Spatial Planning of Low-Carbon Transitions

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1 A low carbon transition is also a land use transition

A low carbon-transition of global economies will require significant changes to the way we use and manage our land resources. This will come from both an energy systems transition away from fossil fuels towards renewable or low-carbon sources that require significant land area [1], as well as a food systems and forestry transition to sustainable land management practices that reduce agricultural emissions and protect and enhance the terrestrial carbon sink.

Globally, 25% of carbon emission are due to electricity and heat production, 14% from transportation, 10% from other energy production (refining, extraction, etc.), and 6% from buildings (for on-site energy and heat production). Collectively, the need for energy in these sectors accounts for 55% of global emissions and will need to be reduced through the combination of low-carbon electricity generation and electrification of buildings and vehicles or the production of low-carbon liquid and gas fuels. Generating low-carbon electricity to both substitute existing fossil fuel electricity and meet these additional energy end-uses will require the massive expansion of new renewable and low-carbon electricity generation and transmission infrastructure, which may also have significant land use requirements and impacts. Land conflicts could in turn stymie the rapid scale-up of renewable energy infrastructure needed to achieve these climate goals—adding to the risks of low-carbon transitions. Reducing the remaining 25% of global emissions from the agriculture, forestry, and other land uses (AFLOU) sector will require us to change how we manage land–e.g., halting the rapid pace of natural habitat loss, improving fertilizer application, adopting conservation tillage, restoring and reforesting degraded lands. How we manage this land use transition can facilitate or hinder a low-carbon transition.

2 Renewable energy infrastructure

2.1 The scale of energy sector land use requirements

Compared to land use for agriculture, forestry, mining, and urbanization, energy land-use requirements have thus far been low—standing at about 2% of land globally [2]. However, the large-scale transition from conventional to low-carbon generation technologies presents new environmental and land use planning challenges. Historically, in a power system dominated by conventional generation, electricity planners did not need to consider the land area requirements and impacts of electricity generation. This is because the operational phase of conventional generation is spatially disaggregated, with the siting of conventional power plants typically separate from the location of upstream processes such as mining and extraction. And because the land use footprint of a conventional power plant is miniscule relative to the energy it generates, large-capacity conventional power plants could be sited with few constraints. Renewable energy technologies, on the other hand, spatially concentrate their operational phases such that fuel extraction and electricity generation occur simultaneously at the site of the power plant, making their power plant footprints larger. Wind and solar power plants also have generation and cost characteristics that are inherently tied to location and siting choices [3] (e.g., when and how strongly the wind blows, the intensity and timing of sunlight), making their rapid growth as much a landscape integration problem as it does a grid integration problem.

These characteristics suggest the potential for "energy sprawl" [4] to be another significant driver of habitat and biodiversity loss [5]. Earlier studies examining 80% penetration of renewable generation by 2050 in the U.S. suggests that land requirements of onshore wind (501 GW) and ground-mounted solar photovoltaic (PV) (371 GW) could range from 85,000 to 110,000 sq km [6], [7]. The most recent study examining pathways to achieve net zero GHG emissions in the U.S. by 2050 (consistent with a 350 ppm target and with keeping global average temperature below 1.5 deg C) shows that the transition will require approximately 1,100 GW of onshore wind capacity and 735 GW of solar PV capacity—or about the land area of New Mexico (315,194 sq km) for on-shore wind including spacing between turbines and the land area of Vermont (24,220 sq km) for ground-mounted solar PV [8].

Comparisons of modeled low-carbon pathways globally and in national case studies show that land use requirements [9] and conservation impacts [10] could be far greater for technology mixes that rely more on bioenergy. In the U.K., up to 18.6% of the total U.K. land area could be required for energy generation, primarily for bioenergy crops, under a scenario with high CCS and bioenergy whereas a high renewable energy (wind and solar) scenario would only require up to 6.5% of total U.K. land [9].

Despite these potentially significant land use requirements for producing renewable energy, detailed regional case studies and global studies have shown that it is possible to generate sufficient quantities of low-carbon electricity from wind and solar technologies to meet climate targets while avoiding negative impacts on natural lands [11]–[14]. These studies show that how we manage siting for achieving renewable energy infrastructure build-outs will largely determine their landscape impacts, and thus, shape their social and political feasibility.

2.2 Renewable energy siting considerations and trade-offs

In addition to the sheer land area required by low-carbon energy technologies, there are several environmental, social, and economic factors to consider within a spatial planning framework. These factors will interact with electricity system-level planning criteria. For example, the location of wind and solar power plants can play an important role in reducing generation variability given when and where the wind blows and sun shines. Optimally siting power plants to best match renewable generation with electricity demand can reduce the need for other conventional (e.g., natural gas) capacity and generation [15]–[17]. The location of wind and solar power plants, and their relative installed capacity, dictates length and location of additional transmission infrastructure, which often involves a lengthy permitting process and can be a bottleneck for project completion [18]–[20]. Spatial planning of renewable energy infrastructure should consider both systems-level (ratepayer costs and transmission) and direct (ecological and social) impacts.

2.2.1 Emerging siting conflicts and trade-offs

Ecological considerations—Given the scale of low-carbon energy land use requirements, wildlife and other habitat impacts can be significant. There is a growing rich body of literature examining the ecological impacts of renewable energy development [21]. Environmental impacts of onshore wind have been well studied for both volant (e.g., flying) and non-volant [22] species, with trends across multiple studies showing that the most common impact is direct bird and bat collision with turbines and that number of collisions are directly correlated with siting wind farms in areas with high bird or bat activity [21], [23]–[25]. These collision impacts have been known to have population-level effects on raptors in particular [26]–[28], though impacts are highly site-specific and conclusions from one study location cannot be extrapolated to other locations [29].

The ecological impacts of utility-scale solar are not as well understood [21], [22], [30], though more recent reviews and studies point to widespread ecosystem disturbance—vegetation loss, soil carbon changes, invasive species introductions, impacts on certain wildlife including birds and insects [31]. Impacts are largely due to habitat loss, as panels and ancillary infrastructure have substantial land area requirements per unit of electricity generation [32], [33]. However, the severity and extent of impacts are determined by project-specific decisions such as site preparation (e.g., grading that removes vegetation and soil), technology, and design or arrangement of panels or mirrors. [30]. By integrating solar PV strategically and deliberately into existing landscapes, particularly those under agricultural production, land can be used more efficiently and negative impacts can be minimized. As an example, agrivoltaics—co-located agricultural and solar systems—have been recently shown to yield multiple synergistic benefits in arid climates, including reducing plant drought stress via shading and increasing PV panel efficiency via reduced heat stress [34]–[37].

The greatest ecological impacts of bioenergy—both biofuel and biomass—are habitat loss and alteration, with ecological impacts determined by the habitat converted [38], [39]. In the U.S., a large proportion of agricultural expansion in the last decade has been due to the low-carbon fuel standard and corn ethanol production [40], [41], with evidence that 4.2 million acres of non-cropland (of which 3.6 million acres were grassland) were converted for corn ethanol production within 100 miles of refineries between 2008 and 2012 [42]. This suggests that ongoing and future bioenergy policies may continue to have significant land conversion impacts and that the siting of bio-refineries will play a significant role in determining the location and hence, direct impacts impacts on habitat and biodiversity. A prospective study showed that bioenergy, compared to wind and solar development, poses a major potential threat to biodiversity globally because half of its production potential occurs in areas with the highest priority for biodiversity protection [43].

Social considerations—The social impacts of and constraints on large-scale infrastructure development are equally important considerations in planning low-carbon technologies. Social acceptance studies of wind power show that there is generally high support and positive attitudes towards wind development, and while opposition persists, the factors that determine opposition are well understood [44]. Research has shown that NIMBY-ism (Not In My Backyard) has failed to explain attitudes towards low carbon infrastructure [44]. Rather, socioeconomic impacts—positive economic benefits (e.g., tax revenue, landowner compensation) [45], [46], negative economic aspects (e.g., decreased tourism, decreases in property value) [47], [48], distributional justice (i.e., distribution of costs and benefits) [49]–[51]—are among the most important factors [44]. Thus, siting decisions have socio-economic distributional impacts both locally and regionally that must be considered and adequately planned for when siting projects [52]. Additionally, fair, participatory planning processes can significantly increase project acceptance and support [49], [53], [54], and local residents' concerns about sound and visual impacts should be taken seriously as they fuel conflict and opposition to projects [45], [55]. While fewer studies of attitudes towards biomass or solar power plants exist [56], [57], there is evidence to suggest that social considerations may be similar to that of wind power [58].

Trade-off analysis—These observed and anticipated impacts of renewable energy development suggest the need for trade-off analysis to plan energy infrastructure build-outs that maximize benefits and minimize impacts. Studies examining trade-offs between social, ecological, and economic siting criteria have found that spatial build-outs for wind that maximize any single criterion share very little spatial overlap between with other build-outs that maximize other single criterion, as well as with build-outs that balance multiple criteria [59], [60]. In fact, these spatial differences in build-out are consistent with observed geographic trends across several regional and national case studies for wind and solar that reveal many instances in which different siting criteria can come in direct conflict with each other [11], [61]. These studies suggest that trade-offs between different stakeholder values (e.g., ecological, social/community, electricity costs) will need to be accounted for and managed in spatial planning of renewable energy technologies.

2.2.2 Land constraints affect direct and indirect costs

Profits earned by developers and electricity costs faced by ratepayers are two key metrics energy planners typically consider that can be affected by siting and land use decisions. The few studies that have examined land use constraints on optimal low-carbon technology pathways and electricity systems costs show that land availability and siting choices are significant drivers of cost differences between scenarios [11], [63], [64]. In a study of 2050 low-carbon pathways for Great Britain, results showed that the two most important drivers of cost increases are the availability of nuclear power and land for variable renewable energy (onshore wind and solar PV), which when highly constrained could alone lead to system cost increases of 13% [63]. A recent study examining pathways for California to achieve 100% clean or renewable energy by 2050 showed that land protections are highly effective in avoiding environmental impacts of wind and solar PV development while meeting renewable energy targets, but increase system costs by 4-6% depending on whether California is able to procure out-of-state generation [64]. This study also found that increasing land use constraints more dramatically reduces wind availability compared to solar PV availability, and this significantly changes the optimal balance between technologies and the degree of reliance on battery storage. We also know that restrictions on the absolute acres of land allocated for all energy generation can shape both the cost and technology mix of optimal energy pathway, with higher land use efficiency technologies like natural gas combined cycle with Carbon Capture and Sequestration (CCS) preferred over ground-mounted solar and hydropower technologies [65].

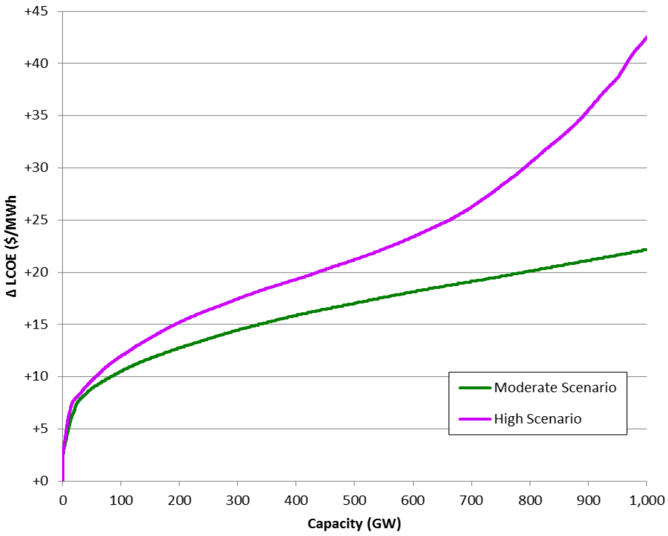

Figure 1: **Incremental levelized costs of electricity for the top 1000 GW of wind potential in the U.S. when accounting for moderate and high siting constraints.** Figure is reproduced from Tegen et al. (2016) [62].

Other studies have examined land use restrictions on specific and single technologies. In a study examining wildlife, social engagement, and radar tower siting costs and considerations alongside transmission constraints showed that the most stringent wind siting barriers result in a 2.3% system cost increase to deploy about 400 GW of wind power in the U.S. by 2050 (or about 35% of projected electricity demand in 2050) [62]. However, in terms of incremental costs impacts, the study found that moderate to high siting barriers result in \$16–\$20/MWh increases in levelized cost of electricity at 400 GW of installed wind capacity (Fig. 1). Similar trends have been observed in other regions, including across several countries within the Southern Africa Power Pool, where an assessment comparing solar PV, concentrating solar power (CSP), and wind showed how technologies differ in their degree of sensitivity to various tiers of siting constraints ([61]). There is also growing evidence suggesting that siting renewable energy in high environmental risk areas does lead to project delays or cancellations. A recent study of wind project cancellation trends in the Great Plains of the U.S. found that projects had a 50% reduction in project cancellation probability if they were sited in low-environmental-risk areas [66], which increases the profit margins of renewable energy developers by lowering transnational costs. These studies together strongly suggest that land constraints affect the electricity system design in terms of where generators should be sited, the technology mix of the system, and the costs.

2.3 Spatial electricity planning frameworks for wind and solar energy infrastructure

What has been lacking thus far in both research and practice is the integration of spatial land use planning considerations into evolving renewable energy planning model frameworks and processes. The attempts made thus far have considered only the land use requirements of bioenergy [67], or applied simplistic land availability assumptions (e.g., constraining the total amount of new land area for any energy development) within a capacity-expansion energy planning model [65]. Other frameworks proposed to address the conflicts between conservation, other human land use, and large-scale renewable energy have thus far failed to address the fact that different siting criteria are important to different energy planners and actors [13], [68]–[70]. While other studies are continuing to demonstrate the importance of various siting constraints and impacts on wildlife and rural communities, these largely do not consider linkages with systems-level energy planning and generation or transmission investment decisions.

What is required in a spatial energy planning framework is the ability to anticipate land use requirements and impacts of energy infrastructure, possible land use constraints or barriers to energy infrastructure development, and how these land use considerations could affect electricity system costs and shape other key metrics in energy planning (e.g., amount of generation that could and should be imported, need for lower-impact distributed energy resources like rooftop PV). To be directly useful for decision-making, the framework should leverage tools and assumptions used in existing energy and land use planning processes. As an example of an integrated framework that leverages existing energy planning processes, we use a recently published study–*The Power Place*—that designed low-impact land use pathways to achieve California's deep decarboniation goals by integrating conservation land use considerations into the state's Integrated Resource Planning (IRP) process [64].

2.3.1 Spatial and land use components of Integrated Resource Planning

The Integrated Resource Planning (IRP) process is an example of an energy planning framework that has been widely adopted and adapted in many jurisdictions within the U.S. and globally for regulated and semi-deregulated electricity markets. An IRP's primary purpose is to plan the energy system in a way that minimizes electricity costs while meeting various reliability, social, economic, and environmental objectives, including GHG emissions targets, by planning for possible long- and short-term risks.

While IRPs vary between jurisdictions, the following steps are are common to nearly all IRPs: (1) future load forecasting, (2) potential (demand and supply-side) resource identification and candidate portfolio creation, (3) portfolio risk assessment, (4) stakeholder engagement and review, and (5) preferred portfolio selection [71], [72]. Of these five steps, the second, 'resource identification and candidate portfolio creation', and third, 'portfolio risk assessment', steps are the most appropriate opportunities for considering land use constraints and impacts, respectively. The *The Power Place* study [64] modified these two stages of California's IRP to account for natural and working (agricultural) land considerations.

2.3.2 California case study integrating electricity and land conservation planning

The integrated land-electricity planning framework modifies the inputs and outputs of an electricity capacity expansion model used to create candidate electricity generation portfolios within a IRP process. In step 1 in Figure 2, high-resolution spatial datasets representing natural and working lands are organized into different categories of environmental risk. These are then used as inputs for spatial site suitability modeling (step 2 in Figure 2) that identifies suitable locations for wind, solar, and geothermal development based on spatially-explicit technical, economic, social, and land use criteria. In order to produce supply curve inputs for the capacity expansion model, these maps of land-constrained suitable resource potential are aggregated over "zones". These spatial units of supply inputs are used by the capacity expansion model for representing the amount of installable generation capacity for each technology over a given area.

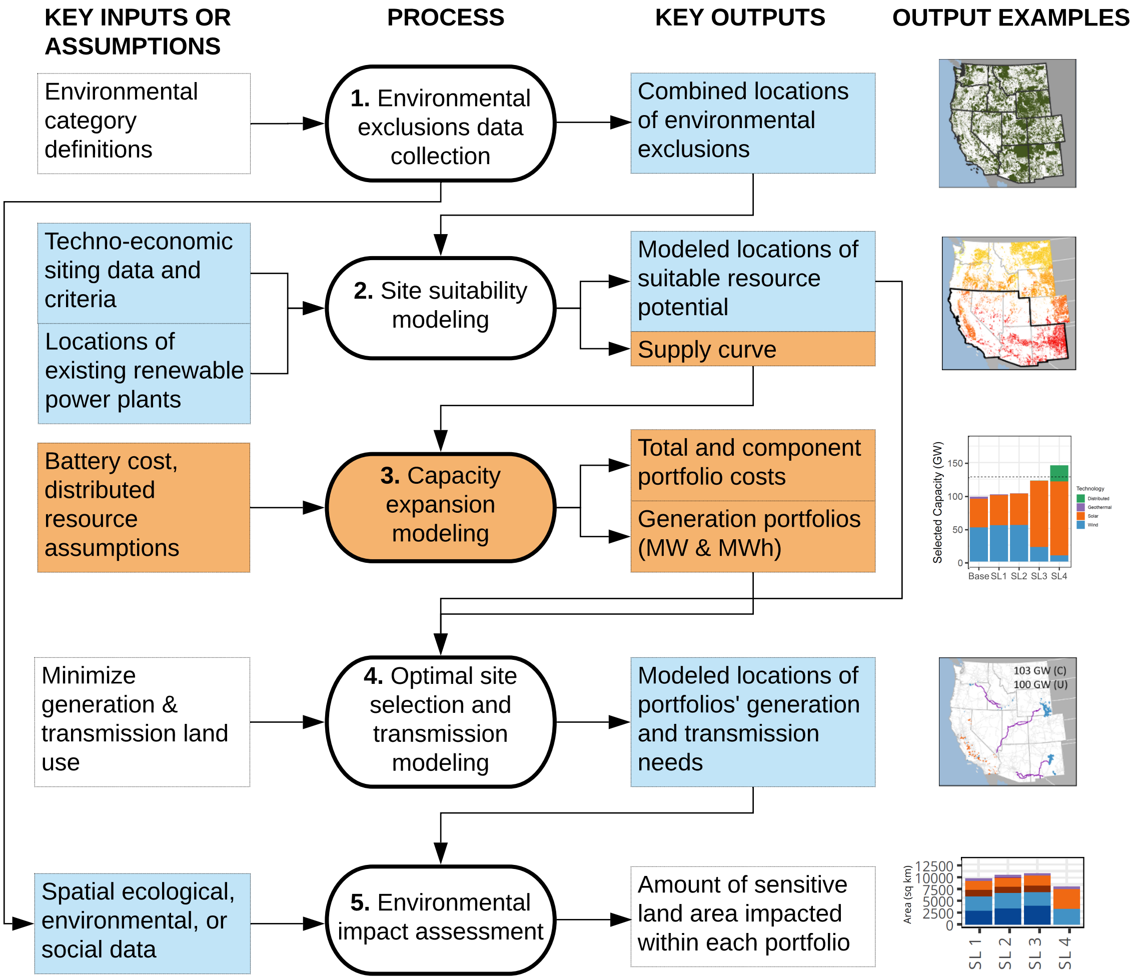

Figure 2: **Framework for integrating land use in energy planning.** Blue boxes indicate spatially-explicit inputs or outputs and orange boxes indicate elements typically found in an IRP. Figure was modified from Wu et al. (2019) [64]. The thumbnail images are for illustrative purposes only. For the full images, please see Wu et al. (2019) [64].

In step 3, the capacity expansion model creates candidate generation portfolios given the land-constrained supply curves and other exogenous assumptions that meet reliability, carbon emissions, and other energy sector objectives. In an IRP process, these candidate portfolios are then compared using multiple decision metrics in the 'portfolio risk assessment' step. In order for potential land use impacts to be estimated and considered as part of this process, these candidate portfolios must be spatially downscaled—that is, the candidate portfolios must be modeled in a spatially-explicit way. To do so, in step 4, sites are selected from the suitable resource areas created in step 2 in order to meet each candidate portfolio's specified MWh for each generation technology within each zone (see created maps in Fig. 3). Transmission corridors to interconnect the selected sites to the nearest existing transmission line can then be spatially modeled using a 'least cost path' approach (see Fig. 4). Using the spatial footprints of these selected generation sites and transmission corridors, a strategic environmental assessment can be performed (step 6) using the spatial footprints of the infrastructure build-out. The number of hectares of various habitat and land cover types can be estimated for each candidate portfolio and used in 'stakeholder engagement and review' and 'preferred portfolio selection' as the final steps of the IRP process.

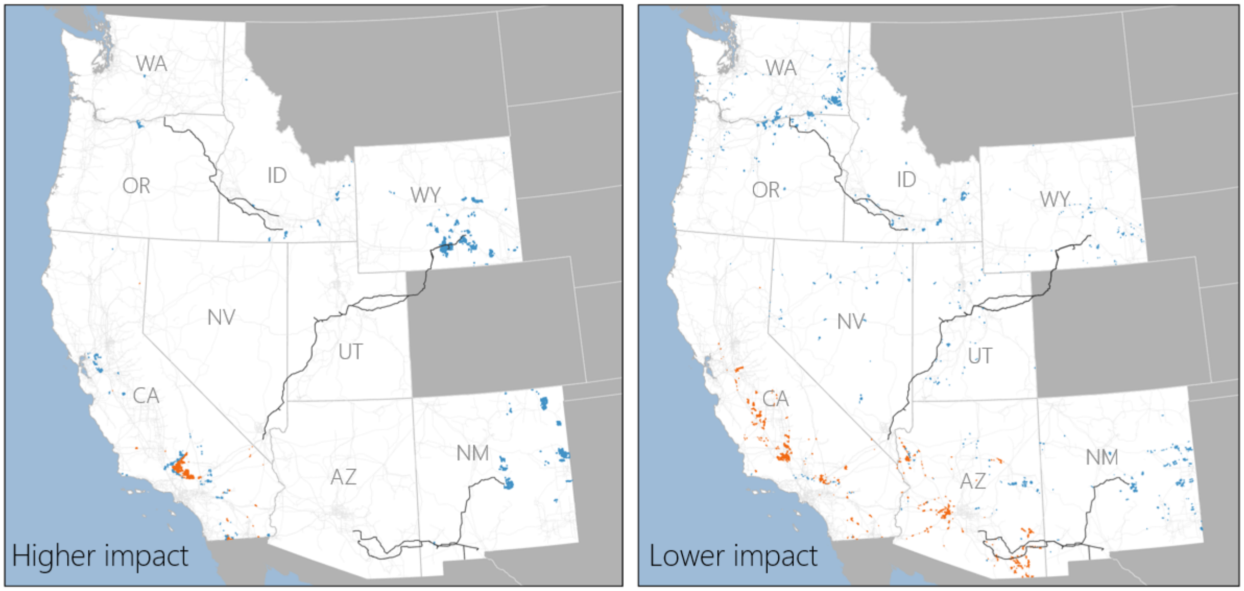

Figure 3: **Spatial build-out of wind and solar power plants required to meet California's 2050 climate targets.** Blue and orange areas are selected wind and solar power plants, respectively. Dark lines are proposed transmission lines in advanced stages of planning or development and lighter lines are existing transmission lines. The two subfigures show build-out differences when areas of high conservation value are not excluded ("Higher impact" scenario) and are excluded from potential wind and solar PV development ("Lower impact" scenario). Figure was modified from Wu et al. (2019) [64]. To view the scenario assumptions, please see Wu et al. (2019) [64].

Using this approach, it is possible to quantitatively anticipate how much and where solar, wind, and geothermal capacity must be built under certain sets of power systems engineering and land use planning criteria. In this way, it is also possible to anticipate what types of land uses are most impacted due to specific technologies of renewable energy development if not properly addressed or integrated. For example, the *Power of Place* study found that one-third to half of all solar PV capacity could be sited on agricultural land in California regardless of the scenario, which allows planners and policymakers to proactively manage potential food-energy conflicts. The study also found that applying land use constraints as inputs to the capacity expansion model is effective in avoiding ecological impacts. Yet, land use constraints do increase total electricity costs, a trend that is consistent with similar studies examining this trade-off [62], [63]. However, this integrated modeling approach found that this trade-off can be offset by other strategies, namely that access to regional renewable resources in other western states could be critical for achieving lower environmental impacts at lower costs for California. Out-of-state development significantly increases transmission requirements, presenting another important trade-off for regional energy trade as a land use and renewable energy integration strategy.

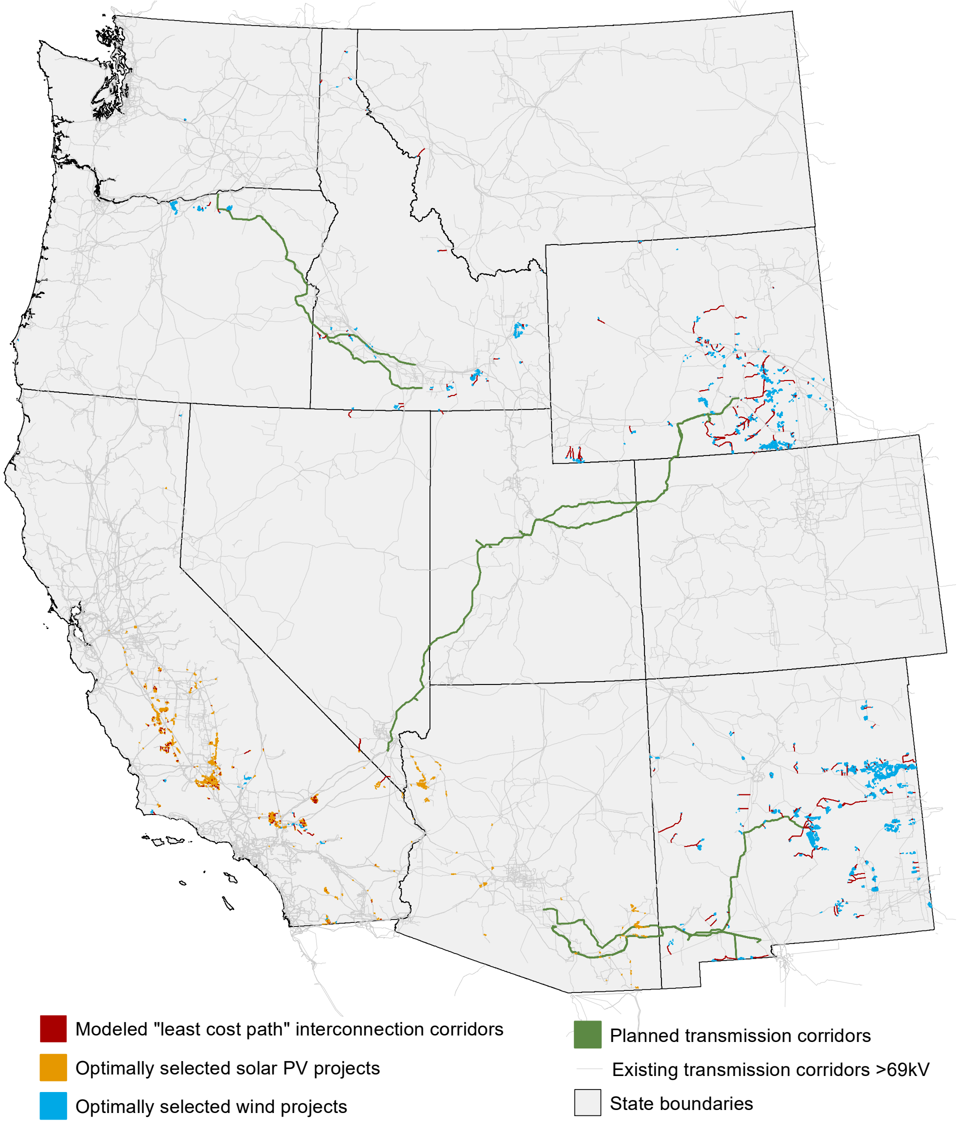

Figure 4: **Transmission interconnection modeling for wind and solar power plants required to meet California's 2050 climate targets.** Blue and orange areas are selected wind and solar power plants, respectively. Green lines are proposed transmission lines in advanced stages of planning or development and lighter lines are existing transmission lines. Red lines are the modeled transmission interconnections required to connect new power plants to the existing network. For maps of other scenarios, please see Wu et al. (2019) [64].

2.4 Technology-specific spatially planning processes and frameworks

The example presented above is one of the first to integrate land use considerations into an electricity planning framework. However, there are many existing examples for spatial planning processes focused on identifying land areas for single generation technologies over specified regions and land ownership types, with the goal of reducing siting barriers for renewable energy development.

Onshore wind and solar—There have been several renewable energy planning and mapping processes led by federal government agencies on public lands. For solar, the Bureau of Land (BLM) Management created a Solar Energy Program for utility-scale solar energy development on BLM administered lands in six southwestern states (Arizona, California, Colorado, Nevada, New Mexico, Utah). The Program identified areas that should be excluded from solar development and areas that should be prioritized for development (i.e., solar energy zones, or SEZ) based on having low resource conflict, having good grid connection, and being economically and technically suitable for solar energy generation. Developers are able to competitively bid for parcels within the 19 SEZs identified. While the number of land use conflicts associated with solar development on public lands has significantly decreased since the Solar Energy Program started, the number of applications and bids from developers has also dramatically declined [73]. Developer criticisms have pointed to the higher land leasing costs on public lands compared to private land [74], [75]. More recently, the BLM updated a similar project for wind, called the West-wide Wind Mapping Project (WWWMP) [76], for BLM managed lands in 11 Western states. This process focused on identifying areas that should be excluded from wind development. And while the project has also identified areas that may be suitable for development, potential siting sensitivities in these areas preclude the BLM from officially designating equivalent wind energy zones. Despite these federal-agency-led mapping efforts, less than 5% of wind capacity in the U.S. is sited on public lands, likely for the same reasons—higher costs and longer permitting times—solar energy zones have failed to garner the interest of private developers [77].

As an example of a more regional planning process for informing renewable energy siting, the Desert Renewable Energy Conservation Plan (DRECP) was created as a multi-agency collaboration between the California Energy Commission, California Department of Fish and Game, US Fish and Wildlife Service, and the district and national BLM offices to manage renewable energy development in the 25 million acres of the California Desert Conservation Area [78]. As part of this process, the agencies completed environmental impact assessments and conservation plans for both federal and non-federal lands and have proceeded with designating 7% of the 10.8 million acres of federal lands as development focus areas available for renewable energy leasing. Renewable energy developer associations and county governments have commented that this is not enough land allocated for future development in the area and that the regulatory process would make projects uneconomical [79]. Conservation groups, however have upheld that the DRECP exemplifies how a participatory planning process can yield a plan that successfully balances renewable energy and conservation goals [80].

Transmission planning—The Western Electricity Coordinating Council (WECC) designed a web-based interactive tool, the Environmental Data Viewer, for quantifying the environmental risk associated with proposed transmission line projects to minimize the cost and impact of transmission projects in the planning phase. The tool uses datasets classified into four environmental risk categories: Category 1 (Least Risk of Environmental or Cultural Resource Sensitivities and Constraints), Category 2 (Low to Moderate Risk of Environmental or Cultural Resource Sensitivities and Constraints), Category 3 (High Risk of Environmental or Cultural Resource Sensitivities and Constraints), Category 4 (Areas Presently Precluded by Law or Regulation). The result is a single aggregated data layer of environmental risk classes ranging from 1 to 4 . A user can draw a proposed transmission corridor and the tool will calculate the number of miles the corridor passes through each environmental risk class as well as the total estimated mitigation costs. This tool can be used within a renewable energy planning framework such as the BLM's Solar Energy Plan, WWWMP, or DRECP to evaluate scenarios for transmission expansion.

3 Summary and Recommendations for Spatial Planning of Renewable Energy

Planning renewable energy without considering land use is like playing chess without a chessboard. The land area required for wind and solar farms to meet deep decarbonization goals in the U.S. will be vast—on the order of the land area of New Mexico for wind (with spacing) and Vermont for utility-scale solar PV. These new renewable energy power plants will in turn require thousands of miles of new transmission lines. Studies have also shown that generation infrastructure siting decisions impact electricity grid planning as well as the extent and severity of land use and conservation impacts. By failing to encourage infrastructure development in lower-impact areas, areas with high conservation value are more likely to become candidates for development. Yet, by optimally siting wind and solar farms based on what time of the day and year wind and solar electricity can be generated, energy planners can reduce the need for other generation or storage technologies and thus reduce the costs of renewable energy integration. Altogether, these findings suggest that land availability and siting choices are significant determinants of generation technology choices, electricity costs for ratepayers, and location of energy infrastructure.

Integrate land use siting constraints and impacts into low-carbon energy planning processes. A low-carbon energy planning framework that integrates land use and spatial considerations can directly address siting constraints as a key barrier to rapid and large-scale renewable energy deployment. First, land-energy integration allows planners and policymakers to identify development opportunities that avoid downstream conflicts such as lengthy project delays or cancellations, negative ecological impacts, and backlash against renewable energy development by local communities leading to outright development bans. Second, integrated land-energy planning can help identify development strategies that address unavoidable anticipated impacts. For example, some of the best areas for wind power in the U.S. is the Great Plains—80% of which is cropland, pastureland, or rangeland. And cropland—being sunny, flat, and accessible—is an ideal location for solar farms. Integrating wind and solar energy into agricultural landscapes in synergistic ways can spur needed economic development in rural communities while avoiding both conflicts over farmland conversion and natural habitat conversion and fragmentation in intact landscapes. How planners and policymakers manage the land use transition that must accompany a low carbon transition can shape the perception of renewable energy infrastructure as either a threat or an opportunity. Third, since energy infrastructure—both generation and transmission—are long-term investments, integrated land-energy planning helps avoid long-term infrastructure lock-ins that lead to undesirable ecological outcomes. By identifying low-impact, high quality areas for wind and solar development, it is possible to coordinate the early planning of the transmission network needed to interconnect new low-impact renewable energy power plants to the grid.

Facilitate regional coordination of generation and transmission development to enable low-cost, low-impact renewable energy development. Despite the vast land area a low-carbon transition will require, it is possible to meet low-carbon electricity goals with minimal conservation and land use impacts. Studies show that sharing renewable energy resources across states can significantly reduce costs of achieving ambitious climate targets while also meeting land conservation goals. Yet, regional energy solutions depend on early and proactive transmission planning. Interstate transmission lines will be needed to transmit low-impact, high quality renewable electricity to demand centers, yet interstate transmission lines take 10 or more years to permit and construct. We must begin planning essential transmission corridors now.

4 Agriculture, Forestry, Other Land Uses, and Novel Negative Emissions Technologies

The demand for food given shifting diets, population growth, and global trade could lead to expansion, contraction, or intensification of crop and pastureland, land use changes that can either emit or sequester carbon. Natural negative emissions strategies like reforestation require the expansion of forests into or restoration from other land uses. Because land competition is growing, accommodating land uses that support climate mitigation or negative emissions technologies will be increasingly difficult.

It is well understood that global terrestrial carbon sinks are highly variable and vulnerable due to land use and land cover change [81]. In the U.S., studies are anticipating constant or declining rates of forest carbon sequestration over the next decade under business as usual scenarios [82], [83]. This trend is expected to continue declining under historical management efforts [83] due to aging stands and disturbance events, despite forest area increasing gradually over the same period. Increasing wildfires and pest outbreaks under a warming climate threatens to further erode the forest carbon sink.

Deploying several other technologies and land strategies critical for driving low-carbon transitions, such as bioenergy, negative emissions technologies (e.g., direct air capture), reforestation, wetland restoration will also require spatial planning tools and frameworks distinct from the ones presented for renewable energy power plants and transmission lines in the preceding sections. Below we describe possible models and analytical frameworks that can be applied for planning bioenergy and land management within the agriculture, forestry, and other land use sectors.

4.1 Analytical approaches for novel negative emissions technologies

Very little research has been conducted on spatially planning NETs systems like DAC or other engineering forms of Carbon Capture and Sequestration (CCS). Nonetheless, chemical CO_2 capture (direct air capture, DAC) requires two geographically-dependent stages: 1) sources of low-carbon thermal and electrical energy (geothermal, solar PV, solar CSP, wind, or nuclear) and 2) geologic storage for captured CO_2 (e.g., sedimentary basins, basalt, ultramafic rocks). Thus, siting of DAC systems requires siting of carbon-free or renewable energy, which was discussed in earlier sections, co-located with geologic storage opportunities, for which maps are available.

4.2 Analytical approaches for bioenergy and the land sector

The provision of biomass for biofuels and generation of bio-electricity is as much an agricultural and/or forestry sector concern as it is an energy sector issue. Bioenergy feedstocks—either purpose grown crops/plantations or residues/waste—are accounted for by the agriculture and forestry planning communities, while biofuel refineries or biomass power plants are modeled by energy planners. Representing the land sectors, including bioenergy feedstocks, requires models that represent at the minimum the supply of major agricultural (crop and livestock) and forestry commodities based on existing and historical data as well as biophysical parameters. However, in order to use these models as one would use a capacity expansion model for guiding investments in electricity infrastructure, the land sector planning models need to be able to combine both supply and demand projections and calculate any resultant changes to land use and carbon emissions. Similar biophysical-economic models can be used to represent the land use and carbon emissions resulting from other major agricultural crop production, forestry products, and other managed or natural land uses (e.g., managed rangelands, natural forests).

4.2.1 Integrated Assessment Models

There are several classes of land sector models that represent agricultural and forestry supply and demand to understand determinants of past and future land use and land cover change [84]. The most widely used for charting global climate change mitigation pathways are detailed Integrated Assessment Models (IAM) that characterize the economic and natural/biophysical processes that emit and sequester GHGs [85]. As such, all IAMs represent the land sectors. General equilibrium economy-wide IAMs, such at the Global Change Assessment Model (GCAM) developed by the Joint Global Change Research Institute [86], dynamically couple the land and energy systems (in addition to water, climate, and the economy). GCAM is one of the six main IAMs used to develop IPCC mitigation pathways and was one of several tools used to inform the the Mid-Century Strategy Report on Deep Decarbonization for the United States [87]. For the Mid-Century Strategy report, GCAM generated several scenarios for mitigation pathways that also tracked changes in major land cover types—forest, cropland, pastureland, cropland for bioenergy—that would be consistent with achieving economy-wide GHG reduction goals in the U.S. by mid-century. As a global general equilibrium model, the spatial resolution of GCAM is coarse—or at the agro-ecological zone level– which makes results useful for regional or national level planning purposes, but does not provide state-level or finer detail on carbon emissions from the land sector.

Partial equilibrium land sector models like the Global Biosphere Management Model (GLOBIOM) [88] and the Model of Agricultural Production and its Impact on the Environment (MAgPIE) [89], [90] are soft-coupled with energy system models (MESSAGE and REMIND, respectively) to form an IAM. When used independently, these types of partial equilibrium land sector models can also be used to project global GHG emissions from the land sectors under varying crop productivity and commodity demand assumptions. Detailed regional and national level versions of GLOBIOM have recently been developed and used to examine national policies like enforcing the forest code or expanding the soy moratorium to the Cerrado in Brazil [91], [92]. Land use and land cover change can be visualized at 50 km x 50 km grid cells, which does allow coarse state or province level land sector carbon projections.

4.2.2 Sector-specific, biophysical and econometric models

While IAMs have been used for informing national-level climate policies, none, to our knowledge, have been used for designing sub-national low-carbon pathways or informing sub-national policy implementation, and it is unknown how appropriate such models are for the level of spatial specificity required in such an application. Yet, like renewable energy power plants and transmission lines, implementing a low-carbon transition for the AFOLU sectors is a local and spatially-specific problem requiring a spatially-explicit modeling framework. Additionally, a spatially-explicit AFOLU modeling framework will necessarily be more complex than one for the energy sectors, primarily due to the fact that agricultural and forestry commodities are traded internationally based on supply and demand. Thus, longer-term land use and land cover projections are sensitive to more structural economic trends and trade decisions.

California is the only state, to our knowledge, that has developed an analytical approach for designing low-carbon pathways for the land sectors. In California's Natural and Working Lands Implementation plan, led by the Department of Natural Resources with analysis conducted by the Lawrence Berkeley National Laboratory, two main mitigation scenarios were presented that would achieve reduction in land sector carbon emissions by 2030 and deliver net negative land sector emissions by 2045 [93], [94]. These scenarios were developed using a combination of two tools: 1) COMET-Planner, which provides estimates of GHG impacts of conservation practices on agricultural lands [95]; 2) the California Natural and Working Lands Carbon and Greenhouse

Gas (CALAND) Model, which is an empirically-based carbon accounting tool that simulates the GHG effects of land management practices and land use and land cover changes [94]. The U.S. Geological Survey and The Nature Conservancy independently developed land sector mitigation pathways for California using the Land Use and Carbon Scenario Simulator (LUCAS) model while also considering land use and land cover impacts under future climate change scenarios [96]. To our knowledge, however, no generalizable analytical framework exists for AFOLU and bioenergy feedstock planning that could be used for other states that considers land use and land cover change impacts of national and international agricultural and forestry commodity trade.

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