examined—including the unmodified RESOLVE Base case—the total annual costs in 2050 ranged from roughly $97 billion to $125 billion (Fig. 5B), or between $0.24 and $0.30 per kilowatt-hour of retail sales (by comparison, California's average rate in 2018 is about $0.16 per kWh). In the RESOLVE Base case sceanrios, which all use resource availability assumptions consistent with those developed for the California Energy Commission study [7], the annual cost of generation reduces as more out-of-state resources are made available ($109 billion In-State, $105 billion in *Part West*, and $97 billion in the *Full West*; Fig. 5B). Increasing the resource availability through regional energy procurement or trade significantly reduces cost.

Effects of Siting Levels Siting Level constraints affect the generation mix as well as the total generation capacity. The amount of (available and selected) wind capacity decreases with increasing Siting Levels in the *Part West* and *Full West* scenarios. Utility-scale and distributed solar capacity increase due to increasing protections (Fig. 5A). By limiting wind availability, increased siting protections also increase the need for more battery storage, with about a 30% (*In-State*), 70% (*Part West*), and 450% (*Full West*) increase in storage between RESOLVE Base case and Siting Level 4 (Fig. 5D). The sharp rise in battery storage between Siting Levels 2 and 3 in the *Full West* Geography closely tracks the steep decline in selected wind capacity.

Siting Level constraints also affect the geographic distribution of selected capacity across states. The most dramatic redistribution is seen in Siting Levels 3 and 4 in the *Full West* Geography

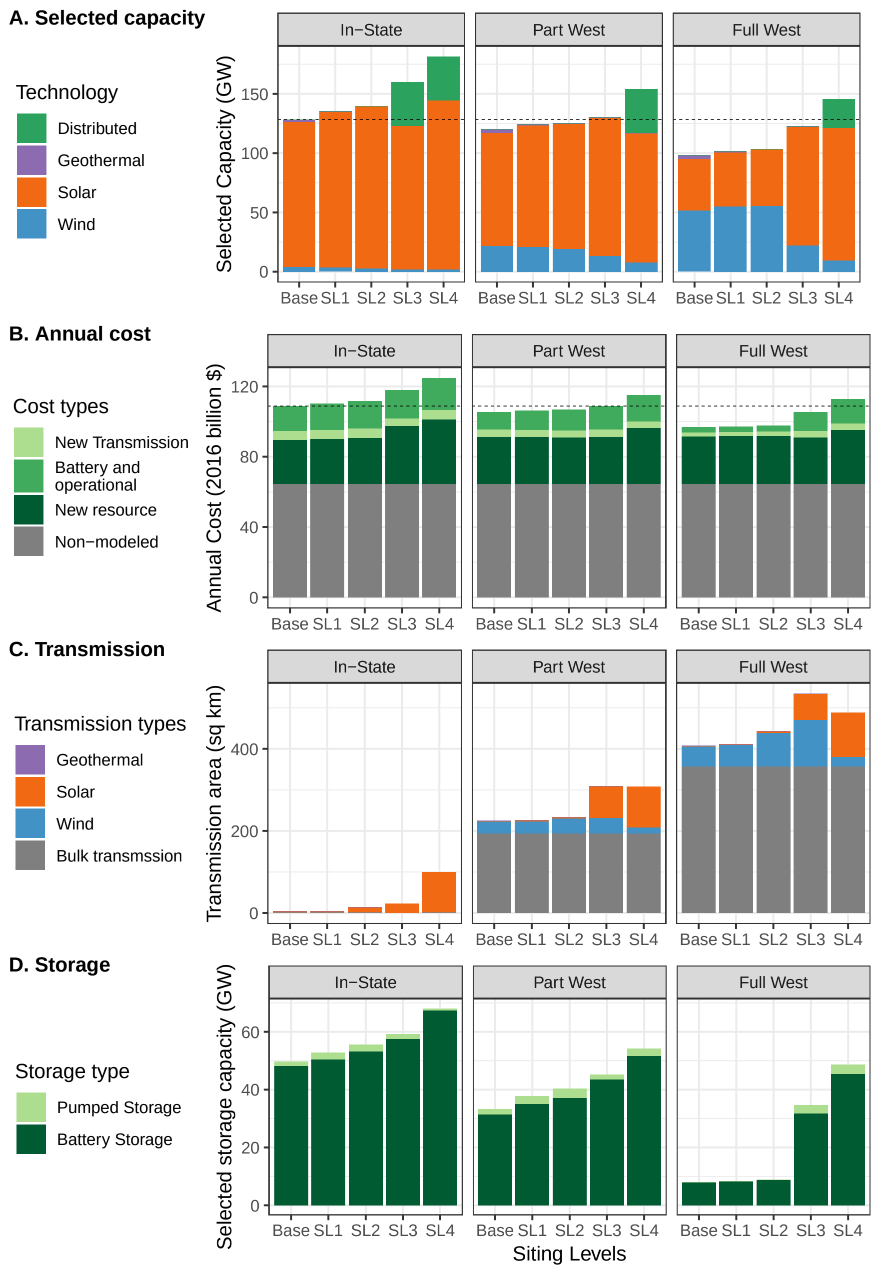


Figure 5: Selected installed capacity of distributed resources, geothermal, solar, and wind by 2050 summed across all RESOLVE Zones (A), total resource cost in 2050 (B), gen-tie and planned bulk transmission land area requirements (C), and pumped and battery storage capacity requirements (D) for the three Geographies (*In-State*, *Part West*, and *Full West*) and four Siting Levels (1-4). As a comparison with business-as-usual, the dotted horizontal line across all three Geography panel plots indicates the value of the *In-State* Base case.

with reduced wind capacity in New Mexico and Wyoming replaced by increased solar capacity in California, Arizona, Nevada, and Utah (Fig. 6).

Siting Levels are also a key determinant of the total cost of RESOLVE portfolios. All else equal, applying more protective siting assumptions increases the total resource cost to meet California's demand. For the *Constrained In-State* scenarios, the total cost increases from $109 billion in the

RESOLVE Base case to $125 billion under Siting Level 4, an increase of $16 billion (Fig. 5B) or 14.5% (Fig. 7A). However, the marginal impact of the application of each successive level of environmental restriction can vary widely. Again for the *Constrained In-State* scenarios, Siting Levels 1 and 2 have modest incremental annual costs impacts ($1.4 billion and $1.3 billion, or 1% and 2.5%, respectively), while the incremental impacts of the SL 3 and 4 are more significant ($6.5 billion and $6.8 billion, or 8% and 14.5%, respectively; Figs. 5B and 7A). This same pattern holds true across the Geographies, with one notable exception: in *Part West*, the marginal impact of achieving Siting Level 3 is only $2.0 billion or about 3% (Figs. 5B and 7A).

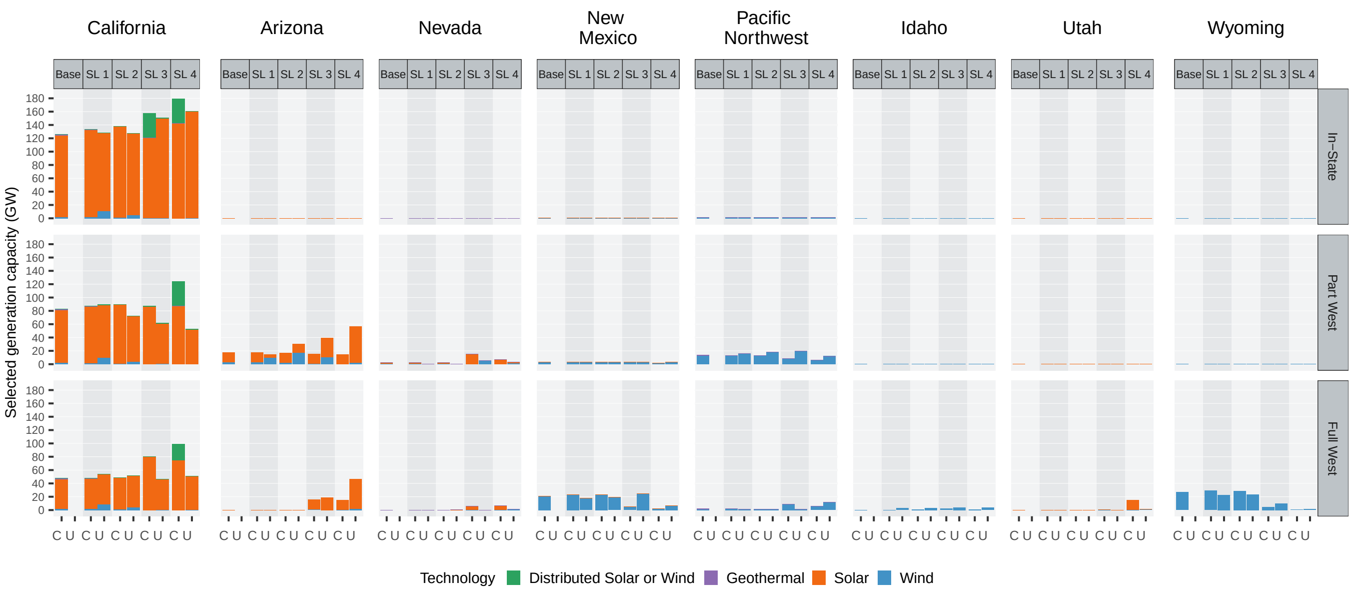


Figure 6: Selected installed generation capacity of distributed resources, geothermal, solar PV, and wind by 2050 for each RESOLVE Zone (or state) for the three Geographic cases (*In-State*, *Part West*, and *Full West*), the four Siting Levels (1-4; grouped bars), and the *Constrained* and *Unconstrained* resource sensitivity assumptions (C and U, respectively, as the x-axis labels). The Pacific Northwest includes Washington and Oregon.

The interaction of Geography and Siting Levels While increasing siting protections increases total costs, expanding geography reduces total costs. Trends for these two assumptions can be combined to produce portfolios that satisfy both land use and cost objectives, to achieve siting protections at lower cost. Generally, we find that procuring renewable electricity from more western states can offset most, but not all, of the cost increase associated with increasing land protections. Results show that under *Constrained* assumptions, the Base case *In-State* incurs nearly the same cost as Siting Level 3 in the *Part West* Geography and is actually 3.1% more expensive than Siting Level 3 in the *Full West* Geography (Fig. 7B). Under *Unconstrained* assumptions, it is actually more cost effective to obtain Siting Level 3 protections in the out-of-state scenarios than the Base case *In-State*. The *Unconstrained* Base case *In-State* is 2% more expensive than Siting Level 3 in *Part West* and is 8% more expensive than Siting Level 3 in the *Full West* Geography. Under the RESOLVE Base case assumptions in the *Constrained* case, *In-State* has a total annual cost of $109 billion, compared to an annual cost of $113 billion in Siting Level 4 in the *Full West* Geography, or only about 3.7% cost increase to achieve the most protective Siting Level (Fig. 7B). In the

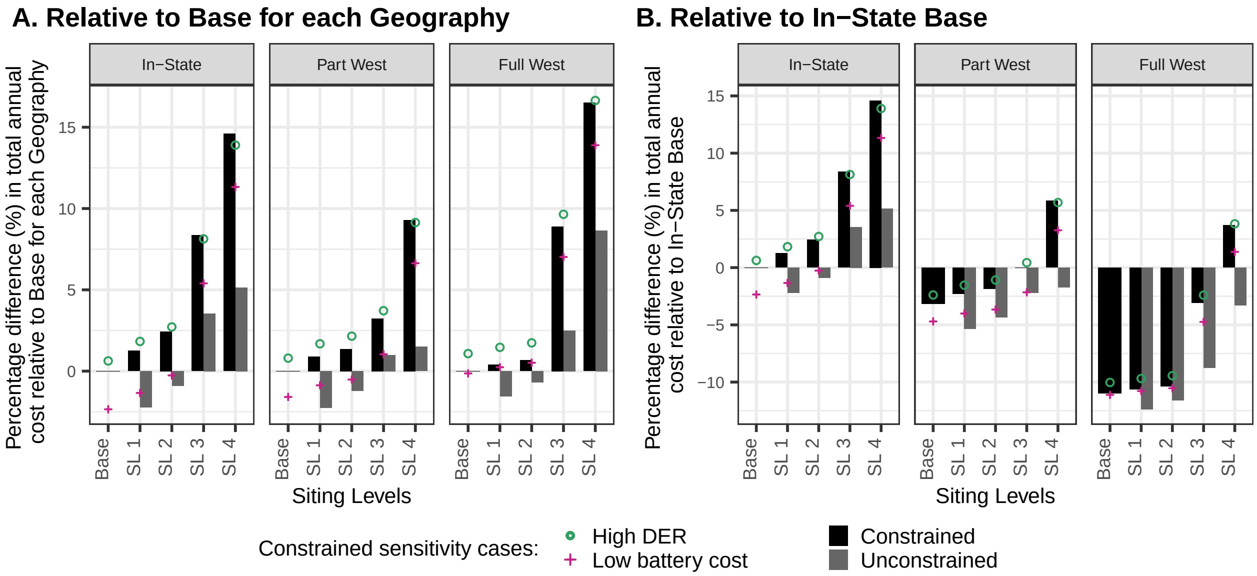


Figure 7: Percentage total resource cost differences relative to the RESOLVE Base within each Geographic case (A) and relative to *In-State* RESOLVE Base (B) for all Siting Levels (x-axis) and *Constrained* and *Unconstrained* Resource Assumption cases. High DER and Low Battery cost sensitivities are shown only for the *Constrained* scenarios. Percentages are calculated using the total resource cost, including the $65 billion in non-modeled costs. For percentage calculations using only modeled costs, see SI Fig. 16.

Unconstrained scenarios, it is actually less expensive to choose Siting Level 4 in the *Part* and *Full West* Geographies (by 2% and 3%, respectively) compared to the RESOLVE Base case in the *In-State* Geography (Fig. 7B).

Effects of *Constrained* vs. *Unconstrained* resource assumptions By expanding resource potential beyond the RESOLVE Zones for other western states and expanding solar resource availability to full technical potential within California (by removing the 80% discount factor for solar resources), the *Unconstrained* portfolios have lower overall generation capacity requirements, increased share of wind capacity, and more evenly distributed capacity across states (Fig. 8). Generally, we find more dramatic differences between *Unconstrained* and *Constrained* assumptions for Siting Levels 3 and 4 compared to Siting Levels 1 and 2 (Fig. 8). *Unconstrained* scenarios allow access to more low-impact, high-quality wind resources outside of RESOLVE Zones and solar resources within California in the more protective Siting Levels 3 and 4, which dampens the effect of increasing land use protections on capacity requirements and loss of wind potential. Specifically, by including resources outside of RESOLVE Zones in the supply curve, RESOLVE is able to select more wind capacity in New Mexico, the Pacific Northwest, and Wyoming under the more protective Siting Levels 3 and 4 in the *Full West* Geography (Fig. 6). As an example of impacts on geographic distribution, in Arizona, a state that does not see much development in the *Constrained* scenarios, there is significantly more wind development under Siting Levels 1–3 and more solar development in Siting Level 4 in the *Part West* Geography (Fig. 6). However, more abundant, higher-quality resource availability in the *Unconstrained* scenarios also causes RESOLVE to select far less commercial distributed solar or wind resources compared to the *Constrained* scenarios. In California, this lack of distributed resources is partially made up by more utility-scale solar.

Results indicate that impacts of *Unconstrained* assumptions on the generation mix and total capacity requirements translate into system cost savings, with greater cost savings in the more protective Siting Levels. These cost reductions are modest for Siting Levels 1 and 2 (under $5 billion annually) but become significant under the more protective Siting Levels 3 and 4 (Fig. 7). For Siting Level 4, increased resource availability leads to savings of $10 billion annually in the *In-State* Geography (or a 5% cost increase as opposed to 14.5% in the *Constrained* case), and $8 billion annually in the *Part West* (1.2% vs 9% cost increase) and *Full West* cases (8% vs. 16.5% cost increase; Figs. 5B, 7). These cost savings are partially achieved through the concentration of resource development in the highest quality resource zones. The most extreme example is the *Unconstrained*, *In-State*, Siting Level 4 scenario, in which the model selects 143 GW of solar in the Westlands Zone, where development had previously been constrained at 28 GW in that zone (Fig. 9, SI Fig. 23). In the *Part* and *Full West* Geographies, these cost savings are due to more availability of low-impact and high-quality wind in Wyoming, New Mexico, and the Pacific Northwest, particularly for Siting Level 3 (Fig. 6).

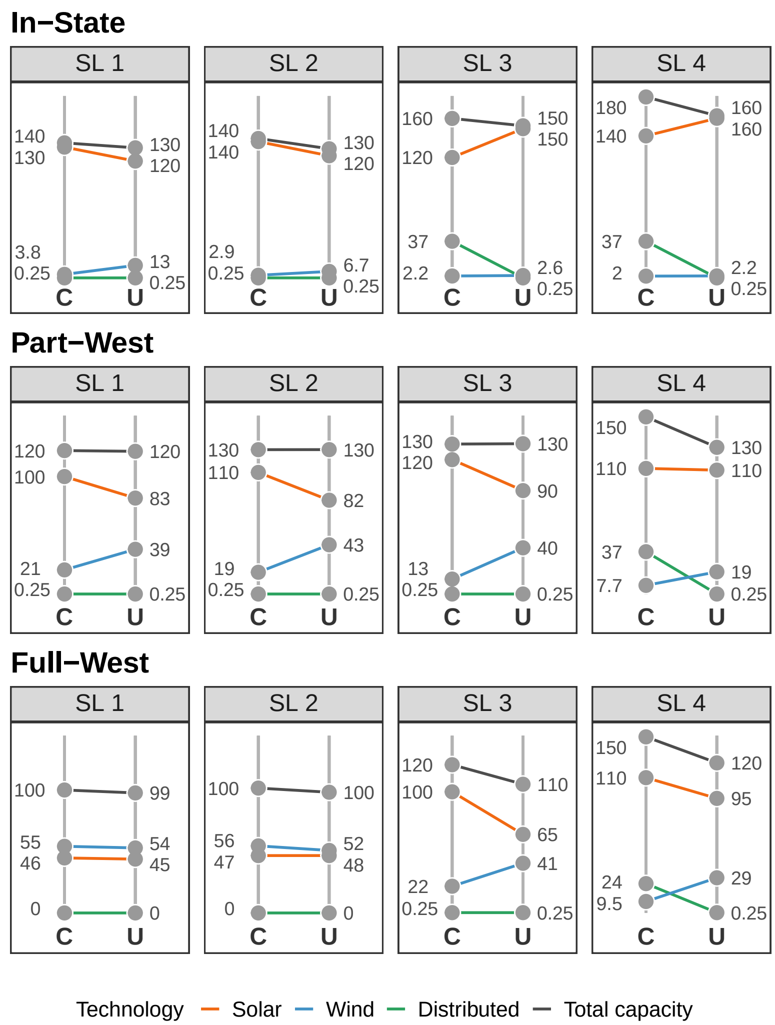


Figure 8: Slope plots comparing *Constrained* and *Unconstrained* resource assumption sensitivity results (C and U, respectively, as the x-axis labels) for selected technology-specific generation capacity (colored lines) and total generation capacity (grey lines) across the four Siting Levels (SL) and three Geographies (*In-State, Part West, Full West*). Numerical labels indicate the amount of selected capacity in gigawatts (GW).

Key cost drivers The annual costs in the various scenarios are primarily driven by two factors: the quality of the solar resources available to the model and the resources available to balance or complement the solar resources. In every case, the model relies heavily on utility-scale solar photovoltaic (PV) resources to meet the increasing demand for carbon-free electricity, reflecting the substantial declines in the price of solar panels in the last decade. The predominance of solar is especially pronounced for the scenarios in which new development is kept *In-State*, as environmental and political restrictions, as well as limited wind resource potential, have sharply limited the potential for new on-shore wind development throughout California. For these *In-State*, *Constrained* scenarios, the model selects 122–142 GW of utility-scale solar for construction by 2050, roughly 10–15 times the existing resources represented in the model (11.3 GW), while only selecting 2–5 GW of wind generation (Fig. 5A). The addition of this much solar to the system requires resources to supply energy to the system during hours with little solar production, i.e., overnight and during winter storms. The model achieves this through a combination of wind and battery resources as determined by the supply curve, given geographical, transmission capacity, and environmental limits. Though battery costs have dropped in recent years, and these improvements are expected to continue in the future, the modeling results indicate that wind generation is generally preferred over battery storage options when sites are available. If generation resources are limited to *In-State* development, balancing the 122 GW to 180 GW of solar requires between 48 GW and 68 GW of battery storage to shift the solar generation to match load (Fig. 5D). If California can take advantage of west-wide wind resources, specifically those high-quality resources in New Mexico and Wyoming, the model will divide the resource build roughly evenly between wind and solar resources (selecting 61 GW of wind generation and 56 GW of solar generation in the *Full West* base case; Fig. 5A) and reduce the amount of battery storage (falling from 48 GW in the *In-State* RESOLVE Base case to 8 GW in the *Full West* RESOLVE Base case; Fig. 5D).

This trade-off between wind generation and battery storage is most obvious in the *Full West* scenarios. As the more protective Siting Levels are applied, there is a dramatic reduction in the wind resources: moving from Siting Level 2 to 3 reduces the total selected wind potential in Wyoming and New Mexico from 52 GW to just under 9 GW. While the model selects all available wind in the *Constrained* Siting Level 3 scenarios, the reduction in the total wind resource available forces the model to select more solar (increasing from 47 GW to 100 GW) and battery (increasing from 9 GW to 32 GW) resources. This increase in battery storage is a key driver of increased cost.

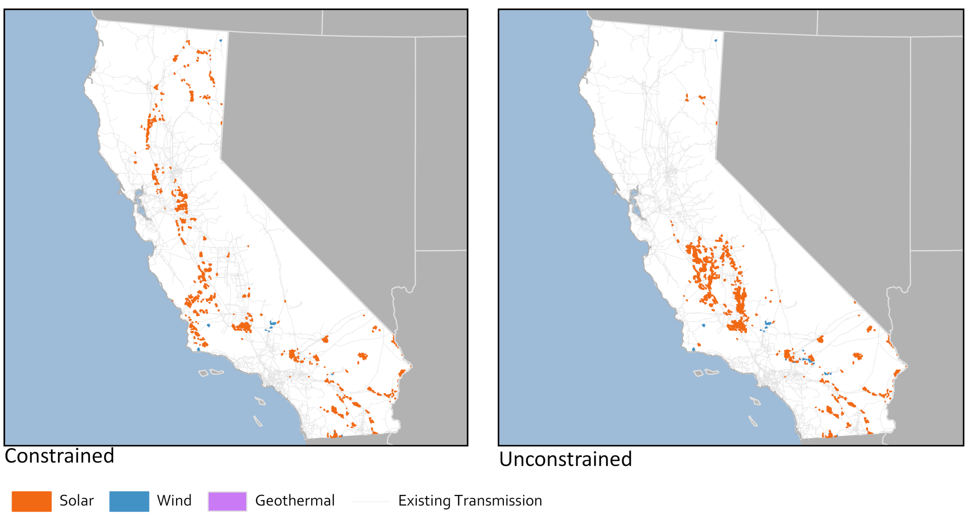


Figure 9: Example Selected Project Areas for *Constrained* and *Unconstrained* assumptions for the *In-State* Siting Level 3 Base scenario.

Effects of lower battery cost and higher behind-the-meter PV adoption Overall, sensitivity analyses increasing the amount of behind-the-meter (BTM) solar PV distributed energy resources (High DER sensitivity case) and reducing battery storage costs (Low Battery Costs sensitivity case) do not significantly alter the generation mix, the distribution of selected capacity between states (SI Fig. 17–20), or the total resource costs (Figs. 7).

Lowering battery costs decreases the overall cost of the portfolio (Fig. 7) but does not cause major shifts in the resource builds between scenarios, nor does it cause the quantity of batteries selected by the model to differ significantly (SI Fig. 17–20). This indicates that the quantity of batteries selected is determined more by the mix of other resources available to the optimization rather than the battery cost. Perhaps the most significant effect of lower battery costs is that no additional pumped hydro storage is selected in any Geography or Siting Level (SI Fig. 17). In scenarios where reducing battery costs changed overall generation mix (*Part* and *Full West*), the effect is a slight increase in solar capacity and a decrease in wind capacity, but with little or no effect on the total selected capacity. The reduction in wind capacity is observed most noticeably in the Pacific Northwest RESOLVE Zone under the Base and Siting Level 1 cases in the *Part West* Geography but is also seen in Wyoming and New Mexico for Siting Levels 1 and 2 (Fig. 18B). Lower Battery Costs do have a larger effect on distribution of selected solar capacity between RESOLVE zones within California. The most significant changes are in the *Part West* case—solar capacity increases in Riverside East Palm Springs and reduces in Greater Imperial in the Base and Siting Level 1 cases (SI Fig. 21).

Increasing BTM DER resources installed by homeowners and businesses by about 35% by 2050 (Table 4) reduced selected utility-developed capacity by about 4-7%—primarily solar capacity in California—across most Siting Levels and Geographic cases (SI Figs. 17A–20A) but had only minor impacts on the geographic distribution of selected resources (SI Figs. 17–20). While the utility costs are lower in the High DER scenarios than in the base cases, the total cost of resources (including the $2.2 billion USD incremental cost of the DER resources borne by homeowners and businesses) generally goes up. However, in scenarios where only lower quality solar resources were available due to more environmental protections (Siting Levels 3 and 4 for the *In-State* Geography, Siting Level 4 in the *Part West* Geography), the total resource cost for the High DER sensitivities are lower than the Base case scenarios (Figs. 5B, 7). In the *In-State* Geography, High DER assumptions reduce Northern California solar in Siting Levels 3 and 4 and reduce Central Valley North Los Banos and Greater Carrizo wind in SL 1 and 2 (SI Fig. 21). In the *Part West* and *High DER* scenarios, Solano and Northern California experience reduced solar development in Siting Levels 3 and 4, respectively, while Riverside East Palm Springs have lower solar capacity in SL 1 and 2.

3.2.2 Transmission requirements

Overall, transmission area and length requirements increase as generation land protections increase and Geography expands—both in absolute transmission area (Fig. 5C) and percentage of total (generation and transmission) infrastructure area (SI Table 18). The land area requirements from the planned bulk inter-state transmission lines exceed that of the total modeled gen-tie lines in the *Part* and *Full West* cases (Fig. 5C). Compared to *Unconstrained* scenarios, *Constrained* scenarios require less gen-tie transmission area, regardless of Geography, except for Siting Level 4 in the *In-State* Geography (Fig. 5C). This is due to more selected wind capacity in the *Unconstrained* scenarios, which we expect to have more transmission requirements given that wind is typically more heterogeneous in quality (more dispersed) and have lower total land use efficiencies.

As expected, among the Geographic cases, *In-State* requires the least amount of additional transmission corridor area, while *Full West* requires the most (Fig. 5C). In the *Part* and *Full West* Geographies, wind dominates total transmission area requirements for Base and Siting Levels 1 and 2 despite comprising a much lower fraction of overall generation capacity. The large selected solar capacity for the same Siting Levels require very little additional transmission area. Although solar generation capacity is not significantly higher in Siting Levels 3 and 4, the solar gen-tie transmission area tends to increase dramatically compared to Siting Levels 1 and 2 (Fig. 5C). In *Part* and *Full West* cases, most of these solar gen-tie transmission requirements are disproportionately due to development primarily in Nevada and secondarily in California (Fig. 10, Fig. 25). Wind transmission requirements are disproportionately greater in Arizona, Nevada, and New Mexico in the *Part West* case and in Idaho and the Pacific Northwest in the *Full West* case, particularly for Siting Level 3 (Fig. 10, Fig. 25).

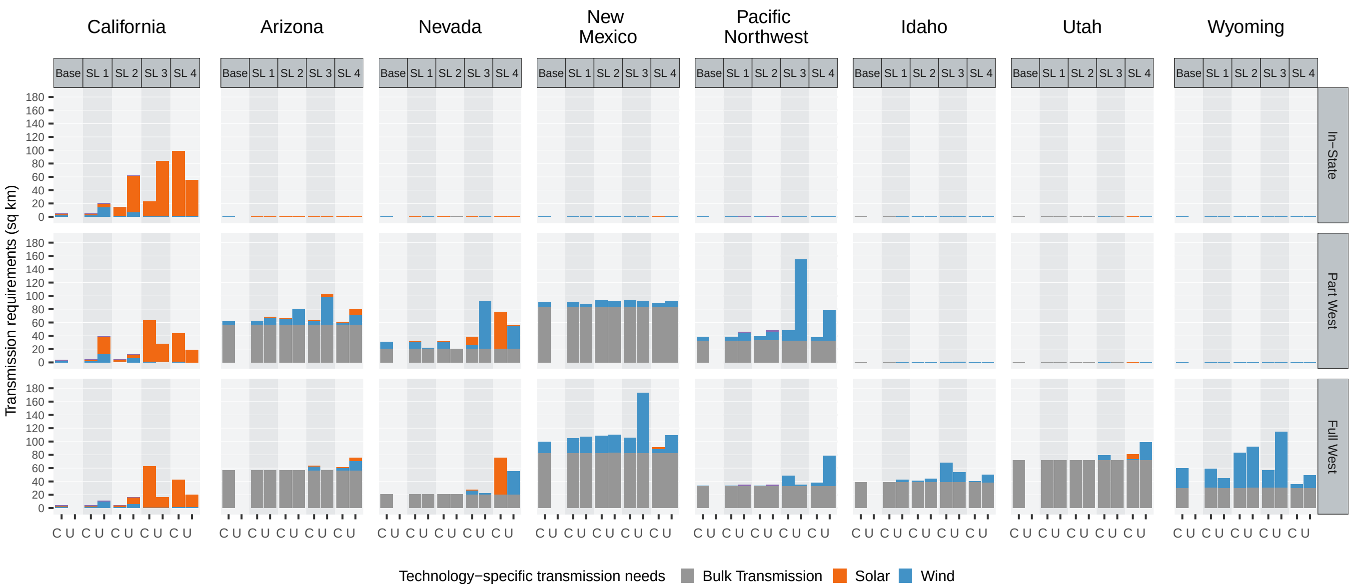


Figure 10: Gen-tie and planned bulk transmission area requirements for each RESOLVE Zone (or state) for the three Geographic cases (*In-State*, *Part West*, and *Full West*), the four Siting Levels (grouped bars), and the *Constrained* and *Unconstrained* resource sensitivity assumptions (C and U, respectively, as the x-axis labels). Gen-tie areas are modeled using least cost analysis. Pacific Northwest includes Washington and Oregon.

3.2.3 Selected Project Areas

For the *In-State* Geography, increasing Siting Levels causes site selection to shift away from Southern California toward Northern California (Fig. 11). As the geographic extent expands from *In-State* to *Part West*, wind development tends to shift from California toward New Mexico and to the Oregon-Washington border, to the maximum extent possible within the constraints of the model since the 3,000 MW transmission limit in New Mexico is binding in the *Part West* Geography. Within the *Part West* Geography, solar distribution continues to shift northward as Siting Levels become more protective, and wind experiences a smaller shift away from New Mexico wind and toward the Pacific Northwest. The *Part West* case includes two new long-distance high-voltage transmission lines, SunZia and Southline, with a total distance of 1,200 km to deliver wind power from New Mexico to California.

Expanding the Geography from *Part West* to *Full West*, new Selected Project Areas occur in Wyoming and New Mexico to the maximum extent possible within the constraints of the model. The 3,000 MW transmission limit for New Mexico wind is lifted in the *Full West* Geography, and additional development occurs in New Mexico as a result, up to 24,000 MW. However, with increasing levels of siting considerations, selected Wyoming and New Mexico wind resources becomes smaller and more dispersed. In the more protective Siting Levels, New Mexico and Wyoming wind resources tend to be replaced by smaller wind resources in the Pacific Northwest and Idaho. The *Full West* scenario includes additional new long-distance high voltage transmission lines, TransWest Express, Gateway South, Gateway West, Boardman to Hemingway, and SWIP North with a total distance of 5,356 km to deliver wind power from Wyoming and Idaho to California.

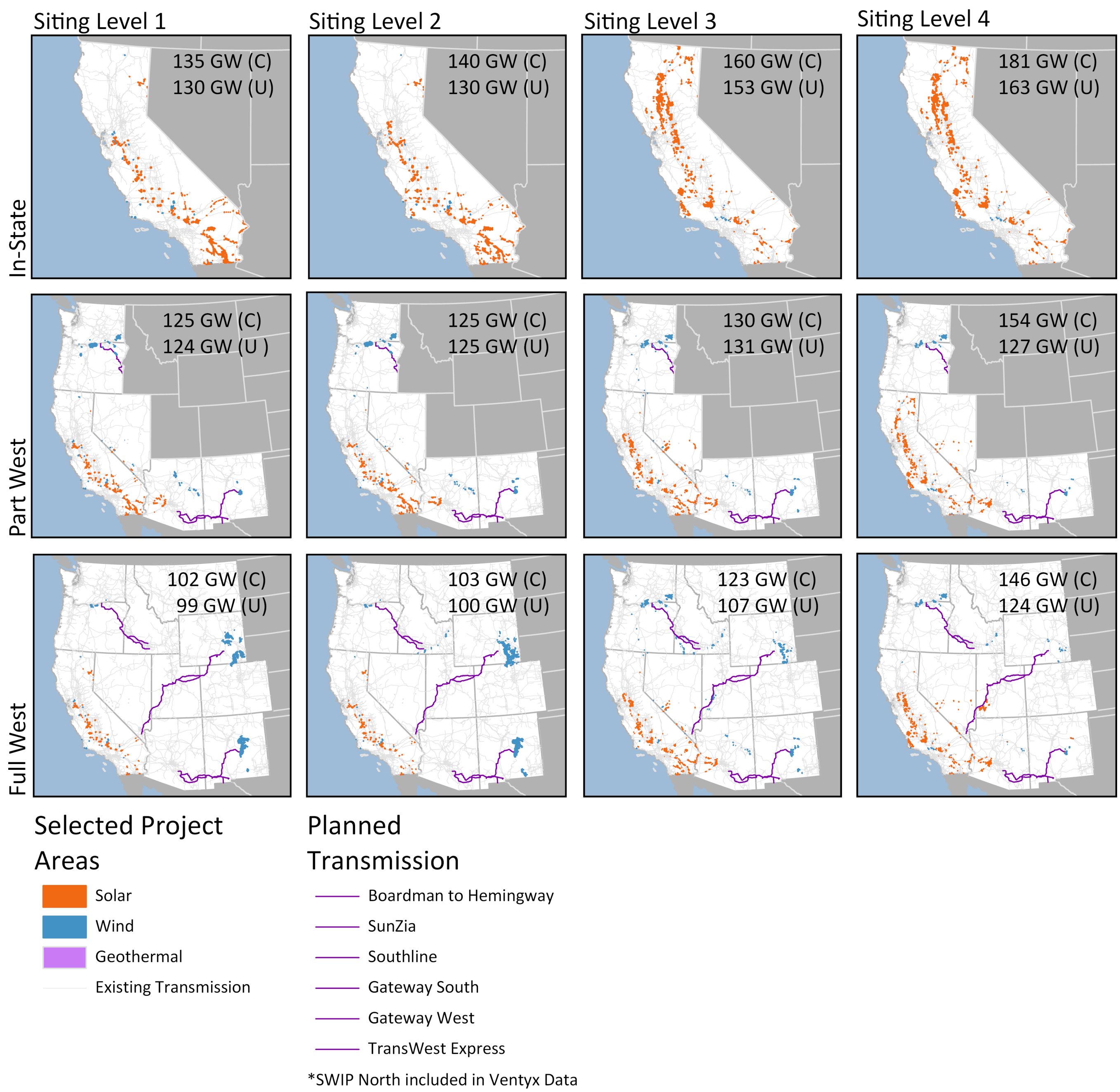


Figure 11: Selected Project Areas (SPAs) in the *Constrained* scenarios. Siting Levels are shown in columns and Geographic cases are shown in rows. Text in each panel shows total installed capacity for *Constrained* scenarios (C) and *Unconstrained* scenarios (U).

3.3 Strategic environmental assessment

3.3.1 Ecological impacts of generation infrastructure

Construction of new solar and wind projects could have significant ecological impacts depending on the level of land protection achieved. There is a high degree of overlap (>50%) between selected project areas and Environmental Exclusion Categories 3 and 4 (Fig. 12A). This suggests that the application of Environmental Exclusions in practice has the potential to significantly affect the build-out of wind and solar power plants, and that the lack of ecological protections above the RESOLVE Base leaves open the potential for the build-out to impact natural lands. In the *Part West* cases, general ecological impacts of solar selected project areas can be equal to or greater than for wind in Base case and Siting Levels 1–3—since prime farmland occupies a significant fraction of the impacts in Base through SL 2. However, in the *Full West* cases, the impacts of wind development are far greater than for solar in Base through Siting Level 2, and are the highest across all scenarios examined. Category 3 and 4 land areas are significantly impacted by *In-State* solar under Siting Level 2 and 3 assumptions.

However, the generation-associated impacts to specific ecological metrics—Critical Habitat, Important Bird Areas, Eagle Habitat, Sage Grouse habitat, Big Game habitat, Wetlands, and Wildlife linkages—are less significant compared to to aggregated Environmental Exclusion Categories (Cat 1-4). This suggests that ecological siting considerations are likely to be dominated by other factors not captured in the specific metrics highlighted here. Example "other factors" include sensitive grassland birds and TNC portfolio areas. In the *In-State* case, impacts to these individual ecological impact metrics are the lowest; impacts are greater under *Part West* and *Full West* geographic assumptions (Fig. 12A).

Wind The most significant ecological impacts from wind development are in Wyoming and the Pacific Northwest (Fis. 26B, 27). Big Game habitat and corridors are impacted for the RESOLVE Base and Siting Level 1 scenarios, with about a quarter and one-third of all wind development overlapping with Big Game areas in the *Part West* (in the Pacific Northwest) and *Full West* (in Wyoming) Geographies, respectively (Fig. 26B, 27). Wildlife Linkage impacts follow a similar trend as Big Game areas but are considerably more significant—comprising up to 50% of all wind development areas—in Siting Levels 2 and 3 in the *Full West* (Wyoming) Geography (SI Fig. 27).

In *Unconstrained* cases, the additional wind development in Arizona (*Part West*) and Wyoming has significant overlap with Wildlife Linkage areas. Sage Grouse habitat is impacted by wind development in Wyoming only for Siting Level 1, while little or no Big Game impacts occur in any state for Siting Levels 2-4 (SI Fig. 31).

Solar Solar development can largely avoid key ecological impacts examined here, except on Important Bird Areas in California for RESOLVE Base and Siting Levels 1 and 2 within the *In-State* and *Part West* Geographies and on Wildlife Linkages in Nevada in Siting Level 3 in the *Part West* Geography (SI Fig. 26). In *Unconstrained* case, there are higher impacts on Important Bird Areas due to solar development in Base and Siting Level 1 scenarios in California across all Geographies (SI Figs. 30, 31).

3.3.2 Agricultural and other land impacts of generation infrastructure

Both wind and solar impacts on agricultural lands are significant. One-third to half of all solar capacity could be sited on agricultural land in California across all Siting Levels and Geographies

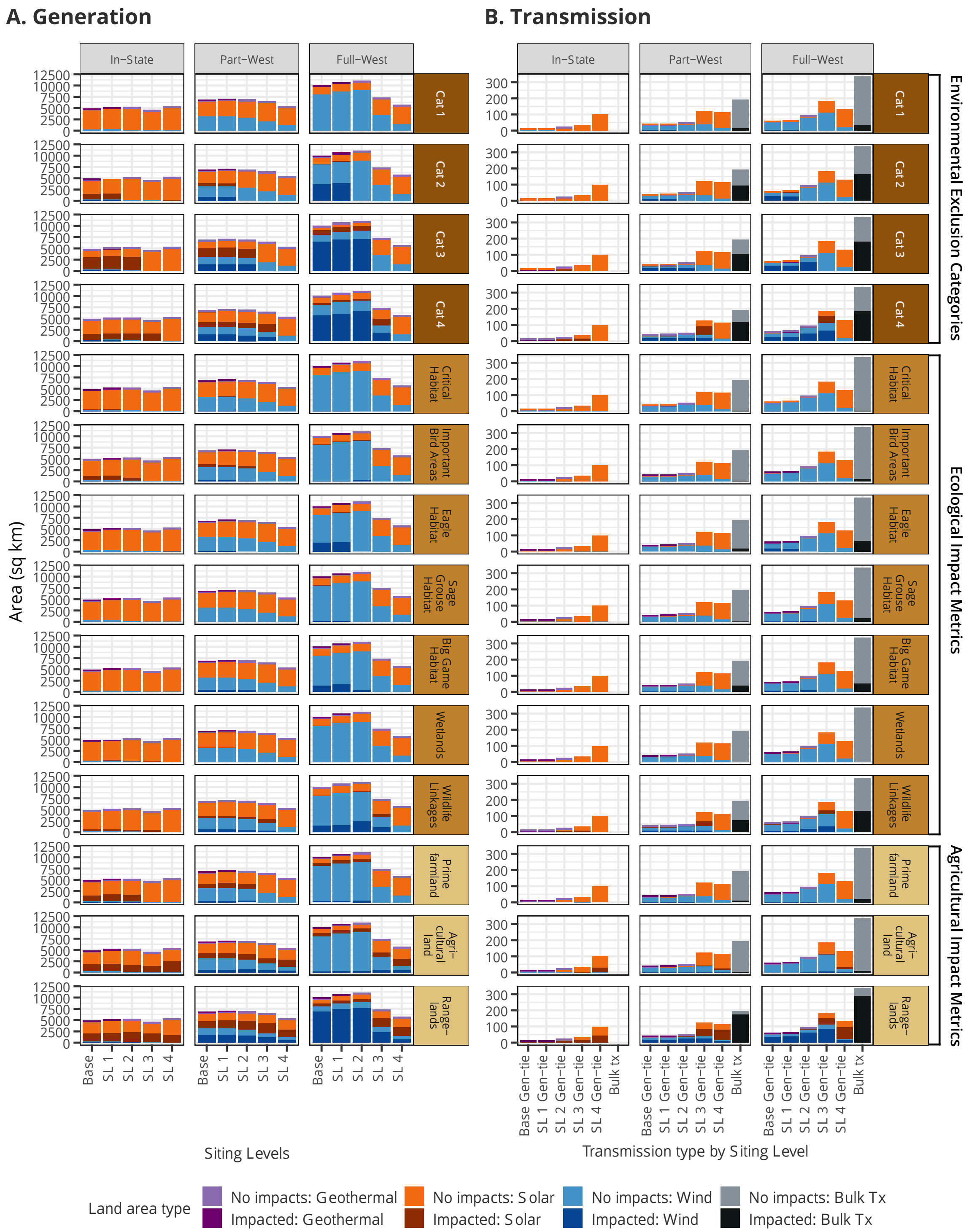


Figure 12: Environmental impacts for generation (A) and modeled gen-tie and planned bulk transmission corridors (B) summed across all regions for the *Constrained* assumptions case. Bulk transmission is shown in a separate column. Cat 1–4 refer to datasets in the Environmental Exclusion Categories created for the site suitability analysis (Section 2.2). No impacts are expected for Siting Levels equal or greater than the Category (e.g., no Category 3 and 4 environmental exclusion impacts should exist for Siting Level 3).

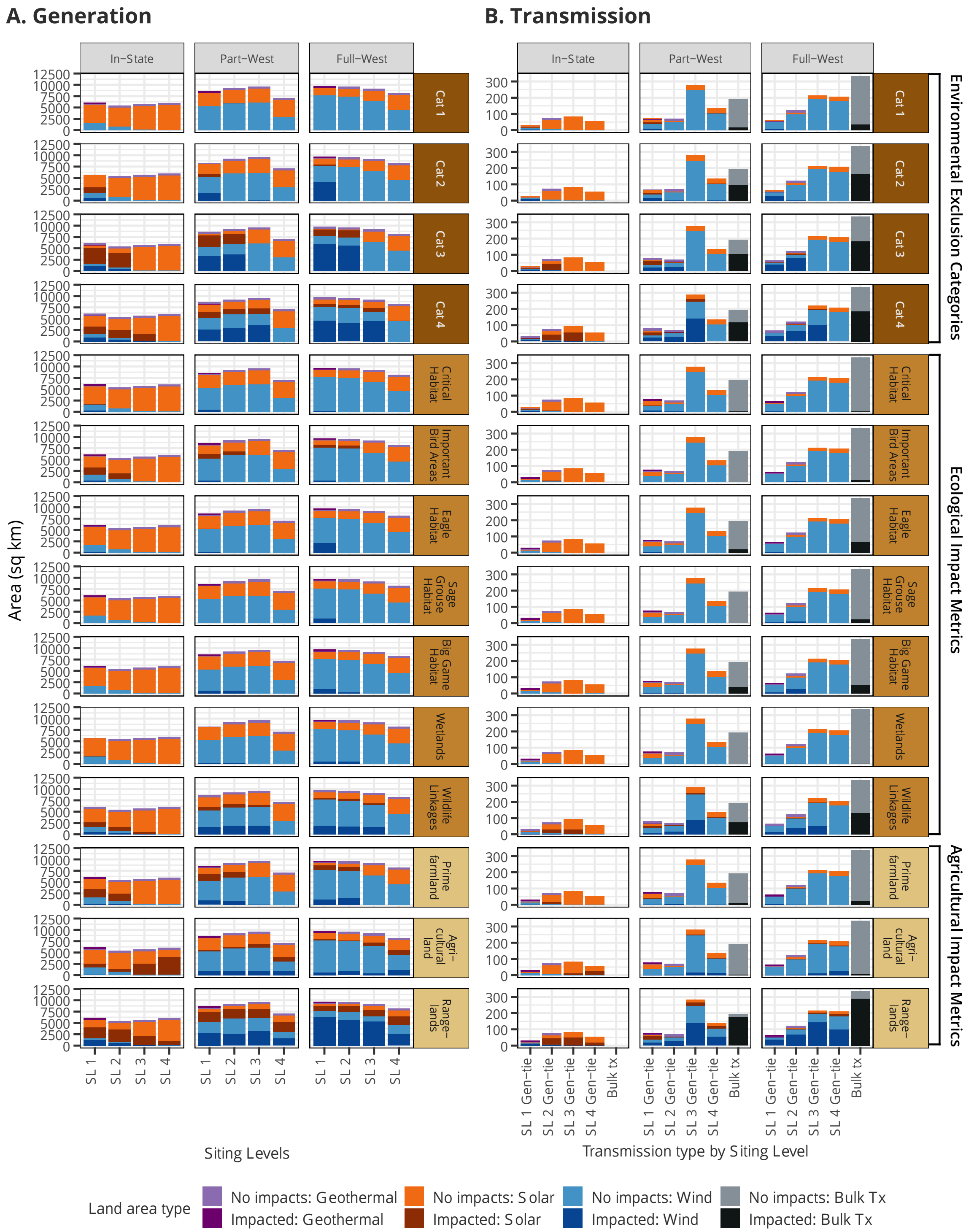


Figure 13: Environmental impacts for generation (A) and modeled gen-tie and planned bulk transmission corridors (B) summed across all regions for the *Unconstrained* assumptions case. Cat 1–4 refer to datasets in the Environmental Exclusion Categories created for the site suitability analysis (Section 2.2). No impacts are expected for Siting Levels equal or greater than the Category (e.g., no Category 3 and 4 environmental exclusion impacts should exist for Siting Level 3).

in the *Constrained* case (SI Fig. 26). Percentage of solar capacity on non-prime agricultural lands increases under higher Siting Levels 3 and 4. Of those agricultural lands impacted, nearly all of it is considered prime farmland in RESOLVE Base and Siting Levels 1–2 (due to environmental exclusions, no impacts are allowed on prime farmland in Siting Levels 3 and 4; Fig. 12A). Lower fractions of wind development overlap with prime or other agricultural lands, with up to half of sites in Pacific Northwest under SL 4 and one-third of sites in New Mexico under SL 1 and 2. Impacts to rangelands, which are native or non-native grass or shrub-like vegetation suitable for grazing or browsing by livestock, are similarly important for solar development across all scenarios, with approximately half of all solar in California and nearly all solar in Arizona and Nevada sited on rangelands (SI Fig. 26). Large fractions of wind generation are also sited on rangelands—a little under 50% of sites in the Pacific Northwest and nearly all sites in New Mexico and Wyoming across all Siting Levels and Geographies (SI Fig. 26). Rangeland habitats tend to have high biodiversity value, provide significant habitat connectivity, and form the foundation for a number of ecosystem services [42]. However, total agricultural and rangelands in both California and the West are abundant relative to impact—less than 1% of agricultural and rangelands are impacted.

Compared to the *Constrained* case, impacts on agricultural lands across all states in the *Unconstrained Part* and *Full West* Geographies are proportionally lower (Figs. 12A, 13A). As with the *Constrained* case, both solar and wind selected in the *Unconstrained* cases are largely sited on rangelands in Arizona, New Mexico, and Wyoming, and to a lesser extent in California with more siting protections in place (SI Figs. 30, 31).

Average housing density of Selected Project Areas generally increases with higher levels of environmental siting protections (Fig. 34). This trend is most clearly observed for solar in the *Part* and *Full West* Geographies (Fig. 34B). On the whole, solar Selected Project Areas have higher housing density compared to wind across all Siting Levels and Geographies (Fig. 34C).

Transmission impacts Compared to the environmental impacts of generation infrastructure, gen-tie transmission impacts in the *In-State* and *Part West* Geographies are proportionally lower (Fig. 13). The three most notable ecological metrics impacted by transmission gen-ties are Wildlife Linkages in California and Wyoming under Siting Level 3, Big Game habitat in Wyoming under SL 3, and Eagle Habitat in Wyoming under SL 1 and 2 (SI Figs. 28, 29). Bulk transmission impacts are proportionally greater than gen-tie impacts in Siting Levels 2-4 (Fig. 13). Almost all bulk transmission corridors planned in the Pacific Northwest could overlap with Big Game habitat (SI Figs. 28, 29). Little agricultural land is impacted by either bulk or gen-tie transmission corridors, except in California in the *In-State* and Siting Level 4 scenarios (SI Fig. 28). Similarly to generation, large percentages of gen-tie and almost all bulk transmission corridors are located on rangelands in nearly all regions except the Pacific Northwest for gen-tie corridors.

4 Discussion

We find that technology choices, resource costs, and the landscape of infrastructure build-out to achieve California's climate targets are highly sensitive to the level of environmental siting protection and whether California has access to renewable resources from other Western states. Importantly, these technology choices and spatial build-outs have different impacts on natural and working lands in the West.

With planning, California can develop the renewable energy required to achieve deep decarbonization in 2050 and limit land impacts. However, the options for achieving multiple policy goals including conservation and renewable energy development have their own sets of benefits and trade-offs, which we discuss below.

In absence of a plan to limit land impacts and scale up renewable energy deployment, impacts to natural and agricultural lands can be high. In the Siting Levels that only exclude current legally and administratively protected areas, overall ecological impacts due to wind and solar generation infrastructure and additional transmission requirements are significant. These impacts include loss of Important Bird Areas, Eagle Habitat, Big Game Habitat, and Wildlife Linkages. However, we find that these ecological impacts can be largely avoided with portfolios created under Siting Level 3 and 4 assumptions, while still meeting clean energy targets, by protecting lands with high conservation value and high landscape intactness (Categories 3 and 4).

Solar and wind development are likely to impact agricultural lands regardless of Geography or Siting Level. Between 35% to 50% of all solar capacity in all *In-State* Geographic scenarios is sited on existing agricultural lands (either cropland or pastureland), with prime farmland comprising the majority of the impacted farmland in Siting Levels Base, 1, and 2. More than half of all wind and solar across all Siting Levels is sited on rangelands in the two out-of-state Geographies. Thus, to reduce or avoid siting conflicts, agrivoltaics [43] and wind-friendly farming and ranching practices, including siting on degraded agricultural lands ([44]), as well as wildlife-friendly design and operational practices will be important for the future of renewable energy development in the Western U.S. In California, it will be important to align solar energy planning with groundwater management activities that will require retirement of agricultural lands driven by the Sustainable Groundwater Management Act. Working lands with wind turbines can have multiple additional uses, due to typical wide spacing of turbines. Strategies to facilitate wind development will be important in areas where wind energy occurs on working lands (e.g., land leasing programs, farmer engagement).

A regional energy market is more cost-effective because it enables access to western wind resources. Interconnection to a wider, regional energy market is more cost-effective than limiting new renewable resource development to California due to the availability of high-value western wind resources. While the *In-State* scenarios require the least new interconnection and bulk transmission investment in comparison to regional scenarios, the *In-State* transmission cost savings are offset by the lower overall cost of decarbonization in the *Full West* scenarios.

Achieving the best conservation outcomes is more cost-effective at a regional scale. While lower impact siting can increase system costs, increasing geographic availability of renewable resources can offset these cost increases. Of the four Siting Levels considered, Siting Level 4 achieves the lowest ecological impacts, but leads to significant cost increases for all Geographies (increases are less significant when current constraints in planning assumptions—discount factor, RESOLVE Zone boundaries—are removed). However, costs do not change linearly between Siting Levels. We find that achieving Siting Level 3 may be much more cost-effective, especially when out-of-state resources are available. When California has access to *Part West* resources, we find that a significantly greater level of protection under Siting Level 3 can be achieved at the same cost as the much lower level of *In-State* protection under the RESOLVE Base case. In the regional scenario (*Full West*), the portfolio protecting high-conservation-value lands (SL 3) is approximately 10% less expensive than the same level of protection in the California (*In State*) scenario.

Environmental impacts are greater outside of California under the business-as-usual scenarios in which only legally and administrative protections are enforced. The finding that environmental impacts are greater in the *Part* and *Full West* Geographies in the less protective scenarios demonstrates the need for ensuring the necessary standards for permitting non-California projects if California compliance regulations do allow out-of-state wind development. Similar standards for low-impact permitting should be in place for out-of-state projects to ensure that greater land protections in California do not lead to leakage of biodiversity impacts. Otherwise, under legal protections alone, there may be impacts to Eagle Habitat, Big Game Habitat, and Wildlife Linkages, among others. Impacts to Wildlife Linkages under Siting Level 3 do remain, which points to the importance of design and operational practices that can minimize impacts to wildlife and habitat. The large overlap of selected capacity in the low protection scenarios (SL 1 and 2) with land areas in Environmental Exclusion Categories 2, 3, and 4 suggests that renewable energy project developers may face siting challenges for a sizable majority of projects (e.g., SL 1 can have Selected Project Areas in Categories 2-4 land areas, as these Categories were not excluded from SL 1, and SL 2 can have Selected Project Areas located in Categories 3 and 4 land areas). This overlap also indicates that a large percentage of desirable development sites also have environmental and social value that state agencies and land managers should anticipate and manage to avoid conflicts. These findings underscore the importance of effective screening tools early in the project development cycle in conjunction with effective planning and procurement practices for renewable energy, alongside incentivizing development in low-impact locations, aggressive energy efficiency, and land-sparing renewable energy technologies.

Out-of-state Geographies significantly increase both gen-tie and planned bulk transmission requirements, presenting an important trade-off. The need for additional transmission—in some cases, an order of magnitude greater—is an important trade-off for an otherwise clear finding that increasing regional resource availability makes sense from both cost and environmental impact points of view. Although transmission land use requirements are a small fraction of the total land use build-out (<5% including planned bulk transmission lines), transmission projects are known to have disproportionate siting impacts due to landscape fragmentation and have long lead times for permitting and construction. They are known to suffer from permitting uncertainty, as well as cost allocation uncertainty, when crossing state boundaries.

Compared to those for solar, siting options for wind are more geographically and environmentally constrained, and drive the prevailing trends in cost and generation mix. The low costs and relative abundance of solar PV enable large shares of solar capacity to be selected across all scenarios (50% or greater). Due to their relatively low costs and because their generation profiles complement that of solar, wind resources tend to be higher value in a high-variable-renewables system. However, compared to solar, wind is more limited in the lower-impact scenarios because there are relatively fewer low-conflict high-quality wind resource areas. Wind resources are generally more heterogeneous (i.e., patchy) across larger spatial scales, while also having lower land use efficiencies when considering turbine spacing, making it more sensitive to land use restrictions. Thus, in wind-limited scenarios (e.g., *In-State* Geographies and Siting Levels 3 and 4 in *Full West*), solar is the vast majority of the capacity selected. A solar-dominated grid requires significant battery storage, driving up total costs.

Removing or relaxing the current *Constrained* resource availability assumptions increases wind capacity two- or three-fold in the more protective Siting Levels, which achieves high levels of land protection at even lower costs. *Unconstrained* resource assumptions allow access to high-quality wind resources in several western states under more protective siting levels, enabling a larger share of wind capacity in the generation mix, reducing the total generation capacity and storage required, and reducing system costs of achieving lower impact development. Moreover, in Siting Level 3, although twice as much wind is selected to meet California's demand when constraints are lifted (about 40 GW compared to 20 GW), 53 GW of wind potential will still be available to meet the needs of other states. Also, by applying limits to solar potential on all zones uniformly, capacity expansion models can underestimate the amount of low-impact potential in high resource quality zones. Although these resources may be captured and identified through resource assessment studies, they should also be reflected in electricity capacity expansion models to ensure that downstream transmission planning studies are able to consider low-impact, high-quality zones.

Distributed energy resources (DER) can play an important role in reducing the land use impacts of renewable energy development, but large quantities of utility-scale solar and wind are still needed to meet clean energy targets. High rooftop solar scenarios (an additional 9 GW compared to baseline 2050 forecast, or a 35% increase) provide multiple benefits: locational value (reduce loads and thus allow deferral of distribution system upgrades), avoided line losses, and land conservation benefits. Results show that about 11–14% of California's 2050 electricity demand can be met with behind-the-meter (BTM) residential solar PV. Compared to the Base case, the high rooftop solar sensitivity scenarios reduced utility-scale capacity build-out by 3–6%, or 200–445 km^2. California will still require 95 GW (*Full West* Base Siting Level) to 132 GW (*In-State* Siting Level 4) of utility-scale generation capacity, or between 3,800 km^2 and 10,700 km^2 of land area. However, there may be opportunities to increase the DER contribution. The scenarios in this study are limited in assuming development of 25% of technical rooftop PV potential (both residential and commercial) in California, which includes rooftop PV on 90% of homes built after 2020. If 50% of technical potential for BTM PV in California can be realized by 2050 (effectively doubling the high BTM PV assumptions in this study), this would likely reduce electricity demand by another 12-14% percentage points, leaving about 70-75% of total demand that will still need to be met by utility-scale generation. However, these DER adoption assumptions do not include exogenous assumptions about non-rooftop BTM commercial PV (e.g., community solar) or other forms of innovative land-sparing distributed PV systems such as floatovoltaics.

4.1 Uncertainties

Policy changes and technology evolution could alter the balance of trade-offs and co-benefits. This study examines only California's electricity demand and whether it can be met by currently available west-wide wind and solar resources. As other states pursue equally ambitious climate goals by increasing renewable energy development, increased competition for the best wind and solar sites may change resource availability in the West, leading to inefficiencies and higher land use impacts if not adequately planned and managed. At high levels of cumulative wind and solar penetration, the marginal value of solar-balancing (storage) or solar-complementary resources (e.g., geographically diverse wind resources) may increase. Development of off-shore wind resources, which are not included in this study, can also alter the balance of options by enabling access to much needed wind generation in an *In-State* case. It will be important to explore the interaction of multiple states' electricity demand and policies and the potential contributions of offshore wind in future work.

Enabling conditions for access to best regional resources and more optimal inter-state resource sharing are uncertain, but some programs and institutions are in place. Changes in any of the following conditions can drive the future toward any one of the scenarios in this study: transmission access (planning, approval, financing and construction of new lines, and agreements on acceptable uses for these new lines), market structure (e.g., Energy Imbalance Market), regulatory framework (existing definitions of three types of Renewable Portfolio Standard eligibility may not easily allow out-of-state resources to qualify towards meeting RPS mandates), and the governance framework for inter-state resource sharing. For example, current RPS definitions tend to drive development toward the *In-State* Geography. Further development of the Energy Imbalance Market can drive states toward the *Full West* Geography. Emerging time-of-day GHG emissions accounting standards (see IRP Clean Net Short calculator) can drive the future toward the *Unconstrained* case, in particular the *Unconstrained* wind resource characterization, because wind hourly profiles tend to complement solar hourly profiles. Hence the value of wind is rising especially for generation during off-solar-peak hours, which encourages more wind development, some of which may be outside of RESOLVE Zones.

5 Conclusions

By accounting for siting impacts in planning processes for renewable energy deployment, it is possible for California to achieve its renewable and carbon-free electricity goals with minimal impacts to the west-wide network of natural and working lands.

Avoided impacts In the business-as-usual scenarios, impacts to natural and working lands in California and across the West are high. When environmental values are explicitly considered in siting of generation and transmission, impacts are avoided or reduced significantly.

Regional resources Our findings show that increasing the level of land use protection can increase portfolio cost, but expanding the geography reduces portfolio cost. When combining protections with a larger geography, these effects can offset each other, resulting in a portfolio that satisfies multiple policy goals (increased protections and lower cost). However, while increasing land protections can increase total resource costs, these costs do not reflect the additional costs that projects in sensitive areas may face due to land-related siting conflicts (e.g., mitigation, permitting, project delays, project resizing), which may be severe and significant in the less protective Siting Levels (SL 1 and 2).

Resource assumptions The cost increase associated with siting protections can be significantly reduced or offset by expanding resource potential estimates beyond current modeling assumption constraints. By enabling development outside of RESOLVE Zones, greater quantities of low-impact wind capacity can be selected, which lowers costs while protecting natural and working lands.

Differences in regional and *In-State* portfolios In the *In-State* scenarios, the vast majority of generation is supplied by solar PV due to the scarcity of wind potential. Thus, these portfolios rely heavily on battery storage to make solar generation available at night. In the regional scenarios, economically competitive wind resources with generation profiles that complement that of solar PV can avoid heavy reliance on battery storage. While regional wind resources are an economically attractive solution, they often occur on lands with high natural resource value.

Solar and wind impacts The working land impacts of both solar and wind are significant in all scenarios; one-third to one-half of all solar could be sited on agricultural land, and more than half of all solar and wind could be sited on rangelands.

6 Definitions

Candidate Project Area A GIS-modeled parcel of land with estimated renewable energy attributes (e.g., square km, MW, capacity factor, estimated annual generation, estimated capital cost, spatial boundary). Candidate Project Areas are the output of the site suitability analysis that apply spatially-explicit techno-economic and environmental exclusions for development that were then subdivided into typical large-scale renewable energy project-sized areas (typically 50-100 MW project size). 6

capacity factor A figure of merit used for evaluating the performance of electricity generation power plants. Expressed as a percentage, indicating the typical generation in a typical year, as a percent of the maximum theoretical generation that could be produced if the plant were operating at maximum capacity at all times. As an example, if a wind power plant has a 30% capacity factor, this means that in a typical meteorological year, this plant generates 30% of the amount of electricity that would theoretically be generated if wind speed remained continuously at maximum rated velocity for this turbine model, for all 8760 hours of the year.. 7

case A group of model runs, made up of a collection of inputs and outputs, that examine a single model modification in combination with changes to other variables (e.g., *In-State* Geographic case, *Unconstrained* case). 7

Constrained A case describing a version of the resource potential estimate that limits the resource potential to areas within the RESOLVE Zones and applies a maximum value on the solar resource potential per zone (20% of that zone's gross resource potential for the California Energy Commission's version of RESOLVE). 7

Environmental Exclusion Category A group of environmental siting criteria that share a common theme (e.g., all data sources in Category 1 fit that Category's definition, "Areas with legal restrictions against energy development"). These Environmental Exclusion Categories are used in the site suitability analysis to "exclude" land from renewable energy development.. 8

Geography Geographic areas within which renewable energy resources are assumed to be available for development. Three Geographies are defined for this study: *In-State* (California), *Part West*, and *Full West*. 16

portfolio A list of renewable energy resources (MW per RESOLVE Zone) selected by the capacity expansion model, representing the total or selected amount of new capacity that must be built to satisfy the model's constraints (e.g., meet electricity demand, achieve greenhouse gas emissions cap, minimize cost). 7

resource potential An estimated value describing the amount of renewable energy which could be developed within a specified area. For example, the estimated amount of wind resource potential within the New Mexico RESOLVE Zone is 36.1 gigawatts (GW). 9

scenario A model run (inputs and outputs) with a unique full combination of input assumptions (e.g., Siting Level 1, *In-State* Geography, *Constrained* resource assumption, base electricity demand forecast, Base battery cost). 16

Selected Project Area A Candidate Project Area (see definition) that was selected through the spatial disaggregation process using capacity requirements in a capacity expansion portfolio (see definition). The capacity expansion model specifies the total amount of energy or generation capacity selected, per RESOLVE Zone, after which the spatial disaggregation process uses the Candidate Project Areas to identify specific project footprints—Selected Project Area—at a finer geographic scale. 8

sensitivity A set of scenarios for which all input assumptions were held constant, except for a single input variable. The single variable was changed in order to determine the magnitude of the impact of that variable on the results. For this study two sensitivity analyses were defined, "High DER" and "Low Battery Cost". 8

Siting Level A case or set of scenarios in which a limited number of Environmental Exclusion Categories were applied. For example, in Siting Level 3, all of the following Environmental Exclusions were applied: Category 1, Category 2, and Category 3. 7

supply curve A list of supply-side power generation resources that are available to the capacity expansion model, including resource characteristics such as resource potential per zone (e.g., in megawatts of capacity) and capacity factor, and typically ranked in order of general economic value (or capacity factor). The model can select its optimal power mix from the supply curve. The supply curves in this study are based on the total amount of generation capacity within all Candidate Project Areas within a RESOLVE Zone. 6

technology Renewable energy generation technology type (e.g., wind, solar, and geothermal are the primary technologies under consideration in this study). 6

Unconstrained A case describing a version of the resource potential estimate that includes resource potential within and outside of RESOLVE Zones (i.e., state-wide) and does not limit the solar resource potential per zone (see definition for *Constrained*). 7

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Appendices

A Additional methods

Table 6: Techno-economic datasets for site suitability modeling

Broad category	Dataset name	Source	Website	Description	Data type/ resolution	Threshold or buffer
Renewable resource	WIND Toolkit dataset	NREL	https://data.nrel.gov/submissions/54 https://www.nrel.gov/grid/wind-toolkit.html	Point locations of simulated wind speeds and estimated annual average capacity factors of quality wind resource areas in the U.S.	CSV with geographic coordinates/ 2 km	Include all areas
Renewable resource	Solar PV capacity factors	NREL	https://sam.nrel.gov/	Point locations of estimated annual average capacity factors for fixed tilt solar PV calculated using SAM [1]	CSV with geographic coordinates/ 10 km	Include all areas
Renewable resource	Geothermal candidate locations	Black&Veatch	https://energyarchive.ca.gov/reti/documents/index.html	Point locations of candidate geothermal locations with estimated MW capacity for WesternU.S.as part of the Western Renewable Energy Zones study [21], and was also included in the Renewable Energy Transmission Initiative (RETI) 1.0 study [20]. The data download link is called,"GIS Data for Phase 2B".	Geodatabase point feature classes	Include all areas, buffered points using a radius calculated using a land use efficiency of 25.5 MW km^{-2}
Technical constraint	Slope	CGIAR	http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1	Calculated slope in percentage from STRM digital elevation model - Resampled 250 m SRTM 90m Digital Elevation Database v4.1	Raster/ 250m	Solar: exclude >5%, Wind: exclude >25%
Physical constraint	Water bodies and rivers	West-wide wind mapping project (WWWMP)	http://wwmp.anl.gov/maps-data/	Permanent water bodies in the U.S. (lakes and rivers)	Shapefile	Wind and solar: include areas >250m outside of water bodies
Socio-economic constraint	Census urban zones	2017 TIGER/ Line®	https://www.census.gov/geo/maps-data/data/tiger-line.html	Urban areas as defined by the U.S. Census	Shapefile	Solar: include areas >500m, Wind: include areas >1000m
Socio-economic constraint	Population density	ORNL Landscan	https://landscan.ornl.gov/	Persons per km^2	Raster/ 1km	Wind and solar: include areas <100 persons/km^2
Socio-economic constraint	Military areas	West-wide wind mapping project (WWWMP)	http://wwmp.anl.gov/maps-data/	Includes the following areas: DOD High Risk of Adverse Impact Zones, DOD Restricted Airspace and Military Training Routes, Utah Test and Training Range	Shapefile	Solar: include areas >1000m, Wind: include areas >5000m

[1] Solar PV capacity factor calculation assumptions for SAM: Ground Mount Fixed-tilt Racking Configuration, DC/AC Ratio = 1.35, Average Annual Soiling Losses = 3%, Module Mismatch Losses = 2%, Diode and Connection Losses = 0.5%, DC Wiring Losses = 2%, AC Wiring Losses = 1%, Availability Losses = 1%, Degradation = 0.35% in first year and 0.7%/year thereafter

Socio-economic constraint	Military areas	Protected Areas Database–U.S.	https://gapanalysis.usgs.gov/padus/	Filtered PAD-US feature class using: Des_Tp = 'MIL'	Geo-database feature class	Solar: include areas >1000m, Wind: include areas >5000m
Hazardous constraint	Active mines	USGS Active mines and mineral plans in the U.S.	https://mrdata.usgs.gov/mineplant/	Mine plants and operations for commodities monitored by the National Minerals Information Center of the USGS. Operations included are those considered active in 2003 and surveyed by the USGS.	CSV of geographic coordinates	Wind and solar: include areas >1000m
Hazardous constraint	Airports and runways	National Transportation Atlas Database (NTAD) from the U.S. Department of Transportation (USDOT) and Bureau of Transportation Statistics	http://osav-usdot.opendata.arcgis.com/datasets?keyword=Aviation	The airports dataset including other aviation facilities is as of July 6, 2017, and is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics' (BTS') National Transportation Atlas Database (NTAD).	Shapefile	Solar: include areas >1000m, Wind: include areas >5000m
Hazardous constraint	Railways	National Transportation Atlas Database (NTAD) from the U.S.DOT and Bureau of Transporation Statistics	http://osav-usdot.opendata.arcgis.com/	The Rail Network is a comprehensive database of North America's railway system at 1:24,000 to 1:100,000 scale as of October 10, 2017.	Shapefile	Wind and Solar: include areas >250m
Hazardous constraint	Flood zones	National Flood Hazard (FEMA) in WECC Environmental Data Viewer Geodatabase	https://ecosystems.azurewebsites.net/WECC/Environmental/	SQL filtered feature class using: "ALLTYPES1" LIKE "Flood Zone" OR "ALLTYPES2" LIKE "Flood Zone" OR "ALLTYPES3" LIKE "Flood Zone" OR "ALLTYPES4" LIKE"Flood Zone"	Geo-database feature class	Wind and Solar: include areas >0m

Table 7: Existing and planned energy infrastructure datasets

Broad category	Dataset name	Source	Website	Description	Data type/ resolution	Usage in study
Existing power plant locations	United States Wind Turbine Database (USWTDB)	USGS, Berkeley Lab, AWEA	https://eerscmap.usgs.gov/uswtdb/data/	Point locations of on-shore and off-shore turbines in the U.S. It is updated quarterly. Accessed on 9/13/18	Shapefile or Geojson	Exclude from potential project areas
Existing power plant locations	Ventyx/ABB EV Energy Map - Existing wind farm boundaries	Ventyx/ABB	https://new.abb.com/enterprise-software/energy-portfolio-management/market-intelligence-services/velocity-suite	The Wind Farm Boundaries EV Energy Map layer depicts the land area for turbines for a particular wind plant site. This layer was developed from various sources such as maps filed with permit applications, FAA obstacle data or aerial imagery and includes both operational and proposed wind plants.	Shapefile	Exclude from potential project areas
Existing power plant locations	Surface area of solar arrays in the conterminous United States as of 2015	USGS [33]	https://www.sciencebase.gov/catalog/item/57a25271e4b006cb45553efa	Footprint area of solar arrays in the conterminous U.S. based on EIA utility-scale facilities data from 2015	Shapefile	Exclude from potential project areas

Existing power plant locations	Surface area of utility-scale solar arrays in California as of 2018	The Nature Conservancy [32]	Unpublished	Footprint area of solar arrays in California created using satellite imagery	Shapefile	Exclude from potential project areas
Existing power plant locations	California's commercial wind and solar project locations	DataBasin, Black & Veatch, Public Utilities Commission	https://databasin.org/maps/365216c4ead144718ed63294035a2646	Existing and commercial wind and solar project locations (those with power purchase agreements from RPS Calculator and the California Public Utilities Commission)	Shapefile (point locations)	Used in conjunction with footprint areas to exclude from potential project areas
Existing power plant locations	Renewable Portfolio Standard Executed Projects (California)	Public Utilities Commission	http://cpuc.ca.gov/RPS_Reports_Data/	Public information of investor owned utility renewable contracts under the RPS program include: contract summaries, contract counterparties, resource type, location, delivery point, expected deliveries, capacity, length of contract, and online date.	Spreadsheet with geographic coordinates of project locations	Used in conjunction with footprint areas to exclude from potential project areas
Transmission infrastructure	California electric transmission line	California Energy Commission	http://caenergy.maps.arcgis.com/home/item.html?id=260b4513acdb4a3a8e4d64e69fc84fee	Transmission line locations as polylines with attribute data on voltages. This data are usually updated quarterly. Accessed on 1/18/2018.	Geodatabase feature class	Selecting potential project areas and modeling transmission corridor needs. Used lines > 69 kV
Transmission infrastructure	EV Energy Map - Transmission lines	Ventyx/ABB	https://new.abb.com/enterprise-software/energy-portfolio-management/market-intelligence-services/velocity-suite	Electric transmission lines EV energy map layer consists of market significant transmission lines generally greater than 115 kV.	Geodatabase feature class	Selecting potential project areas and modeling transmission corridor needs. Used lines > 69 kV
Transmission infrastructure	BLM recently approved Transmission lines	Environmental Planning Group LLC, Bureau of Land Management, Argonne National Labs	View lines: https://bogi.evs.anl.gov/section368/portal/	We included the following planned transmission corridors in "advanced development" and "recently approved": Gateway South, Gateway West, Southline, SunZia, TransWest Express, SWIP North, and Boardman to Hemingway. Spatial data can be requested from Argonne National Labs. These lines are listed as being in Phase 2 or 3 of the WECC Path Rating Process in the California Energy Commission's RETI 2.0 report "RETI 2.0 Western States Outreach Project Report" (https://www.energy.ca.gov/reti/reti2/documents/)	Geodatabase feature class	Selecting potential project areas and modeling transmission corridor needs. Buffered lines using project reports' planned corridor width

Table 8: Planned interstate bulk transmission data and corridor width assumptions

Transmission line name	Average corridor width source	Spatial data format	Average corridor width
TransWest Express	https://eplanning.blm.gov/epl-front-office/projects/nepa/65198/92789/111798/AppB_TWE_POD.pdf	Polyline	250 ft
Boardman to Hemingway	https://boardmantohemingway.com/documents/11-26-18/USFS_ROD_Nov_2018.pdf	Polyline	250 ft

SunZia	https://openei.org/w/images/b/b7/SunZia_Southwest_Transmission_Project_FEIS_and_Proposed_RMP_Amendments.pdf	Polyline	400 ft
Southline	NA	Polygon	NA
Gateway South	https://eplanning.blm.gov/epl-front-office/projects/nepa/53044/92847/111847/EGS-RecordofDecision.pdf	Polyline	250 ft
Gateway West	https://eplanning.blm.gov/epl-front-office/projects/nepa/39829/95570/115576/GWW_Segments_8_and_9_FINAL_ROD_without_appendices.pdf	Polyline	250 ft

Table 9: Datasets for environmental impact metrics

Metric	Dataset name	Source	Environmental Exclusion Category	Unique ID	Data type/ resolution
Critical habitat	Critical habitat		2	0051	Shapefile
Critical habitat	Desert tortoise critical habitat	WWWMP (high level)	2	0075	Shapefile
Critical habitat	Coastal critical habitat		2	0101	Shapefile
Critical habitat	Critical habitat	WWWMP (high level)	2	0262	Shapefile
Sage Grouse habitat	Priority habitat management area - exclusion	WWWMP - BLM	2	0257	Shapefile
Sage Grouse habitat	Priority habitat management area, high level siting considerations	WWWMP - BLM	2	0258	Shapefile
Sage Grouse habitat	General habitat management area, high level siting considerations	WWWMP - BLM	3	0259	Shapefile
Sage Grouse habitat	General habitat management area, moderate level siting considerations	WWWMP - BLM	3	0260	Shapefile
Sage Grouse habitat	Greater sage grouse priority areas for conservation	FWS	2	0266	Shapefile
Important Bird Areas	Important Bird Areas - state and globally important (Apr 2018)	Audubon Society	3	0110	Shapefile
Wetlands	National Wetlands Inventory	USFWS	2	0052	Shapefile
Wetlands	Priority Wetlands Inventory - Nevada	Nevada Natural Heritage Program	2	0054	Shapefile
Wetlands	Globally important wetlands	Site Wind Right (TNC)	2	0249	Shapefile
Wetlands	Playa wetland clusters	Site Wind Right (TNC)	3	0137	Shapefile
Wetlands	Vernal pools	USFWS	2	0077	Shapefile
Wetlands	Vernal pools - Great Valley, CA (Witham et al. 2014 update)	USFWS	2	0078	Shapefile
Wetlands	Vernal pools - San Diego	USGS	2	0079	Shapefile
Wetlands	Vernal pools - South Coast Range	California Department of Fish and Wildlife	2	0080	Shapefile
Wetlands	Vernal pools - Modoc National Forest	U.S.Forest Service	2	0081	Shapefile
Wetlands	California state wetlands	California Department of Fish and Game	2	0046	Shapefile
Big game corridors	Wyoming Big Game Crucial Habitat (Elk, Mule Deer, Bighorn Sheep, Pronghorn, White-tailed Deer)	Wyoming Game and Fish	2	0100	Shapefile
Big game corridors	WECC Big Game (ALLTYPES3 LIKE '%Big Game Winter Range%')	WECC	3	0105	Shapefile
Big game corridors	Washington Deer areas	Washington Department of Fish and Wildlife	3	0123	Shapefile
Big game corridors	Washington Elk areas	Washington Department of Fish and Wildlife	3	0124	Shapefile
Big game corridors	Oregon Elk and Deer Winter Range	Oregon Department of Fish and Wildlife	3	0149	Shapefile
Big game corridors	Columbian White-tailed deer range	USFWS	3	0155	Shapefile
Wildlife linkages	Wildlife linkages with corridor values > 34.3428	The Wilderness Society [40]	4	0172	Shapefile

Eagle habitat	Bald Eagle habitat	WWWMP - BLM	2 (wind only)	0076	Shapefile
Eagle habitat	West-wide eagle risk data using the 2 of quantile bins (top 30% of eagle habitat)	USFWS (Bedrosian et al. 2018)	2 (wind only)	0102	Shapefile
Eagle habitat	Golden Eagle habitat	WWWMP	2 (wind only)	0228	Shapefile
Prime farmland	Prime farmland based on high quality soils	Natural Resources Conservation Service	3	0267	Shapefile
Agricultural land	Crop and pasturelands (used class #556-Cultivated Cropland and #557-Pasture/Hay)	National GAP Landcover https://gapanalysis.usgs.gov/gaplandcover/data/download/	NA	NA	raster/ 30m
Rangelands	U.S.rangelands extent using NRI-LANDFIRE model	[41]	NA	NA	raster/ 30m
Housing density	Housing density (2010)	USFS http://silvis.forest.wisc.edu/data/housing-block-change/	NA	NA	geo-database

Table 10: Datasets for Environmental Exclusion Category 1 (site suitability). Definitions: Exclude development (EX), Avoid development (AV), WECC Environmental Risk Class (RC 1, 2, 3, 4), BLM High Level Siting Considerations (HLSC), BLM Moderate Level Siting Considerations (MLSC), Information not available (NA)

Unique Data ID	Environmental Category	Technology	Data Publisher Organization	Dataset Name	ORB 2015	BLM WSEP	BLM WWW-MP	BLM DRECP	WECC	WREZ	RETI CPUC
1	1	All	National Park Service	NPS boundaries - National Historic Trails	EX	EX	EX	EX	RC 2	EX	EX
2	1	All	BLM - WWWMP	National Scenic Trails	NA	EX	EX	EX	NA	EX	NA
3	1	All	BLM - WWWMP	National Historic Landmarks	NA	NA	EX	NA	NA	NA	NA
4	1	All	BLM - WWWMP	National Natural Landmarks	NA	NA	EX	NA	NA	NA	NA
5	1	All	United States Geological Survey	Wild and Scenic Rivers	NA	EX	EX	NA	RC 3	EX	EX
6	1	All	Natural Resources Conservation Service	Easements	EX	NA	NA	NA	RC 3	EX	EX
8	1	All	National Conservation Easement Database	Conservation Easements	NA	NA	NA	NA	NA	NA	NA
9	1	All	Bureau of Land Management	BLM Solar Energy Program SEZ non-dev	NA	EX	NA	NA	NA	NA	NA
10	1	All	BLM - WWWMP	Visual Resource Management	NA	EX	EX	NA	NA	AV	NA
11	1	All	Bureau of Land Management	BLM Solar Energy Program exclusions	NA	NA	NA	NA	NA	NA	NA
12	1	All	USGS PAD-US	National Primitive Area	EX	NA	NA	NA	RC 4	EX	NA
13	1	All	USGS PAD-US	National Wildlife Refuge	EX	NA	NA	NA	RC 4	EX	EX
14	1	All	USGS PAD-US	Units of the National Parks System (excluding National Recreation Areas and National Trails)	EX	EX	NA	NA	RC 4	EX	EX
15	1	All	USGS PAD-US	Wilderness Area	EX	EX	EX	NA	RC 4	EX	EX
16	1	All	USGS PAD-US	Wilderness Area (Recommended)	NA	NA	NA	NA	RC 4	EX	NA
17	1	All	USGS PAD-US	Wilderness Study Area	EX	EX	EX	NA	RC 4	EX	EX
20	1	All	BLM - WWWMP	National Conservation Area	EX	EX	EX	NA	RC 3	EX	EX
21	1	All	USGS PAD-US	National Monument	EX	EX	EX	NA	RC 3	EX	EX
22	1	All	USGS PAD-US	National Recreation Area	EX	NA	NA	NA	RC 3	EX	EX
23	1	All	USGS PAD-US	Research Natural Area – Proposed	EX	NA	NA	NA	RC 3	NA	NA
24	1	All	BLM - WWWMP	Desert Renewable Energy Conservation Plan Special Recreation Management Area	EX	EX	EX in CA; MLSC elsewhere.	EX	NA	AV	EX in DRECP area
25	1	All	USGS PAD-US	State Park	EX	NA	NA	NA	RC 3	EX	EX
26	1	All	USGS PAD-US	State Wildlife Management Areas	EX	NA	NA	NA	RC 3	AV	NA
28	1	All	BLM - WWWMP	National Register Historic Places		NA	EX	NA	NA	NA	NA
29	1	All	USGS PAD-US	State Wilderness Areas	EX	NA	NA	NA	NA	EX	EX

30	1	All	USGS PAD-US	DFW Wildlife Areas and Ecological Reserves	EX	NA	NA	NA	NA	NA	NA
31	1	All	USGS PAD-US	Existing Conservation and Mitigation Bank	EX	NA	NA	NA	NA	EX	EX
32	1	All	USGS PAD-US	Watershed Protection Area	EX	NA	NA	NA	NA	EX	NA
33	1	All	USGS PAD-US	Marine Protected Area	EX	NA	NA	NA	NA	EX	NA
34	1	All	USGS PAD-US	Historic or Cultural Area	EX	EX	NA	NA	NA	AV	EX
35	1	All	California State Agencies	Habitat Conservation Plan	AV	NA	NA	NA	Non-preferred dataset	AV	EX
36	1	All	California State Agencies	Natural Community Conservation Plan	AV	NA	NA	NA	Non-preferred dataset	AV	EX
38	1	All	BLM - WWWMP	DRECP NCL	NA	NA	NA	EX	NA	NA	NA
39	1	All	BLM - WWWMP	Park boundaries	NA	NA	NA	NA	NA	NA	NA
43	1	All	BLM - WWWMP	vrmII	NA	NA	NA	NA	NA	NA	NA
190	1,2	Cat1(s); Cat2 (w,g)	USGS PAD-US	Right of Way exclusion	NA	NA	NA	NA	RC 3	NA	NA
240	1,2	All	Colorado Natural Heritage Program	Colorado protected lands	NA	NA	NA	NA	NA	NA	NA
252	1	All	BLM - WWWMP	conservation	NA	NA	EX	NA	NA	NA	NA
256	1	All	BLM - WWWMP	Right of Way exclusion	NA	NA	EX	NA	NA	NA	NA

Table 11: Datasets for Environmental Exclusion Category 2 (site suitability). Definitions: Exclude development (EX), Avoid development (AV), WECC Environmental Risk Class (RC 1, 2, 3, 4), BLM High Level Siting Considerations (HLSC), BLM Moderate Level Siting Considerations (MLSC), Information not available (NA)

Unique Data ID	Environmental Category	Technology	Data Publisher Organization	Data Set Name (subset of area type)	ORB 2015	BLM WSEP	BLM WWWMP	BLM DRECP	WECC	WREZ	RETI CPUC
18	2	All	BLM - WWWMP	Areas of Critical Environmental Concern	EX	EX	EX	EX	RC 3	EX	EX
27	2	All	New Mexico County governments	New Mexico County wind ordinances	NA	NA	NA	NA	NA	NA	NA
42	2	All	U.S.Census Bureau	Tribal Lands	NA	NA	NA	NA	RC 2	NA	NA
43	2	All	BLM - WWWMP	Visual Resource Management II	NA	NA	HLSC	NA	NA	NA	NA
44	2	All	USGS PAD-US	State Forest	EX	NA	NA	NA	RC 3	EX	EX
45	2	All	BLM - WWWMP	National Park Service Areas of High Potential Resource Conflict	NA	NA	MLSC	NA	NA	NA	AV
46	2	All	California Department of Fish and Game	Central Valley Wetland and Riparian Areas	EX	NA	NA	NA	RC 3	EX	EX
47	2	All	BLM - WWWMP	No Surface Occupancy	EX	EX	HLSC	NA	NA	NA	NA

51	2	All	United States Fish and Wildlife Service	Critical Habitat for Threatened and Endangered Species Composite Layer	AV	EX	HLSC	NA	RC 3	NA	AV
52	2	All	United States Fish and Wildlife Service	Wetlands - prc	EX	NA	NA	NA	RC 2	EX	NA
53	2	All	United States Forest Service	National Inventoried Roadless Areas	EX	NA	NA	NA	RC 3	EX	EX
54	2	All	Nevada Natural Heritage Program	Priority Wetlands Inventory	NA	NA	NA	NA	RC 2	NA	NA
55	2	All	Wyoming Game and Fish	crucial winter areas	NA	NA	NA	NA	RC 3	NA	NA
56	2	All	Wyoming Game and Fish	crucial winter areas	NA	NA	NA	NA	RC 3	NA	NA
57	2	All	USGS PAD-US	Special Interest Area	AV	NA	NA	NA	RC 3	AV	NA
58	2	All	BLM - WWWMP	Desert Renewable Energy Conservation Plan Extensive Recreation Management Area	NA	NA	HLSC	AV	NA	NA	NA
59	2	All	BLM - WWWMP	Desert Renewable Energy Conservation Plan Wildlife Allocation	NA	NA	EX	AV	NA	NA	EX in DRECP
60	2	All	BLM - WWWMP	Desert Renewable Energy Conservation Plan Off Highway Vehicles	NA	NA	EX	EX	NA	AV	NA
61	2	All	BLM - WWWMP	Off Highway Vehicle	NA	NA	MLSC	NA	NA	AV	NA
62	2	Wind	BLM - WWWMP	Development Focus Area - solar and geothermal only (excluding wind)	NA	NA	EX	Prioritize (varies by technology)	NA	NA	NA, except in SJV/ DRECP screen
63	2	All	USGS PAD-US	U.S. Army Corps of Engineers Land	NA	NA	NA	NA	RC 2	NA	NA
64	2	All	USGS PAD-US	Native Allotments	NA	NA	NA	NA	RC 2	NA	NA
65	2	All	USGS PAD-US	Other private non-profit land	EX	NA	NA	NA	RC 2	NA	NA
66	2	All	TNC WAFO	TNC__Lands__Features	EX	NA	NA	NA	NA	NA	EX
67	2	All	WA DNR	Spotted Owl Management Units	NA	NA	NA	NA	NA	EX	EX
68	2	All	WA DNR	Habitat Conservation Plan Lands	NA	NA	NA	NA	NA	EX	EX
71	2	All	USGS PAD-US	State Reserves	AV	NA	NA	NA	NA	NA	NA
72	2	All	USGS PAD-US	Other wildlife areas and ecological reserves	AV	NA	NA	NA	NA	NA	NA
73	2	All	Los Angeles County	Significant ecological areas	AV	NA	NA	NA	NA	NA	AV
75	2	All	BLM - WWWMP	Desert Tortoise Critical Habitat	AV	NA	HLSC	NA	NA	NA	NA
76	2	Wind	BLM - WWWMP	Bald Eagle	NA	NA	MLSC	NA	NA	NA	NA
77	2	All	USFWS	Vernal pools	NA	NA	NA	NA	NA	NA	AV
78	2	All	USFWS	2012RemapVernalPoolsFINAL.zip	NA	NA	NA	NA	NA	NA	AV
79	2	All	CDFW	SANGIS__ECO__VERNAL__POOLS.shp	NA	NA	NA	NA	NA	NA	AV
80	2	All	CDFW	ds948.shp	NA	NA	NA	NA	NA	NA	AV
81	2	All	USDA Forest Service, Modoc National Forest.	Vernal pools, Modoc. ds949.zip	NA	NA	NA	NA	NA	NA	AV

82	2	All	BLM	BLM Lands with Wilderness Characteristics (DRECP)	NA	EX	EX	See CMAs	NA	AV	NA
83	2	All	BLM - WWWMP	BLM Lands with Wilderness Characteristics (WWWMP)	NA	EX	EX	See CMAs	NA	AV	NA
85	2	All	Bureau of Land Management DRECP	National Landscape Conservation Survey Preferred Subareas	NA	EX	EX	EX	NA	EX	NA
91	2	Wind	TNC ”Site Wind Right” study	Cooperative Whooping Crane Tracking Project database Pearse et al. (2015) National Wetlands Inventory	NA	NA	NA	NA	NA	NA	NA
92	2	Wind	University of Kansas, Kansas Biological Survey	SGPCHAT	NA	NA	NA	NA	NA	NA	NA
96	2	All	Colorado Parks and Wildlife	Preble S Jumping Mouse	NA	NA	NA	NA	NA	NA	NA
97	2	All	Colorado Parks and Wildlife	Mule deer	NA	NA	NA	NA	NA	NA	NA
100	2	Wind	Wyoming Game and Fish	Big Game Crucial Habitat	NA	NA	NA	NA	RC 3	NA	NA
101	2	All	NOAA/USFWS	Critical Habitat Designations (map service layer)	AV	NA	NA	NA	NA	NA	NA
102	2	Wind	FWS	West-Wide Eagle Risk Data	NA	NA	NA	NA	NA	NA	NA
185	2	All	USGS PAD-US	Research Natural Area	EX/AV	NA	NA	NA	RC 3	AV	EX
194	2	All	USGS PAD-US	Native American Lands	NA	NA	NA	NA	RC 2	NA	NA
225	2	All	WSDOT	WSDOT - Tribal Reservation and Trust Lands	NA	NA	NA	NA	RC 2	NA	NA
228	2	Wind	BLM - WWWMP	Golden Eagle suitable habitat	NA	NA	MLSC	NA	NA	NA	NA
234	2	Wind	Colorado Parks and Wildlife	Bald Eagle nest sites, roosting sites, concentration areas	NA	NA	NA	NA	NA	NA	NA
239	2	Wind	Colorado Parks and Wildlife	Colorado Least Tern nesting and foraging sites	NA	NA	NA	NA	NA	NA	NA
240	1,2	All	Colorado Natural Heritage Program	Colorado protected lands	NA	NA	NA	NA	NA	NA	NA
248	2	All	Contact TNC MT chapter for more information.	Montana Wetland Areas	NA	NA	NA	NA	NA	NA	NA
249	2	All	WHSRN	Globally important wetlands	NA	NA	NA	NA	NA	NA	NA
257	2	Wind	BLM - WWWMP	Sage Grouse Priority Habitat Management Area exclusion	NA	NA	EX	NA	NA	NA	NA
258	2	Wind	BLM - WWWMP	Sage Grouse Priority Habitat Management Area, High Level Siting Requirements	NA	NA	HLSC	NA	NA	NA	NA
262	2	All	BLM - WWWMP	critical habitat	NA	NA	HLSC	NA	NA	NA	NA
263	2	All	BLM - WWWMP	Special Recreation Management Area	NA	NA	HLSC	EX	NA	NA	NA
266	2	Wind	TNC	GreaterSageGrousePACs.gdb	NA	NA	NA	NA	NA	NA	NA
271	2	Wind and solar only, geothermal is an exception	County government	Imperial County: areas outside Renewable Energy Overlay	NA	NA	NA	NA	NA	NA	NA

272	2	All	County government	Inyo County: areas outside Solar Energy Development Areas (SEDAs)	NA	NA	NA	NA	NA	NA	NA

Table 12: Datasets for Environmental Exclusion Category 3 (site suitability). Definitions: Exclude development (EX), Avoid development (AV), WECC Environmental Risk Class (RC 1, 2, 3, 4), BLM High Level Siting Considerations (HLSC), BLM Moderate Level Siting Considerations (MLSC), Information not available (NA)

Unique Data ID	Environmental Category	Technology	Data Publisher Organization	Dataset Name	ORB 2015	BLM WSEP	BLM WWW-MP	BLM DRECP	WECC	WREZ	RETI CPUC
49	3	All	Montana Dept of Fish Wildlife and Parks: Crucial Areas Planning System (CAPS)	Bighorn Sheep & Mountain Goat Habitat	AV	NA	NA	NA	RC 3	NA	NA
103	3	All	BLM - WWWMP	Visual Resource Management lands level III	NA	NA	MLSC	NA	NA	NA	NA
104	3	All	Colorado Division of Wildlife	Species Activitiy Data: Severe Winter Range, Winter Concentration, Winter Range, Migration Patters, and Migration Corridor	NA	NA	NA	NA	RC 3	NA	NA
105	3	All	Montana Dept of Fish Wildlife and Parks: Crucial Areas Planning System (CAPS)	Big Game Winter Range Habitat	NA	NA	NA	NA	RC 3	NA	NA
111	3	All	Federal Highway Administration	America's Byways	NA	NA	NA	NA	RC 2	NA	NA
112	3	All	Caltrans	California Scenic Highways	NA	NA	NA	NA	RC 2	NA	NA
113	3	All	Idaho Department o Transportation	Scenic Byways of Idaho	NA	NA	NA	NA	RC 2	NA	NA
114	3	All	Colorado Department of Transportation	Colorado Scenic and Historic Byways	NA	NA	NA	NA	RC 2	NA	NA
115	3	All	Washington State Department of Transportation	Washington Scenic Highways	NA	NA	NA	NA	RC 2	NA	NA
118	3	All	Wyoming Game and Fish	Shapefile: WYPrairieDogComplexes_WGFDWAFWA.	NA	NA	NA	NA	NA	NA	NA
121	3	Wind	Wyoming Natural Heritage Program	WYGrasslandBirds	NA	NA	NA	NA	NA	NA	NA
123	3	All	WDFW	Deer Areas (Polygons)	NA	NA	NA	NA	NA	NA	NA
124	3	All	WDFW	Elk Areas (Polygons)	NA	NA	NA	NA	NA	NA	NA
125	3	All	U.S. Fish and Wildlife Service	USFWS Upland Species Recovery Units	AV	NA	NA	NA	NA	NA	NA
126	3	All	California Department of Conservation	Williamson act –Farmland Mapping and Monitoring Program (FMMP) in CA	Cat3	NA	NA	NA	EX	EX	EX
127	3	All	The Nature Conservancy	Mojave Ecorgeional Assessment	Cat3	NA	NA	NA	NA	NA	NA
129	3	All	Herpetological Conservation and Biology	Mojave Desert Tortoise Linkages	Cat3	NA	MLSC	NA	NA	NA	NA
133	3	All	BLM - WWWMP	Desert Tortoise Connectivity	NA	NA	MLSC	NA	NA	NA	NA

136	3	All	TNC	High integrity grasslands	NA	NA	NA	NA	NA	NA	NA
137	3	Wind	Playa Lakes Joint Venture	Playa clusters	NA	NA	NA	NA	NA	NA	NA
138	3	Wind	Colorado Parks and Wildlife	Greater prairie-chicken optimal habitat	NA	NA	NA	NA	NA	NA	NA
139	3	All	Colorado Natural Heritage Program	Potential Conservation Areas	NA	NA	NA	NA	NA	NA	NA
140	3	Wind	Colorado Parks and Wildlife	Columbian sharptail grouse production areas and winter range	NA	NA	NA	NA	NA	NA	NA
141	3	Wind	Colorado Parks and Wildlife	Plains sharptail grouse concentration areas, winter concentration areas, migratino corridors, severe winter range	NA	NA	NA	NA	NA	NA	NA
142	3	All	Colorado Parks and Wildlife	Pronghorn	NA	NA	NA	NA	NA	NA	NA
143	3	Wind	Colorado Parks and Wildlife	Least tern production areas and foraging areas	NA	NA	NA	NA	NA	NA	NA
144	3	Wind	Colorado Parks and Wildlife	Piipng plover production areas and foraging areas	NA	NA	NA	NA	NA	NA	NA
145	3	Wind	Colorado Parks and Wildlife	CPW Nest area and potential nesting area	NA	NA	NA	NA	NA	NA	NA
146	3	Wind	Wyoming Natural Heritage Program	Tree roosting bats (Silver-haired bat, Hoary, Eastern Red)	NA	NA	NA	NA	NA	NA	NA
148	3	All	New Mexico Department of Game and Fish	Big Game Priority Habitat	NA	NA	NA	NA	RC 3	NA	NA
149	3	All	Oregon Department of Fish and Wildlife	Elk and Deer Winter Range	NA	NA	NA	NA	RC 3	NA	NA
150	3	All	New Mexico Department of Transportation	New Mexico State and National Scenic Byways	NA	NA	NA	NA	RC 2	NA	NA
151	3	All	Oregon Department of Transportation	Oregon Scenic Byways	NA	NA	NA	NA	RC 2	NA	NA
152	3	All	Wyoming Department of Transportation	Wyoming Scenic Highways and Byways	NA	NA	NA	NA	RC 2	NA	NA
155	3	All	USFWS	Columbian white-tailed deer	NA	NA	NA	NA	NA	NA	NA
156	3	All	BLM	BLM Nominated ACECs	NA	NA	NA	NA	NA	NA	NA
157	3	All	TNC	TNC Nominated ACECs. Areas with high conservation value as determined through TNC ecoregional analysis (if/when they become ACEC they would move up to Cat 2).	NA	NA	NA	NA	NA	NA	NA
158	3	All	TNC	Ecologically core areas. Contact TNC NV chapter for more information,	NA	NA	NA	NA	NA	NA	NA
159	3	All	TNC OR	The Nature Conservancy Portfolio Areas	Cat3	NA	NA	NA	NA	NA	NA
160	3	All	ODFW	Oregon Conservation Strategy	NA	NA	NA	NA	NA	NA	NA
161	3	All	TNC	TNC Nevada priority landscapes layer	NA	NA	NA	NA	NA	NA	NA
162	3	All	NDOW	Critical habitat rank 1 or 2	NA	NA	NA	NA	NA	NA	NA

164	3	All	Arizona Department of Roads	Arizona Scenic Roads	NA	NA	NA	NA	RC 2	NA	NA
170	3	All	CEC and USGS, Las Vegas Field Station	Mohave Ground Squirrel (candidate species) Maxent site suitability model at 0.438 cutoff	Cat4	NA	NA	NA	NA	NA	NA
187	3, 4	All	TNC	The Nature Conservancy Portfolio Areas	NA	NA	NA	NA	NA	NA	NA
241	3	All	Colorado natural Heritage Program	Potential Conservation Areas (CO)	NA	NA	NA	NA	NA	NA	NA
259	3	All	BLM - WWWMP	Sage Grouse General Habitat Management Area, High Level Siting Requirements	NA	NA	HLSC	NA	NA	NA	NA
260	3	All	BLM - WWWMP	Sage Grouse General Habitat Management Area, Moderate Level Siting Requirements	NA	NA	MLSC	NA	NA	NA	NA
261	3	All	BLM - WWWMP	Sagebrush Focal Area	NA	NA	EX	NA	NA	NA	NA
267	3	All	NRCS	Westwide Prime farmland classification	NA	NA	NA	NA	NA	NA	EX
268	3	All	TNC	Priority Conservation Areas	NA	NA	NA	NA	NA	NA	NA
269	3	All	NatureServe	Mojave Desert Tortoise Species Distribution Model - Threshold	NA	NA	NA	NA	NA	NA	NA

Table 13: Datasets for Environmental Exclusion Category 4 (site suitability). Definitions: Exclude development (EX), Avoid development (AV), WECC Environmental Risk Class (RC 1, 2, 3, 4), BLM High Level Siting Considerations (HLSC), BLM Moderate Level Siting Considerations (MLSC), Information not available (NA)

Unique Data ID	Environmental Category	Technology	Data Publisher Organization	Dataset Name	ORB 2015	BLM WSEP	BLM WWW-MP	BLM DRECP	WECC	WREZ	RETI CPUC
165	4	All	Conservation Science Partners Inc.	Landscape intactness	NA	NA	NA	NA	NA	NA	NA
166	4	All	TNC	The Nature Conservancy Ecologically Intact for CA deserts	Cat4	NA	NA	NA	NA	NA	NA
169	4	All	CDOT, CDFG, and FHA	Essential Connectivity areas of California	Cat4	NA	NA	NA	RC 3	NA	NA
172	4	All	The Wilderness Society	Least cost linkages	NA	NA	NA	NA	NA	NA	NA
173	4	All	AGFD	AZ multi-species corridors	NA	NA	NA	NA	NA	NA	NA

Table 14: Scenario List

Number	Name
1	In-State Base
2	In-State Base High DER
3	In-State Base Low Battery Cost
4	In-State Siting Level 1 Constrained Base
5	In-State Siting Level 1 Constrained High DER
6	In-State Siting Level 1 Constrained Low Battery Cost
7	In-State Siting Level 1 Unconstrained Base
8	In-State Siting Level 2 Constrained Base
9	In-State Siting Level 2 Constrained High DER
10	In-State Siting Level 2 Constrained Low Battery Cost
11	In-State Siting Level 2 Unconstrained Base
12	In-State Siting Level 3 Constrained Base
13	In-State Siting Level 3 Constrained High DER
14	In-State Siting Level 3 Constrained Low Battery Cost
15	In-State Siting Level 3 Unconstrained Base
16	In-State Siting Level 3 Unconstrained High DER
17	In-State Siting Level 3 Unconstrained Low Battery Cost
18	In-State Siting Level 4 Constrained Base
19	In-State Siting Level 4 Constrained High DER
20	In-State Siting Level 4 Constrained Low Battery Cost
21	In-State Siting Level 4 Unconstrained Base
22	Part West Base
23	Part West Base High DER
24	Part West Base Low Battery Cost
25	Part West Siting Level 1 Constrained Base
26	Part West Siting Level 1 Constrained High DER
27	Part West Siting Level 1 Constrained Low Battery Cost
28	Part West Siting Level 1 Unconstrained Base
29	Part West Siting Level 2 Constrained Base
30	Part West Siting Level 2 Constrained High DER
31	Part West Siting Level 2 Constrained Low Battery Cost
32	Part West Siting Level 2 Unconstrained Base
33	Part West Siting Level 3 Constrained Base
34	Part West Siting Level 3 Constrained High DER
35	Part West Siting Level 3 Constrained Low Battery Cost
36	Part West Siting Level 3 Unconstrained Base
37	Part West Siting Level 4 Constrained Base
38	Part West Siting Level 4 Constrained High DER
39	Part West Siting Level 4 Constrained Low Battery Cost
40	Part West Siting Level 4 Unconstrained Base
41	Full West Base
42	Full West Base High DER
43	Full West Base Low Battery Cost
44	Full West Siting Level 1 Constrained Base
45	Full West Siting Level 1 Constrained High DER
46	Full West Siting Level 1 Constrained Low Battery Cost
47	Full West Siting Level 1 Unconstrained Base
48	Full West Siting Level 2 Constrained Base
49	Full West Siting Level 2 Constrained High DER
50	Full West Siting Level 2 Constrained Low Battery Cost
51	Full West Siting Level 2 Unconstrained Base
52	Full West Siting Level 3 Constrained Base
53	Full West Siting Level 3 Constrained High DER
54	Full West Siting Level 3 Constrained Low Battery Cost
55	Full West Siting Level 3 Unconstrained Base

56	Full West Siting Level 3 Unconstrained High DER
57	Full West Siting Level 3 Unconstrained Low Battery Cost
58	Full West Siting Level 4 Constrained Base
59	Full West Siting Level 4 Constrained High DER
60	Full West Siting Level 4 Constrained Low Battery Cost
61	Full West Siting Level 4 Unconstrained Base

B Additional results

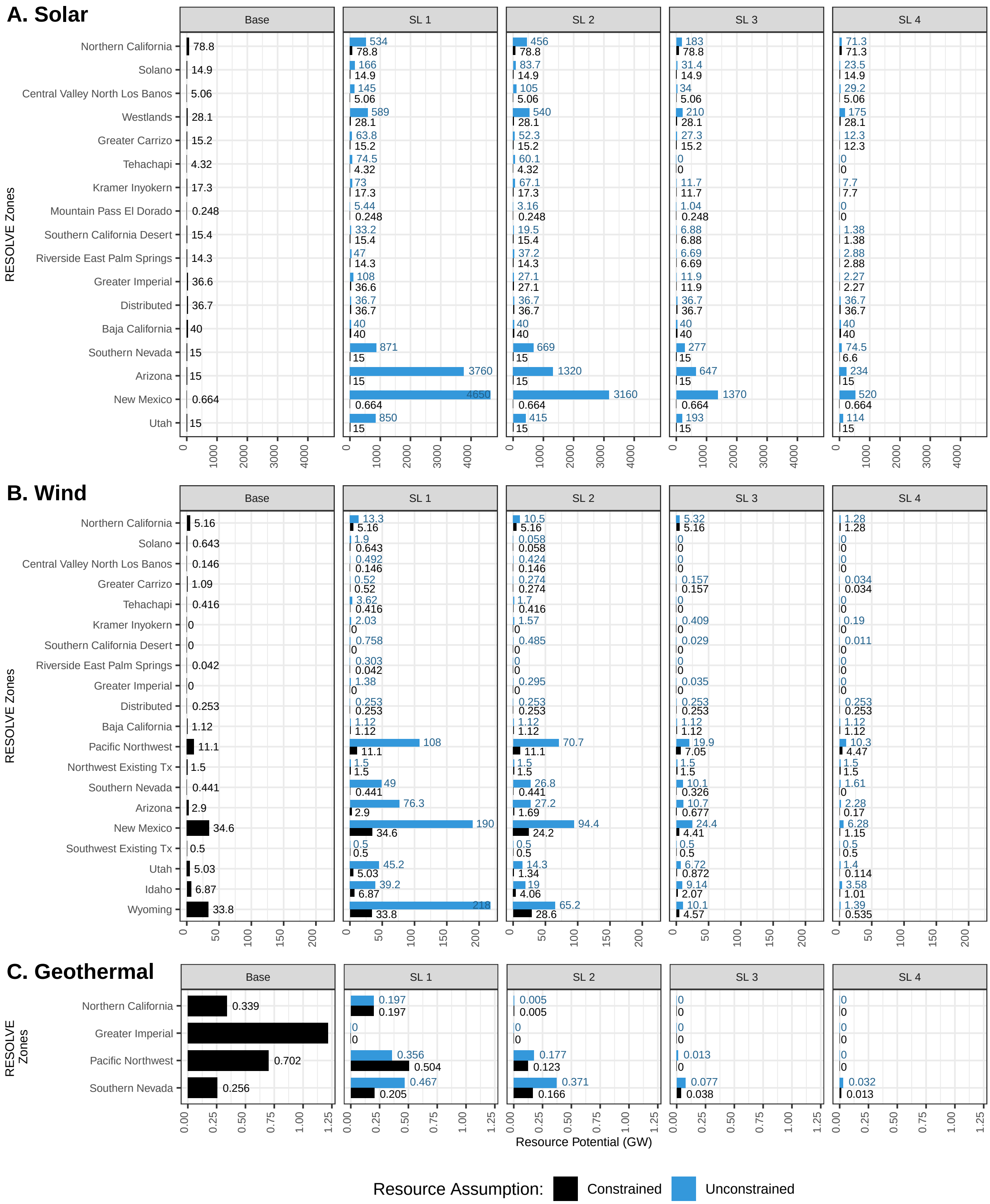

Figure 14: Supply curves (resource potential estimates from sites suitability analysis) for each Siting Level used as inputs to RESOLVE for solar (A), wind (B), and geothermal (C) technologies for the *Constrained* (bars and data values in black) and *Unconstrained* (bars and data values in blue) resource assumption case. No *Unconstrained* bars are in the Base panel plots because the RESOLVE Base case assumes *Constrained* resources.

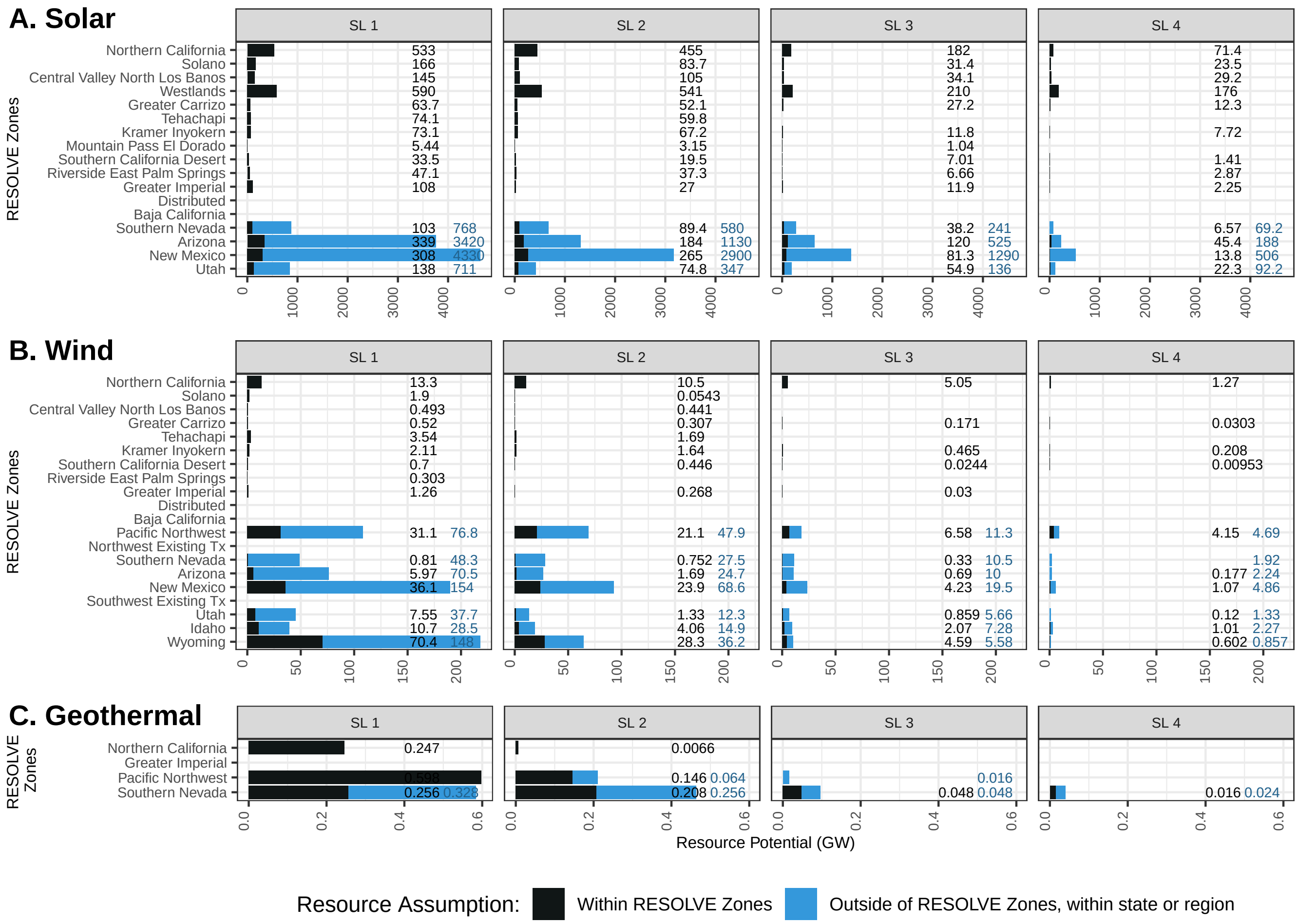

Figure 15: Unadjusted supply curves under each Siting Level for solar (A), wind (B), and geothermal (C) technologies with stacked bars showing the amount of potential within RESOLVE Zones (black bars) and outside of RESOLVE Zones within the region or state for non-California regions (grey bars). The "within RESOLVE zones" data label is the left-most label and the "Outside of RESOLVE Zone" data labels is the far right label within each panel. The "Outside of RESOLVE Zone" data labels indicate the amount of potential within the grey bars, not of the absolute length of the bars. The absolute length of the bars is the sum of the two data labels, and it indicates the amount of resource potential in the *Unconstrained* case.

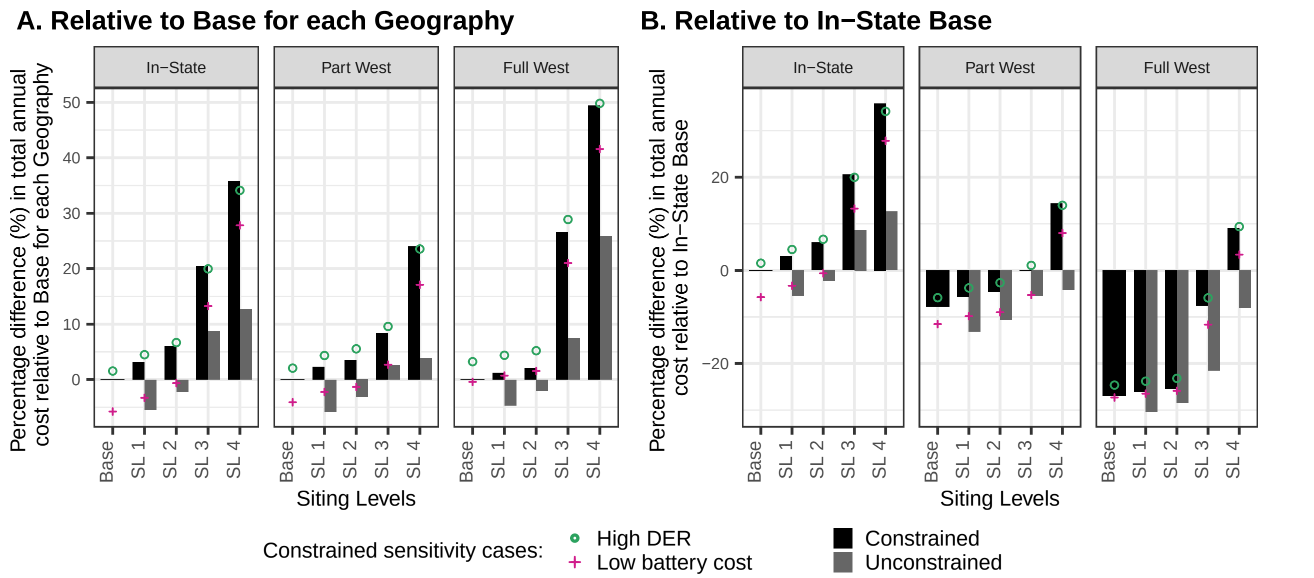

Figure 16: Percentage cost differences of only modeled resource costs relative to the RESOLVE Base for each Geographic case (A) and relative to *In-State* RESOLVE Base (B) for all Siting Levels and *Constrained* and *Unconstrained* assumptions case. See Fig. 7 for percentage cost differences using total (modeled and non-modeled) costs.

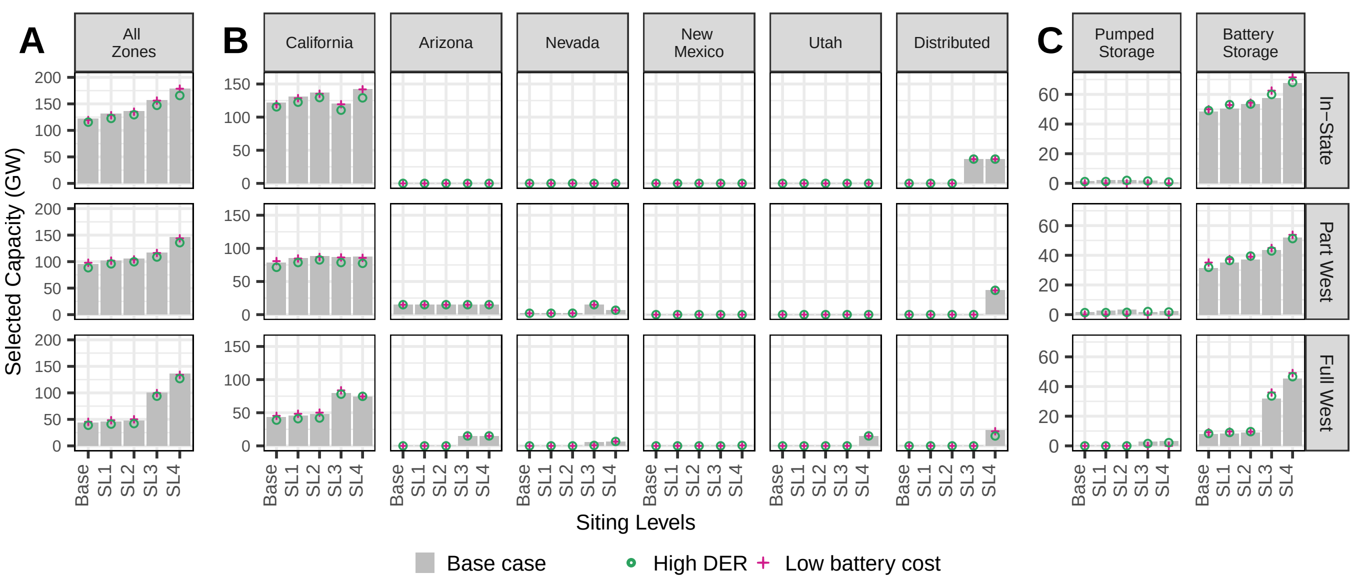

Figure 17: Selected solar capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases for the *Constrained* assumptions case.

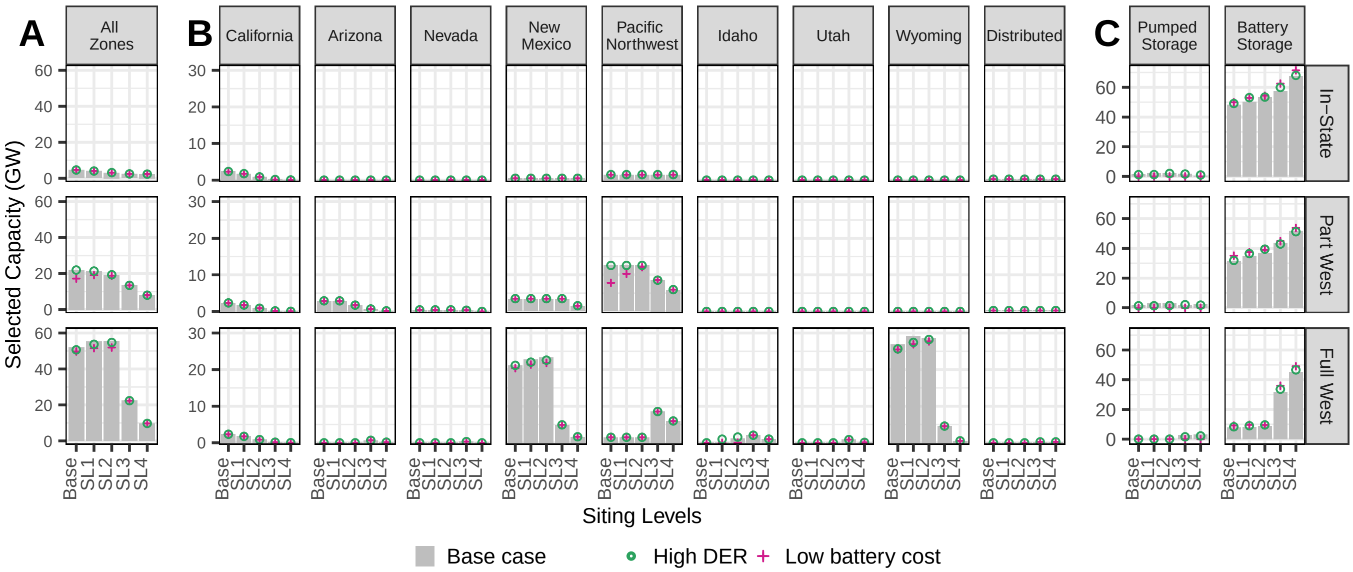

Figure 18: Selected wind capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases for the *Constrained* assumptions case.

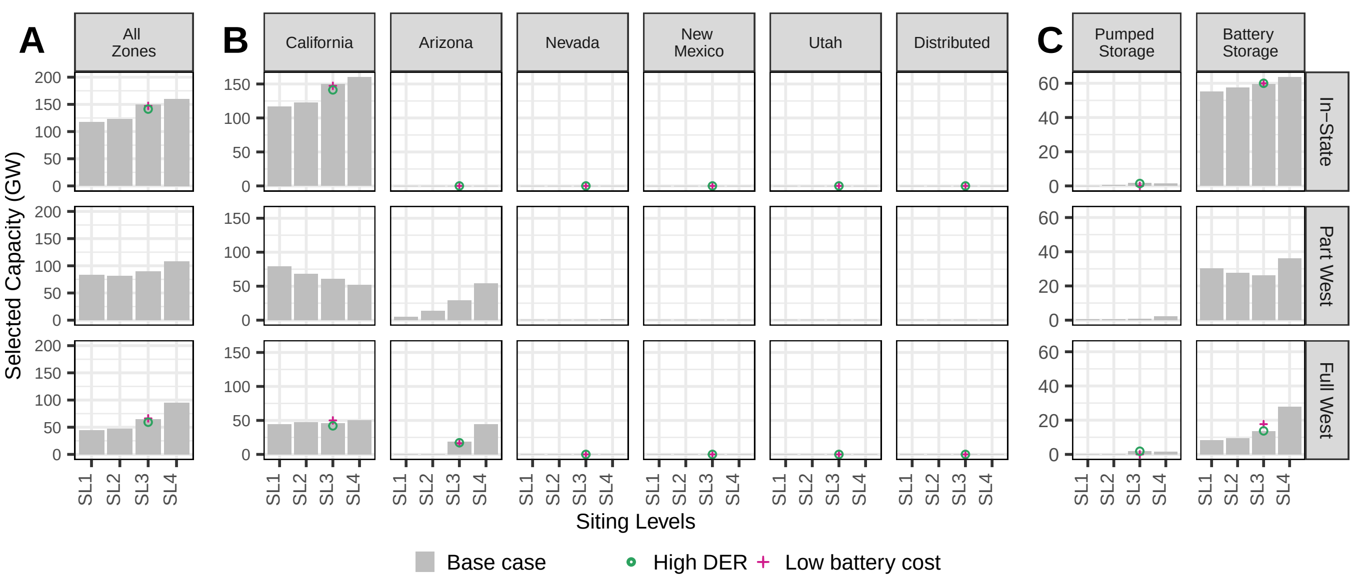

Figure 19: Selected solar capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases in the *Unconstrained* assumptions case. Note, since we did not expect sensitivities to affect results significantly, we only performed DER and Battery cost sensitivity analyses on Siting Level 3 for the *In-State* and *Full West* cases.

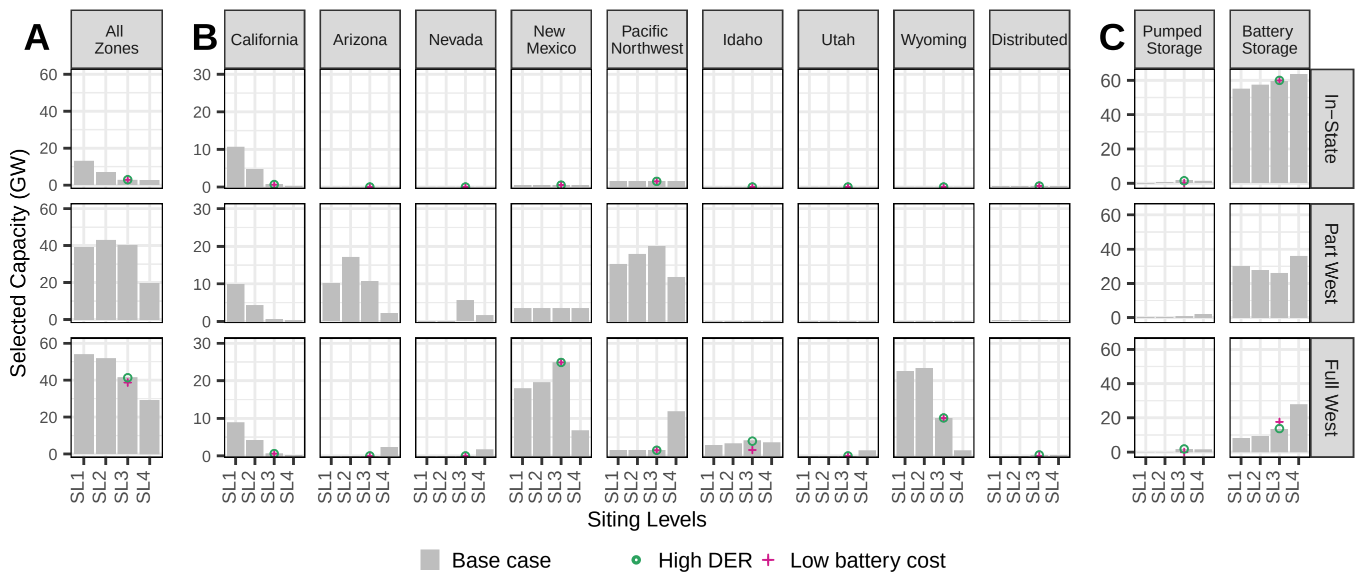

Figure 20: Selected wind capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases in the *Unconstrained* assumptions case.

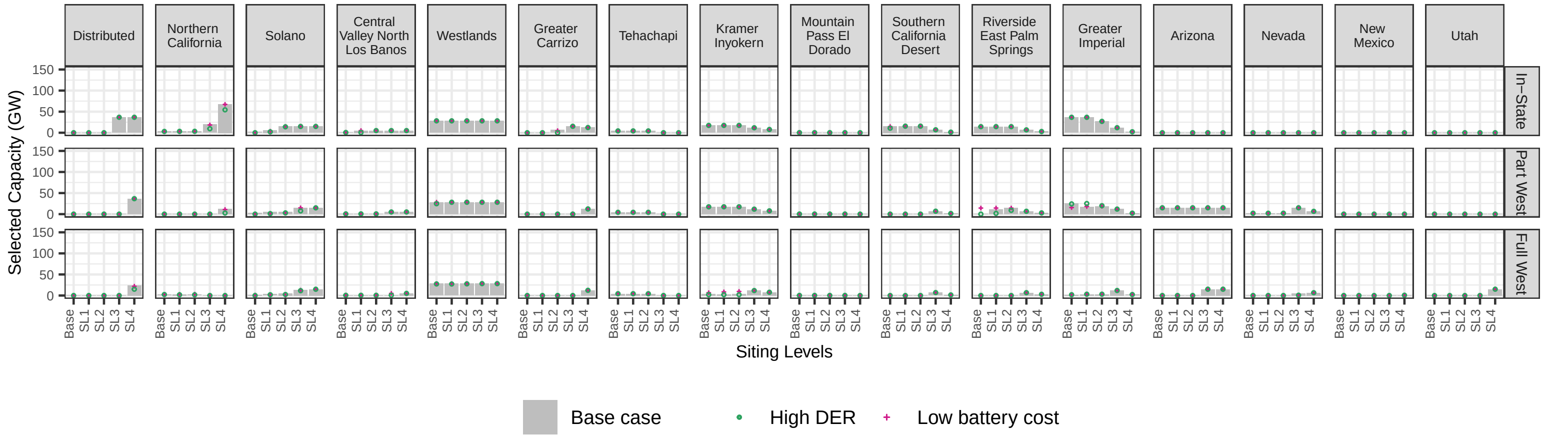

Figure 21: Comparison between California solar RESOLVE Zones for the *Constrained* assumptions case— Selected solar capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases. RESOLVE Zones within California have been included here (compared to Fig. 17) in order to show the effect on solar distribution within California.

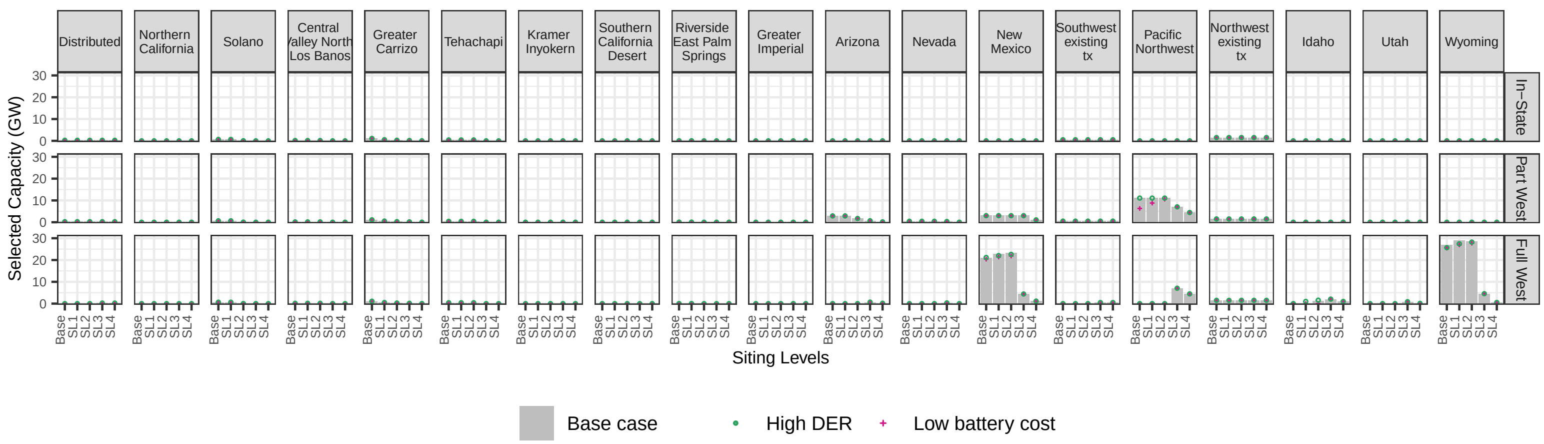

Figure 22: Comparison between California wind RESOLVE Zones for the *Constrained* assumptions case— Selected wind capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases. RESOLVE Zones within California have been included here (compared to Fig. 18) in order to show the effect on wind distribution within California.

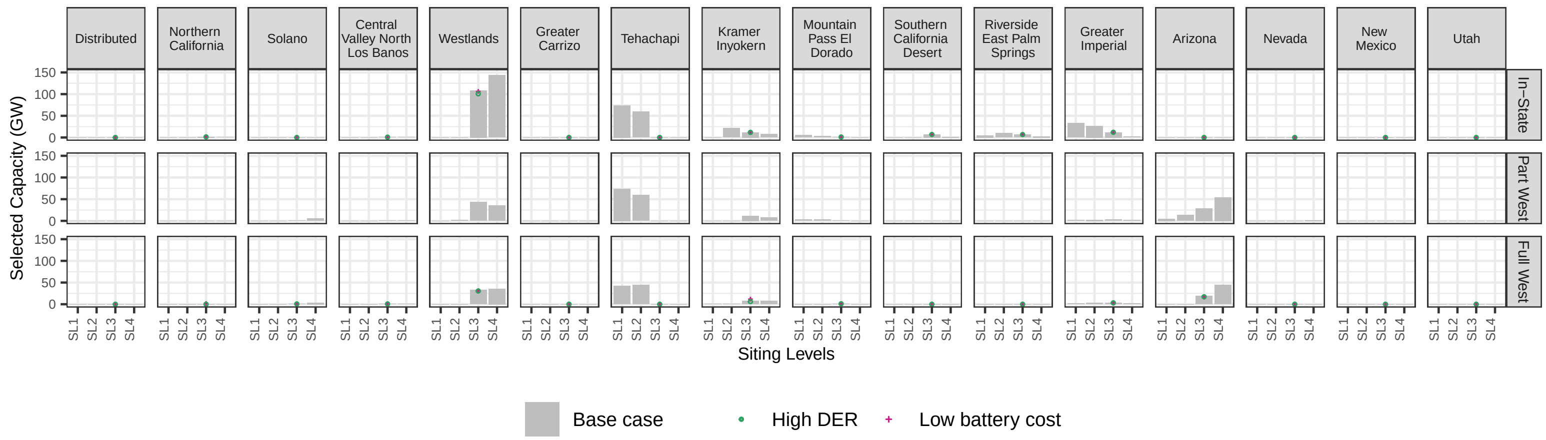

Figure 23: Comparison between California solar RESOLVE Zones for the *Unconstrained* assumptions case—Selected solar capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases. RESOLVE Zones within California have been included here (compared to Fig. 17) in order to show the effect on solar distribution within California.

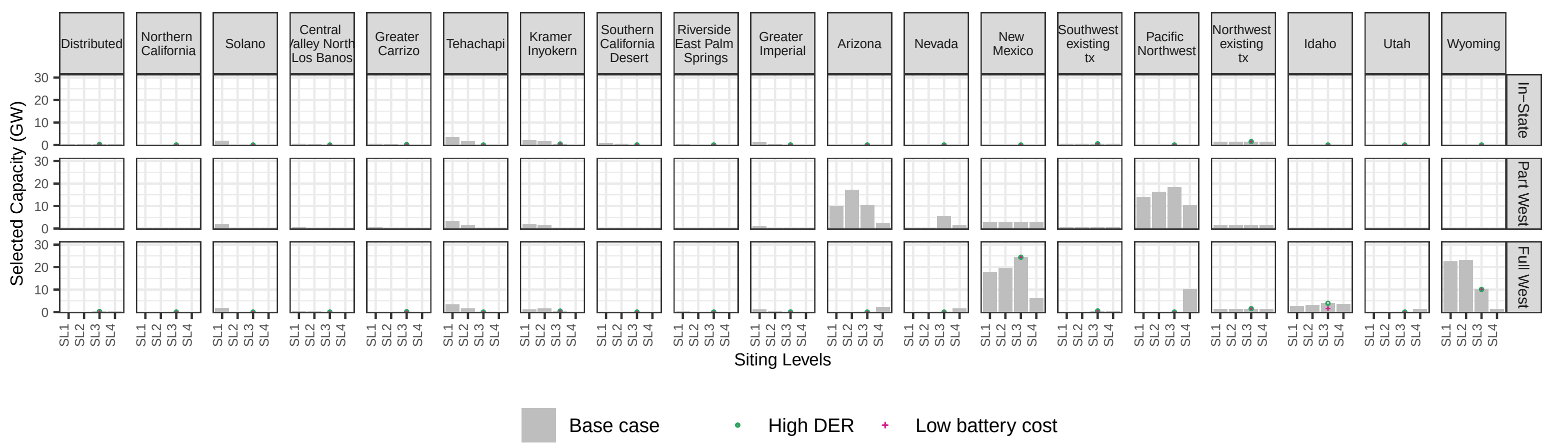

Figure 24: Comparison between California wind RESOLVE Zones for the *Unconstrained* assumptions case—Selected wind capacity comparing the Base case with Low Battery Cost and High DER sensitivity cases. RESOLVE Zones within California have been included here (compared to Fig. 18) in order to show the effect on wind distribution within California.

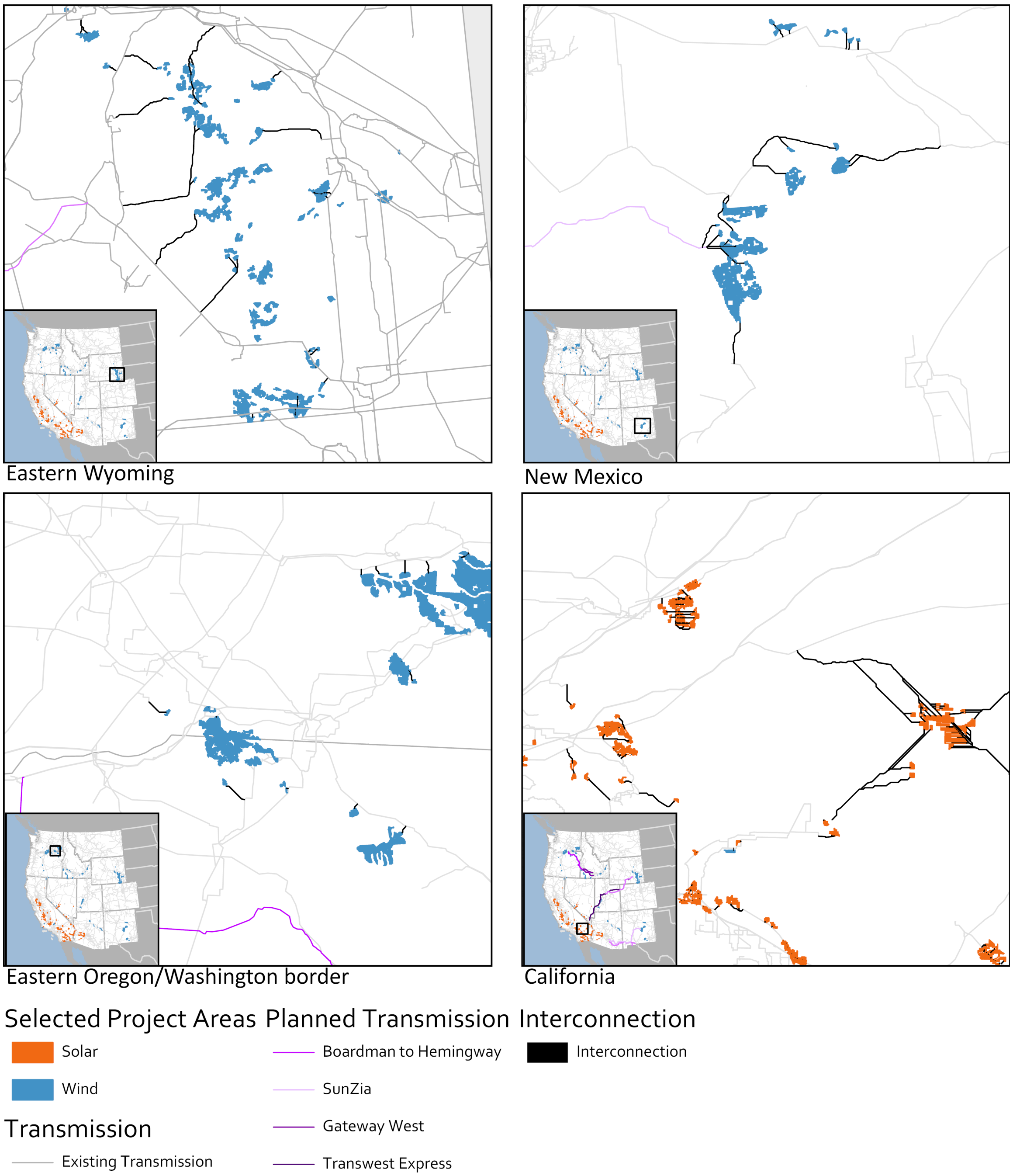

Figure 25: Representative Selected Project Areas and least cost path gen-tie transmission corridors to serve selected generation project areas in the *Full West*, Siting Level 3, *Constrained* scenario.

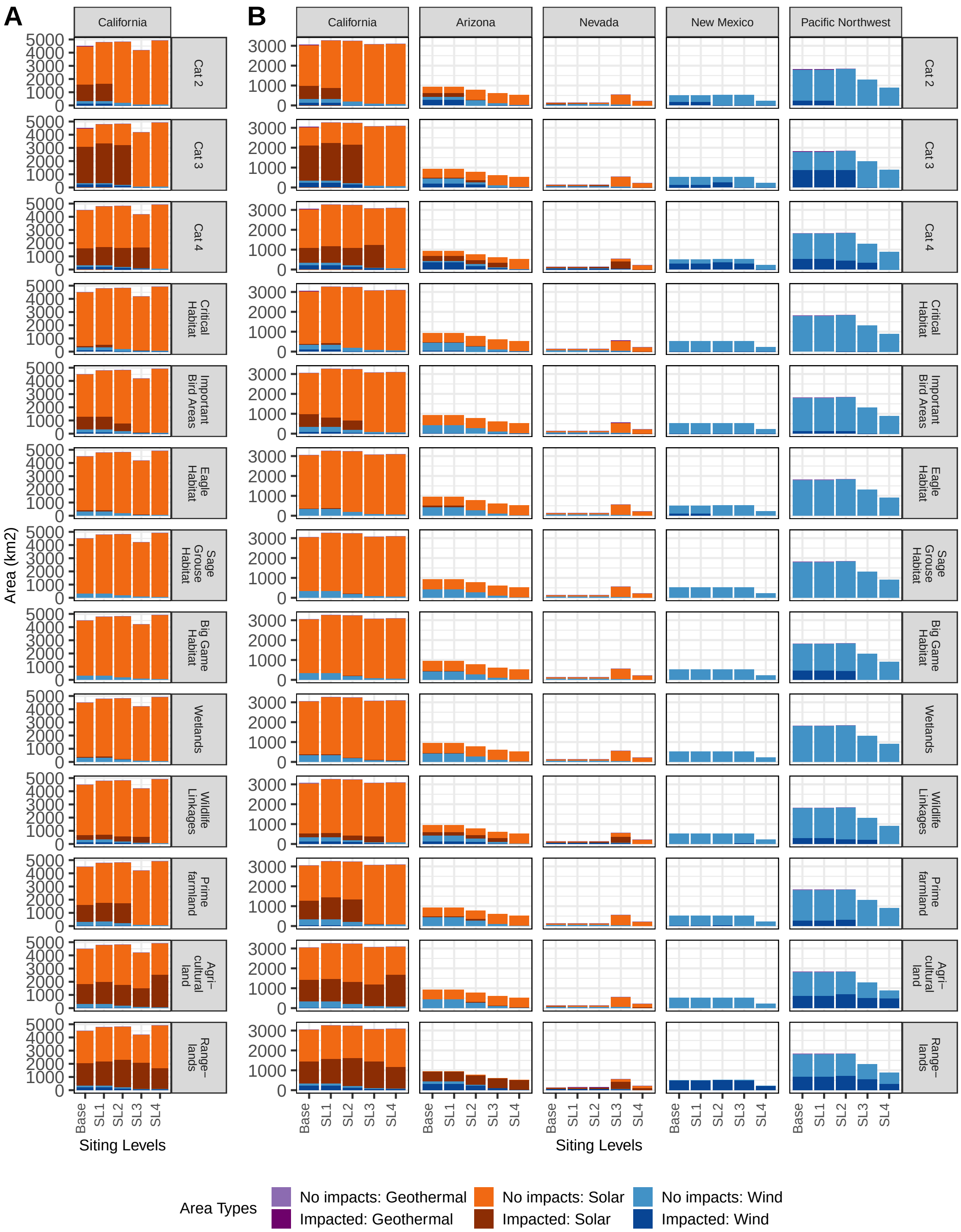

Figure 26: Environmental impacts of selected generation projects within each state for the *In-State* (A) and *Part West* (B) Geographic cases in the *Constrained* assumptions case.

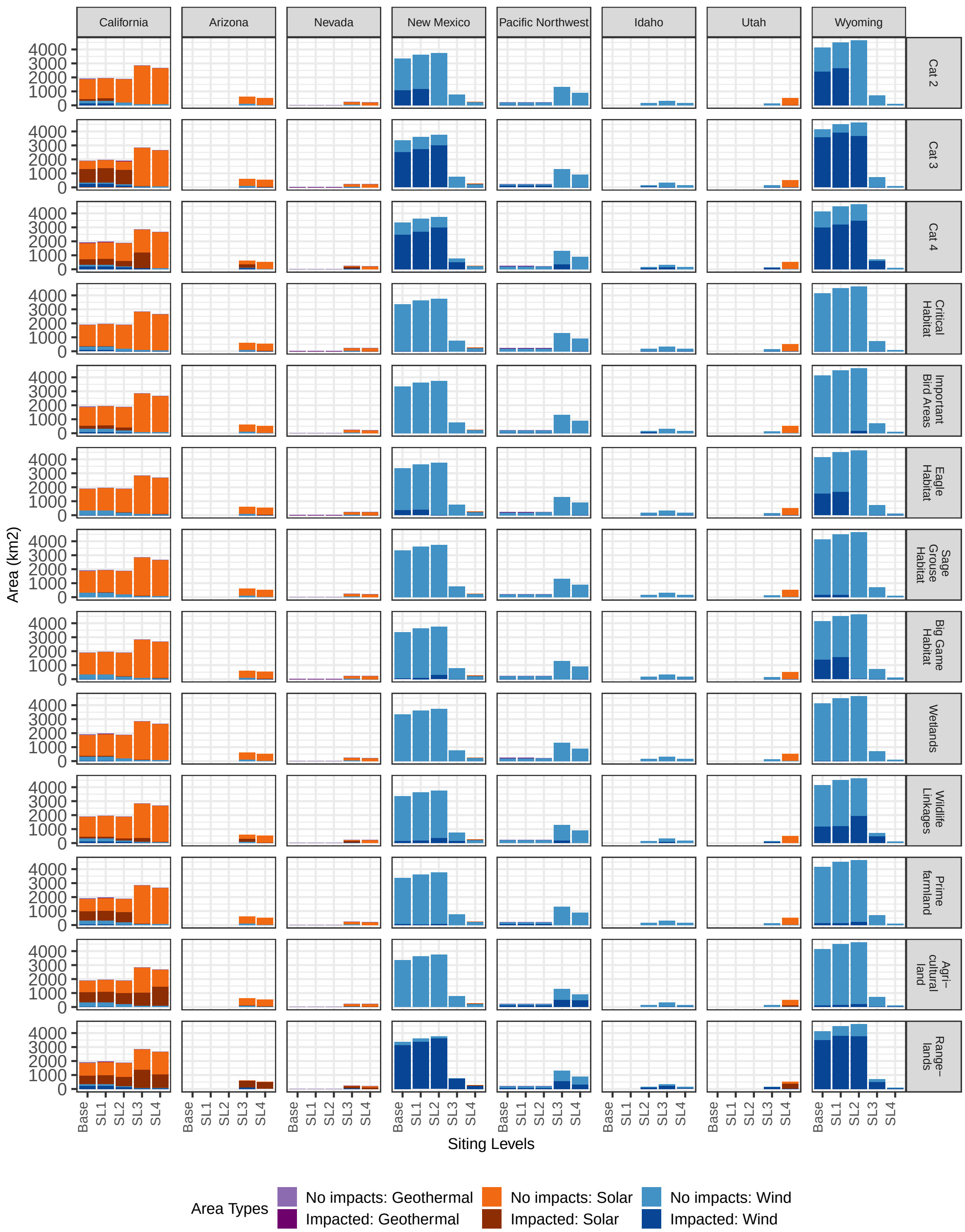

Figure 27: Environmental impacts of selected generation projects within each state for the *Full West* Geographic cases and in the *Constrained* assumptions case.

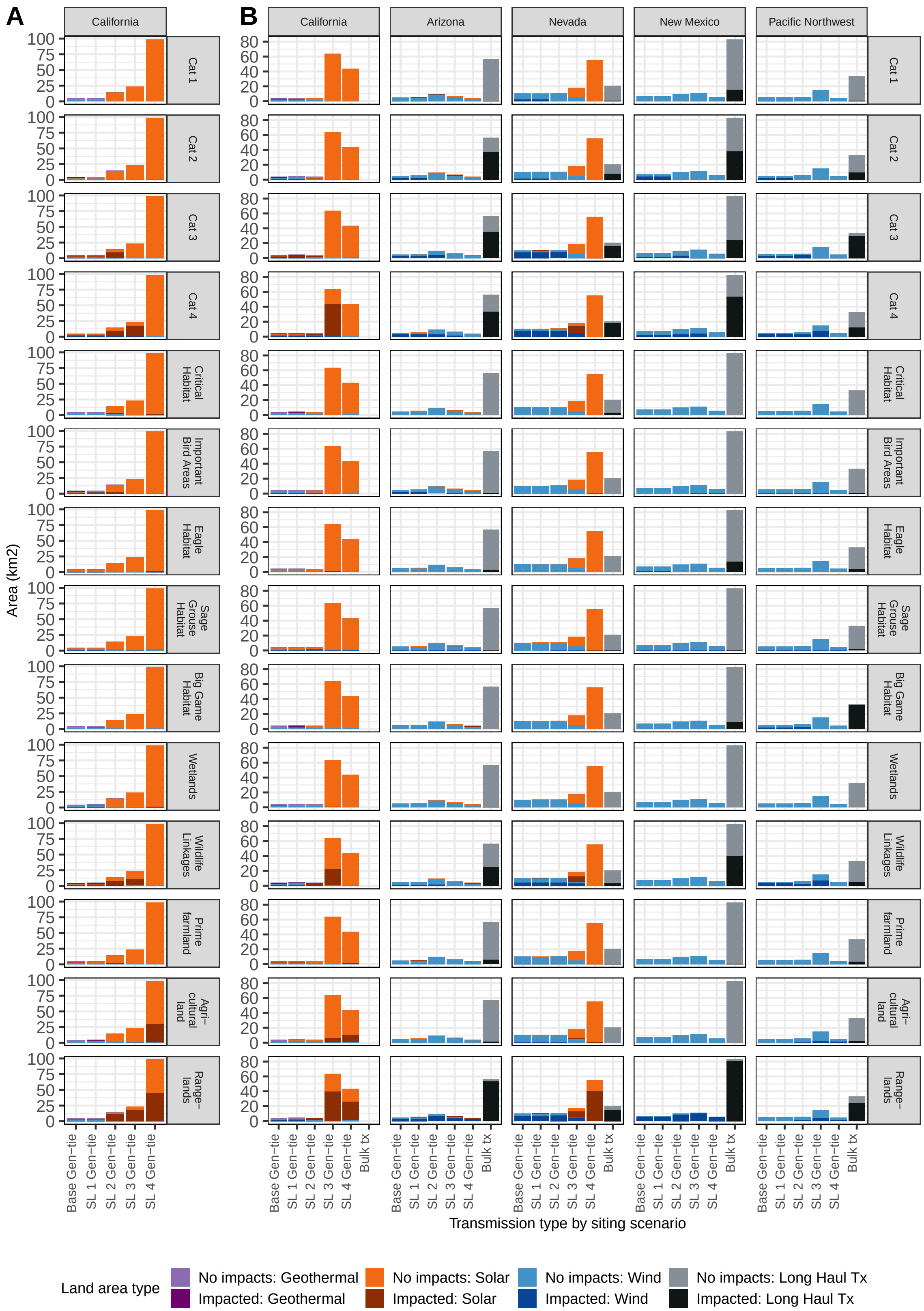

Figure 28: Environmental impacts of gen-tie and bulk transmission corridors within each state for the *In-State* (A) and *Part West* (B) Geographic cases in the *Constrained* assumptions case.

Figure 29: Environmental impacts of gen-tie and bulk transmission corridors within each state for the *Full West* Geographic cases in the *Constrained* assumptions case.

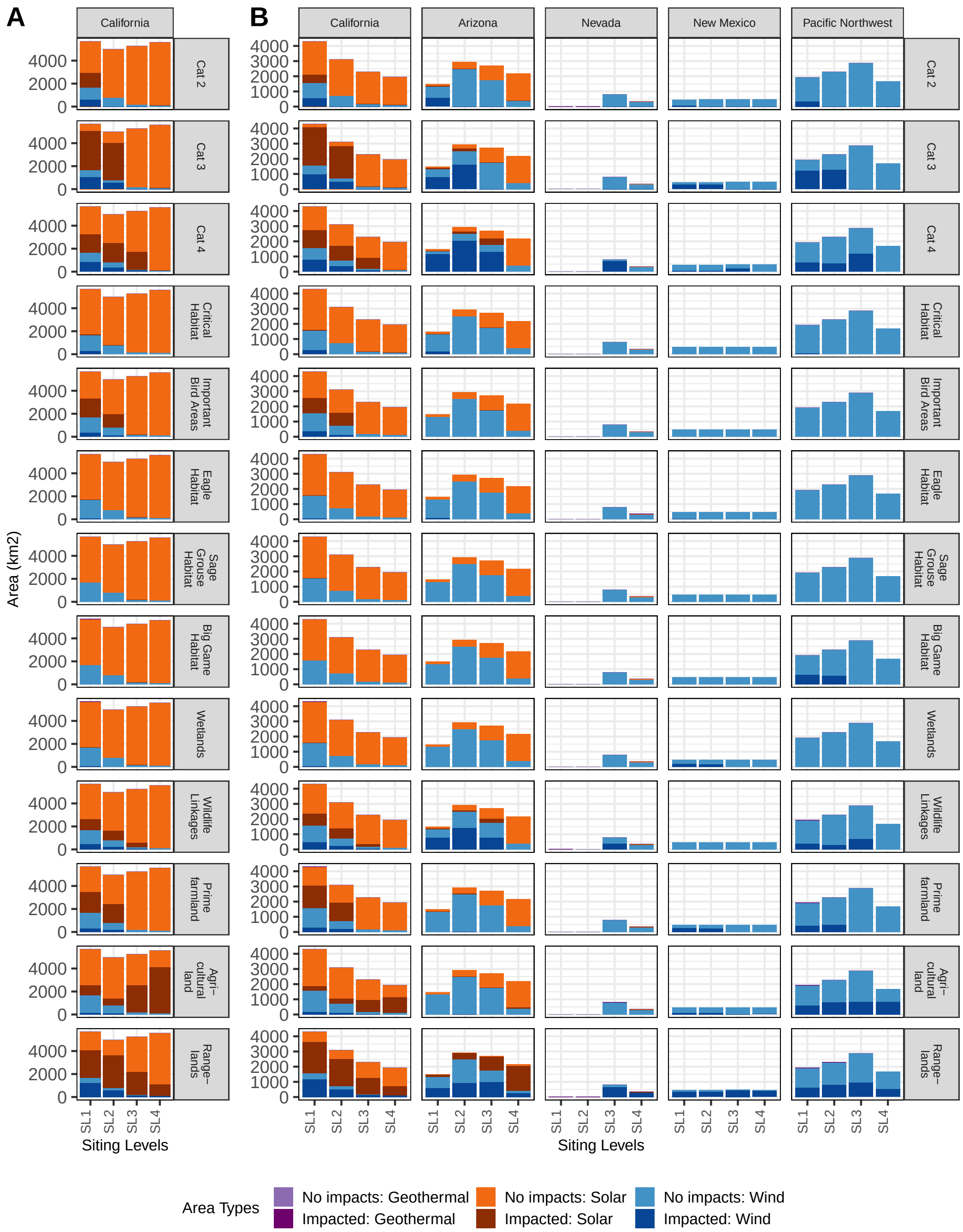

Figure 30: Environmental impacts for selected generation project areas within each state for the *In-State* (A) and *Part West* (B) Geographic cases for the *Unconstrained* assumptions case.

Figure 31: Environmental impacts for selected generation project areas in the *Full West* Geographic cases for the *Unconstrained* assumptions case.

Figure 32: Environmental impacts for modeled gen-tie and planned bulk transmission corridors within each state for the *In-State* (A) and *Part West* (B) Geographic cases for the *Unconstrained* assumptions case.

Figure 33: Environmental impacts for modeled gen-tie and planned bulk transmission corridors within each state in the *Full West* Geographic cases for the *Unconstrained* assumptions case.

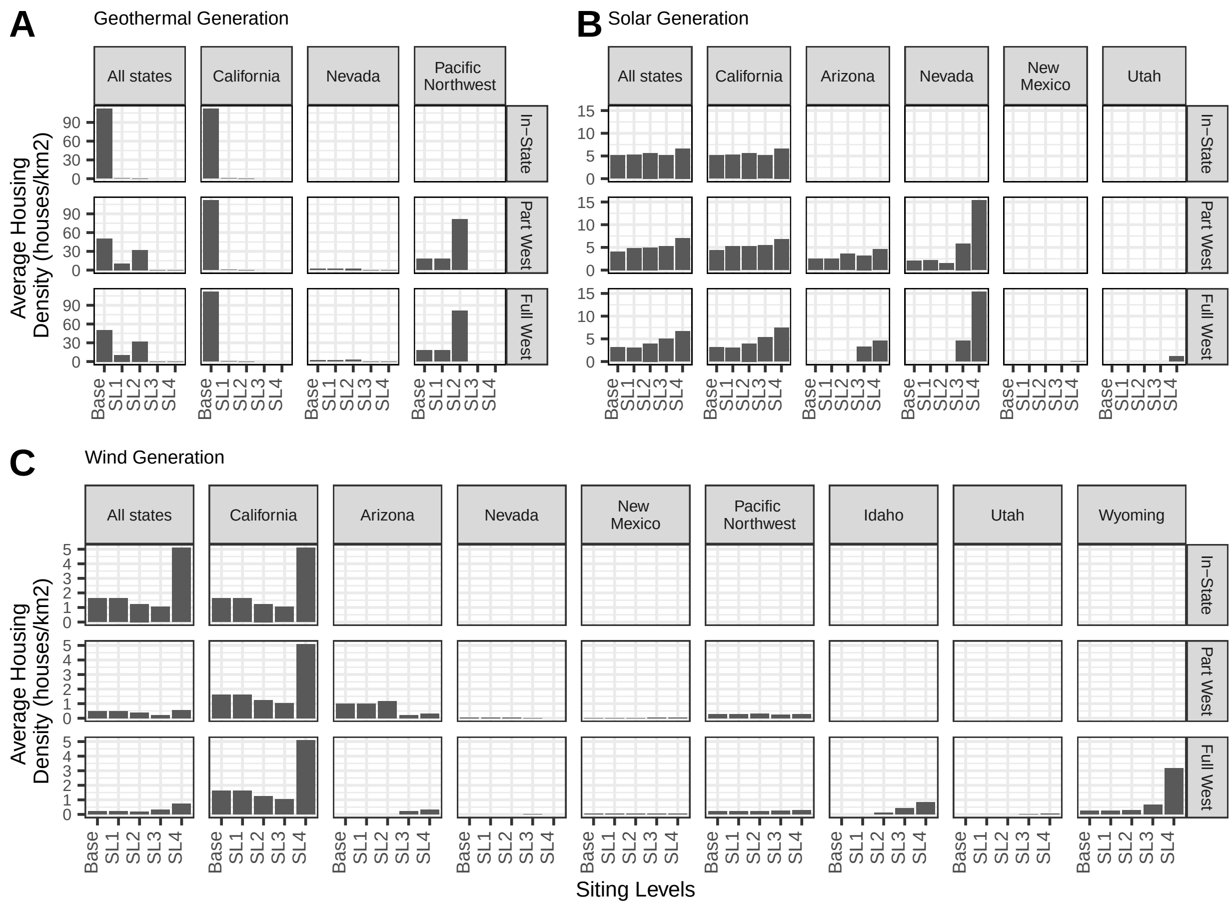

Figure 34: Average housing density for selected generation project areas in the *Constrained* assumptions case.

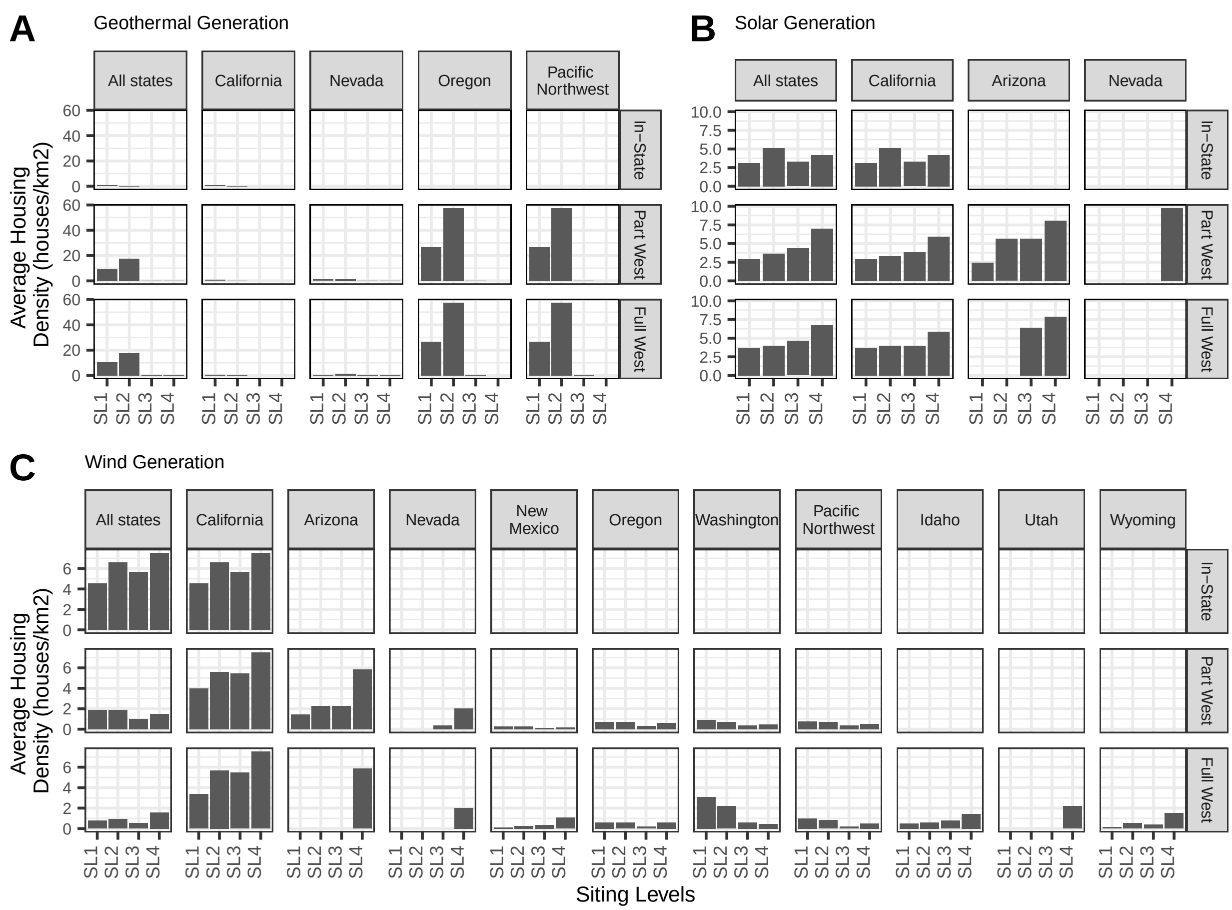

Figure 35: Average housing density for selected generation project areas in *Unconstrained* assumptions case.

Table 15: Generation land area (km^2) for each technology for each scenario

	Technology	Geographic scenario	RESOLVE sensitivity	Base	Cat1	Cat2	Cat3	Cat4
1	Geothermal	Full West	Constrained Basecase	54	43	14	2	1
2	Geothermal	Full West	Constrained High DER	54	43	14	2	1
3	Geothermal	Full West	Constrained Low Battery Cost	54	43	14	2	1
4	Geothermal	Full West	Unconstrained Basecase		41	27	4	2
5	Geothermal	Full West	Unconstrained High DER				4	
6	Geothermal	Full West	Unconstrained Low Battery Cost				4	
7	Geothermal	Part West	Constrained Basecase	54	43	14	2	1
8	Geothermal	Part West	Constrained High DER	54	43	14	2	1
9	Geothermal	Part West	Constrained Low Battery Cost	54	43	14	2	1
10	Geothermal	Part West	Unconstrained Basecase		49	27	4	2
11	Geothermal	InState	Constrained Basecase	20	10	0	0	0
12	Geothermal	InState	Constrained High DER	20	10	0	0	0
13	Geothermal	InState	Constrained Low Battery Cost	20	10	0	0	0
14	Geothermal	InState	Unconstrained Basecase		10	0	0	0
15	Geothermal	InState	Unconstrained High DER				0	
16	Geothermal	InState	Unconstrained Low Battery Cost				0	
17	Solar	Full West	Constrained Basecase	1545	1611	1676	3434	3821
18	Solar	Full West	Constrained High DER	1392	1461	1497	3215	3821
19	Solar	Full West	Constrained Low Battery Cost	1605	1708	1763	3407	3821
20	Solar	Full West	Unconstrained Basecase		1591	1690	2255	3236
21	Solar	Full West	Unconstrained High DER				2067	
22	Solar	Full West	Unconstrained Low Battery Cost				2292	
23	Solar	Part West	Constrained Basecase	3264	3483	3610	3978	3724
24	Solar	Part West	Constrained High DER	3042	3276	3415	3708	3388
25	Solar	Part West	Constrained Low Battery Cost	3343	3476	3560	3967	3661
26	Solar	Part West	Unconstrained Basecase		2882	2818	3070	3660
27	Solar	InState	Constrained Basecase	4152	4455	4626	4107	4844
28	Solar	InState	Constrained High DER	3937	4172	4394	3767	4398
29	Solar	InState	Constrained Low Battery Cost	4070	4367	4575	4061	4827
30	Solar	InState	Unconstrained Basecase		4003	4184	5080	5468
31	Solar	InState	Unconstrained High DER				4801	
32	Solar	InState	Unconstrained Low Battery Cost				5001	
33	Wind	Full West	Constrained Basecase	8056	8682	8979	3512	1517
34	Wind	Full West	Constrained High DER	7861	8421	8822	3512	1517
35	Wind	Full West	Constrained Low Battery Cost	7698	8094	8362	3512	1517
36	Wind	Full West	Unconstrained Basecase		7681	7457	6500	4545
37	Wind	Full West	Unconstrained High DER				6478	
38	Wind	Full West	Unconstrained Low Battery Cost				6144	
39	Wind	Part West	Constrained Basecase	3170	3170	2910	2092	1235
40	Wind	Part West	Constrained High DER	3170	3170	2910	2092	1235
41	Wind	Part West	Constrained Low Battery Cost	2456	2822	2834	2092	1235
42	Wind	Part West	Unconstrained Basecase		5285	5972	6098	2996
43	Wind	InState	Constrained Basecase	341	341	207	95	82
44	Wind	InState	Constrained High DER	341	341	207	95	82
45	Wind	InState	Constrained Low Battery Cost	341	341	207	95	82
46	Wind	InState	Unconstrained Basecase		1678	798	183	119
47	Wind	InState	Unconstrained High DER				183	
48	Wind	InState	Unconstrained Low Battery Cost				183	

Table 16: Gen-tie transmission land area (km2) for each technology for each scenario

	Technology	Geographic scenario	RESOLVE sensitivity	Base	Cat1	Cat2	Cat3	Cat4
1	Geothermal	Full West	Constrained Basecase	1	1.1	0.0	0.0	0.0
2	Geothermal	Full West	Constrained High DER	1	1.1	0.0	0.0	0.0
3	Geothermal	Full West	Constrained Low Battery Cost	1	1.1	0.0	0.0	0.0
4	Geothermal	Full West	Unconstrained Basecase		2.9	1.8	0.0	0.0
5	Geothermal	Full West	Unconstrained High DER				0.0	
6	Geothermal	Full West	Unconstrained Low Battery Cost				0.0	
7	Geothermal	Part West	Constrained Basecase	1	1.1	0.0	0.0	0.0
8	Geothermal	Part West	Constrained High DER	1	1.1	0.0	0.0	0.0
9	Geothermal	Part West	Constrained Low Battery Cost	1	1.1	0.0	0.0	0.0
10	Geothermal	Part West	Unconstrained Basecase		2.9	1.8	0.0	0.0
11	Geothermal	InState	Constrained Basecase	1	1.1	0.0	0.0	0.0
12	Geothermal	InState	Constrained High DER	1	1.1	0.0	0.0	0.0
13	Geothermal	InState	Constrained Low Battery Cost	1	1.1	0.0	0.0	0.0
14	Geothermal	InState	Unconstrained Basecase		1.1	0.0	0.0	0.0
15	Geothermal	InState	Unconstrained High DER				0.0	
16	Geothermal	InState	Unconstrained Low Battery Cost				0.0	
17	Solar	Full West	Constrained Basecase	1	0.7	2.6	64.1	107.5
18	Solar	Full West	Constrained High DER	1	0.9	2.9	62.9	107.5
19	Solar	Full West	Constrained Low Battery Cost	1	0.8	2.6	64.0	107.5
20	Solar	Full West	Unconstrained Basecase		0.2	10.0	15.2	23.1
21	Solar	Full West	Unconstrained High DER				15.7	
22	Solar	Full West	Unconstrained Low Battery Cost				25.2	
23	Solar	Part West	Constrained Basecase	1	2.1	2.7	76.1	98.8
24	Solar	Part West	Constrained High DER	1	2.1	0.1	74.3	98.5
25	Solar	Part West	Constrained Low Battery Cost	2	2.0	2.6	62.7	98.8
26	Solar	Part West	Unconstrained Basecase		26.7	5.2	30.9	26.5
27	Solar	InState	Constrained Basecase	1	1.6	12.9	22.5	97.5
28	Solar	InState	Constrained High DER	1	1.3	12.8	18.0	61.7
29	Solar	InState	Constrained Low Battery Cost	1	1.6	12.8	83.2	94.7
30	Solar	InState	Unconstrained Basecase		4.8	55.3	82.0	53.5
31	Solar	InState	Unconstrained High DER				79.4	
32	Solar	InState	Unconstrained Low Battery Cost				81.4	
33	Wind	Full West	Constrained Basecase	49	52.7	82.2	112.3	22.8
34	Wind	Full West	Constrained High DER	49	49.7	81.7	112.3	22.8
35	Wind	Full West	Constrained Low Battery Cost	47	48.9	81.3	112.3	22.8
36	Wind	Full West	Unconstrained Basecase		52.3	99.7	194.2	179.2
37	Wind	Full West	Unconstrained High DER				190.3	
38	Wind	Full West	Unconstrained Low Battery Cost				181.1	
39	Wind	Part West	Constrained Basecase	30	30.1	37.5	38.8	15.1
40	Wind	Part West	Constrained High DER	30	30.1	37.5	38.8	15.1
41	Wind	Part West	Constrained Low Battery Cost	28	29.2	36.9	38.8	15.1
42	Wind	Part West	Unconstrained Basecase		38.8	51.6	246.3	104.5
43	Wind	InState	Constrained Basecase	2	2.2	1.5	0.9	1.3
44	Wind	InState	Constrained High DER	2	2.2	1.5	0.9	1.3
45	Wind	InState	Constrained Low Battery Cost	2	2.2	1.5	0.9	1.3
46	Wind	InState	Unconstrained Basecase		14.7	6.9	1.4	1.8
47	Wind	InState	Unconstrained High DER				1.4	
48	Wind	InState	Unconstrained Low Battery Cost				1.4	

Table 17: Gen-tie transmission land area percentage (%) out of total area (gen-tie transmission and generation) for each technology for each scenario

	Technology	Geographic scenario	RESOLVE sensitivity	Base	Cat1	Cat2	Cat3	Cat4
1	Geothermal	Full West	Constrained Basecase	2	2.6	0.0	0.0	0.0
2	Geothermal	Full West	Constrained High DER	2	2.6	0.0	0.0	0.0
3	Geothermal	Full West	Constrained Low Battery Cost	2	2.6	0.0	0.0	0.0
4	Geothermal	Full West	Unconstrained Basecase		6.6	6.2	0.0	0.0
5	Geothermal	Full West	Unconstrained High DER				0.0	
6	Geothermal	Full West	Unconstrained Low Battery Cost				0.0	
7	Geothermal	Part West	Constrained Basecase	2	2.6	0.0	0.0	0.0
8	Geothermal	Part West	Constrained High DER	2	2.6	0.0	0.0	0.0
9	Geothermal	Part West	Constrained Low Battery Cost	2	2.6	0.0	0.0	0.0
10	Geothermal	Part West	Unconstrained Basecase		5.6	6.2	0.0	0.0
11	Geothermal	InState	Constrained Basecase	5	10.5	0.0		
12	Geothermal	InState	Constrained High DER	5	10.5	0.0		
13	Geothermal	InState	Constrained Low Battery Cost	5	10.5	0.0		
14	Geothermal	InState	Unconstrained Basecase		10.5	0.0		
15	Geothermal	InState	Unconstrained High DER					
16	Geothermal	InState	Unconstrained Low Battery Cost					
17	Solar	Full West	Constrained Basecase	0	0.0	0.2	1.8	2.7
18	Solar	Full West	Constrained High DER	0	0.1	0.2	1.9	2.7
19	Solar	Full West	Constrained Low Battery Cost	0	0.0	0.1	1.8	2.7
20	Solar	Full West	Unconstrained Basecase		0.0	0.6	0.7	0.7
21	Solar	Full West	Unconstrained High DER				0.8	
22	Solar	Full West	Unconstrained Low Battery Cost				1.1	
23	Solar	Part West	Constrained Basecase	0	0.1	0.1	1.9	2.6
24	Solar	Part West	Constrained High DER	0	0.1	0.0	2.0	2.8
25	Solar	Part West	Constrained Low Battery Cost	0	0.1	0.1	1.6	2.6
26	Solar	Part West	Unconstrained Basecase		0.9	0.2	1.0	0.7
27	Solar	InState	Constrained Basecase	0	0.0	0.3	0.5	2.0
28	Solar	InState	Constrained High DER	0	0.0	0.3	0.5	1.4
29	Solar	InState	Constrained Low Battery Cost	0	0.0	0.3	2.0	1.9
30	Solar	InState	Unconstrained Basecase		0.1	1.3	1.6	1.0
31	Solar	InState	Unconstrained High DER				1.6	
32	Solar	InState	Unconstrained Low Battery Cost				1.6	
33	Wind	Full West	Constrained Basecase	1	0.6	0.9	3.1	1.5
34	Wind	Full West	Constrained High DER	1	0.6	0.9	3.1	1.5
35	Wind	Full West	Constrained Low Battery Cost	1	0.6	1.0	3.1	1.5
36	Wind	Full West	Unconstrained Basecase		0.7	1.3	2.9	3.8
37	Wind	Full West	Unconstrained High DER				2.9	
38	Wind	Full West	Unconstrained Low Battery Cost				2.9	
39	Wind	Part West	Constrained Basecase	1	0.9	1.3	1.8	1.2
40	Wind	Part West	Constrained High DER	1	0.9	1.3	1.8	1.2
41	Wind	Part West	Constrained Low Battery Cost	1	1.0	1.3	1.8	1.2
42	Wind	Part West	Unconstrained Basecase		0.7	0.9	3.9	3.4
43	Wind	InState	Constrained Basecase	1	0.6	0.7	0.9	1.6
44	Wind	InState	Constrained High DER	1	0.6	0.7	0.9	1.6
45	Wind	InState	Constrained Low Battery Cost	1	0.6	0.7	0.9	1.6
46	Wind	InState	Unconstrained Basecase		0.9	0.9	0.8	1.5
47	Wind	InState	Unconstrained High DER				0.8	
48	Wind	InState	Unconstrained Low Battery Cost				0.8	

Table 18: Gen-tie transmission land area percentage (%) out of total area (gen-tie transmission and generation) summed across technologies for each scenario

	Geographic scenario	RESOLVE sensitivity	Base	Cat1	Cat2	Cat3	Cat4
1	Full West	Constrained Basecase	1	0.5	0.8	2.5	2.4
2	Full West	Constrained High DER	1	0.5	0.8	2.5	2.4
3	Full West	Constrained Low Battery Cost	1	0.5	0.8	2.5	2.4
4	Full West	Unconstrained Basecase		0.6	1.2	2.3	2.5
5	Full West	Unconstrained High DER				2.4	
6	Full West	Unconstrained Low Battery Cost				2.4	
7	Part West	Constrained Basecase	0	0.5	0.6	1.9	2.2
8	Part West	Constrained High DER	1	0.5	0.6	1.9	2.4
9	Part West	Constrained Low Battery Cost	1	0.5	0.6	1.6	2.3
10	Part West	Unconstrained Basecase		0.8	0.7	2.9	1.9
11	InState	Constrained Basecase	0	0.1	0.3	0.6	2.0
12	InState	Constrained High DER	0	0.1	0.3	0.5	1.4
13	InState	Constrained Low Battery Cost	0	0.1	0.3	2.0	1.9
14	InState	Unconstrained Basecase		0.4	1.2	1.6	1.0
15	InState	Unconstrained High DER				1.6	
16	InState	Unconstrained Low Battery Cost				1.6	