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Solar Energy-driven Land-cover Change Could Alter Landscapes Critical to Animal Movement in the Continental United States

Michael O. Levin,* Elizabeth L. Kalies, Emma Forester, Elizabeth L. A. Jackson, Andrew H. Levin, Caitlin Markus, Patrick F. McKenzie, Jared B. Meek, and Rebecca R. Hernandez

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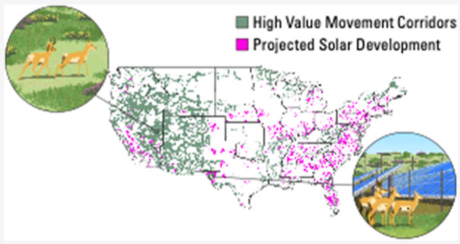
ABSTRACT: The United States may produce as much as 45% of its electricity using solar energy technology by 2050, which could require more than 40,000 km^2 of land to be converted to large-scale solar energy production facilities. Little is known about how such development may impact animal movement. Here, we use five spatially explicit projections of solar energy development through 2050 to assess the extent to which ground-mounted photovoltaic solar energy expansion in the continental United States may impact land-cover and alter areas important for animal movement. Our results suggest that there could be a substantial overlap between solar energy development and land important for animal movement: across projections, 7−17% of total development is expected to occur on land with high value for movement between large protected areas, while 27−33% of total development is expected to occur on land with high value for climate-change-induced migration. We also found substantial variation in the potential overlap of development and land important for movement at the state level. Solar energy development, and the policies that shape it, may align goals for biodiversity and climate change by incorporating the preservation of animal movement as a consideration in the planning process.



KEYWORDS: *solar energy, photovoltaic, land-cover change, animal movement, GIS*

1. INTRODUCTION

The dual crises of climate change and biodiversity loss require the implementation of urgent solutions to mitigate their worst effects for all life on Earth. Each of these crises is, on its own, a wicked problem, proving intractable due to institutional inconsistency, feedback loops, stakeholder conflicts, and other logistical hurdles.[1,2] One challenging characteristic of these particularly wicked problems is that they are inherently linked but tend to be studied independently. A 2021 report jointly released by the Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services warned that research communities studying climate change are unique from those that study biodiversity loss, increasing risk that solution-based actions toward one may undermine those of the other.[3] To overcome this "green-versus-green dilemma," where actions to address climate change and biodiversity loss are approached in a disjointed fashion, solutions are needed that account for both crises and reinforce their shared goals.[4,5]

One facet of this dilemma may arise where requirements for the conservation of landscape connectivity intersect with the physical footprint of renewable energy expansion. Species are going extinct at a rate 1000 times faster than would be expected under scenarios without anthropogenic influence,[6] and the primary driver of this increased extinction rate is the alteration of land.[7] Habitat loss and fragmentation affect wildlife in various ways, but notably through the decline of landscape connectivity: the extent to which a landscape supports (or hinders) the movement of wildlife between resource areas.[8] Connectivity contributes to higher species fitness, occurrence, and distribution, as well as improved genetic diversity and community diversity.[9] As such, the maintenance of connectivity often becomes a central component of any landscape-scale conservation strategy.

Conserving connectivity to protect biodiversity may directly conflict with renewable energy development, particularly the construction of large, ground-mounted photovoltaic (PV) solar energy facilities. Similar conflicts between development and conservation have been documented in the continental United States (U.S.) with other land uses such as agriculture and residential/commercial development, as well as with other forms of energy. Agriculture comprises over 40% of the U.S.'s land area, whereas urban areas and roads comprise approximately 5%.[10] The physical footprint of energy development in the U.S. through the early 2020s has been dominated by the production of biofuels, which, owing to conversion of agricultural land and substantial conversion of non-agricultural

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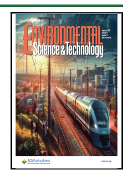

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land, characterizes more than 200,000 km^2.[11,12] Fossil fuel-based energy generation (i.e., via coal, oil, and natural gas) is also responsible for considerable land-cover change. For example, by 2020, the total area of land converted to support the development of oil and gas well pads, roads, and associated storage facilities in the U.S. was approximately 30,000 km^2—an area similar to that of the state of Maryland.[13] The substantial footprints of these energy sources have negative impacts on biodiversity, including reductions in vertebrate abundance, species diversity, and ecosystem services.[13,14]

Solar energy technologies are poised to contribute similarly substantial land-cover changes through 2050. As of 2021, renewable energy development is responsible for less land conversion than bioenergy or fossil fuels—wind and solar characterized only 28,700 km^2 of U.S. land in 2021.[12] However, wind and solar have greater land-use intensities of energy (LUIE; the area an electricity-producing facility occupies divided by the facility's annual energy production) than those of coal and natural gas.[15] Wind energy has a substantially larger LUIE than ground-mounted PV solar, but turbines can be better integrated into existing land uses like croplands and pasture.[16] PV installations can also be integrated on rooftops and other facets of the built environment; however, to date, large, ground-mounted PV solar energy facilities (hereafter solar energy facilities) that produce electricity at scales comparable to wind turbines have typically not been integrated into the built environment. In some cases, development can drive wholesale transformation of all biophysical capacity of land to an industrial, energy-producing, and often "abiotic" landscape (Figure 1). In part, this is because the conventional preparation of a solar energy facility commonly involves the removal of standing vegetation, soil grading and compaction, and fencing and road construction.[17,18] Therefore, depending on the type of development and how much development occurs in the coming decades, solar energy expansion could increasingly conflict with conservation priorities.

The velocity and spatial extent of solar energy's future expansion is unknown, but PV solar energy capacity increased by 33.6% per annum in the U.S. between 2011 and 2021.[19] Furthermore, recent policy targets indicate the extent to which PV development could drive land-cover change in the U.S.; the recently published Solar Futures Study estimates that, for the U.S. to decarbonize its energy grid and produce 45% of its electricity using solar energy technology by 2050, between 26,628 and 41,683 km^2 of land may be converted to solar energy production.[10] Thus, the "green-versus-green dilemma" may arise where the development and operation of large-scale, ground-mounted PV solar facilities have direct and indirect impacts on animal movement within and around their footprints. One recent analysis found that solar expansion is not predicted to conflict with conservation priorities at the global scale but noted that the U.S. was an outlier in terms of the number of predicted overlaps between the two.[20] Furthermore, there are already at least 33 solar facilities with capacities of at least 10 MW in the U.S. that intersect with wilderness areas (regions without any industrial-scale human pressures that generate significant disturbance[21]) and at least four that intersect with protected areas.[22]

Major knowledge gaps remain in our understanding of the relationship between solar energy infrastructure and wildlife.[4,23,24] To date, empirical research has documented direct negative impacts on biodiversity for plants and animals within

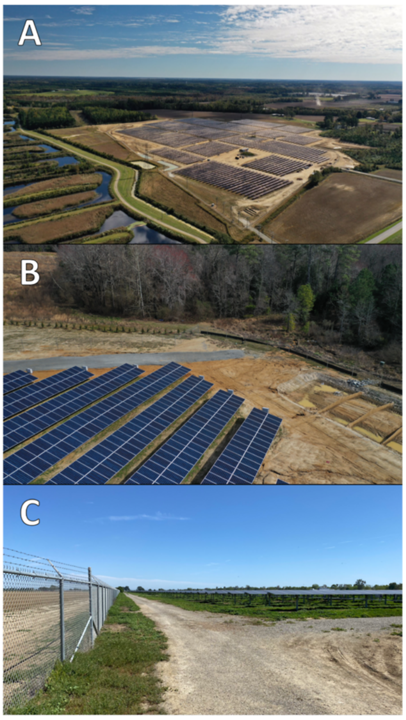

Figure 1. The construction of a solar energy facility may involve the conversion of existing land-cover to a highly managed industrial land-cover. (A) Solar facilities can often be found within a broad matrix of other land-cover categories, including agriculture, residential areas, and forest patches. (B) The conversion of land required for the construction of a solar energy facility extends beyond the footprint of the panels themselves, and may include additional, intensive alteration of the land to make management of a facility more efficient (e.g., the construction of storm water retention ponds). (C) In addition to land-cover change, solar facilities must be fenced to comply with the National Electric Code, creating a barrier that may be difficult or impossible for terrestrial wildlife to traverse. Photo credit for panels A & B: Margaret Fields, The Nature Conservancy. Photo credit for panel C: Rebecca R. Hernandez, UC Davis.

large, ground-mounted facility footprints during the construction and operation of PV and concentrating solar power facilities.[18,25−27] Other studies have reported avian richness in large, ground-mounted solar facilities to be comparable to that of active pasture/cropland, but less than that of abandoned cropland,[28] as well as lower species density and richness inside of large, ground-mounted solar facilities compared to that of facility boundary zones and unaltered controls.[29−31] Beyond these studies, there is little data regarding other topics such as solar infrastructure's influence on species ranges, behavior, occupancy/density, and, critically, movement. One study describes negative impacts of solar development on ungulates, including barrier effects on both resident and migratory populations as well as direct and indirect habitat loss,[32] but more data are needed to characterize the relationship between solar energy infrastructure and animal movement.

Here, we contribute some understanding of solar PV development's impact on animal movement at the national scale by (1) anticipating future changes in continental U.S. land-cover driven by large, ground-mounted PV solar energy development using spatially explicit predictions of renewable energy expansion from several modeling scenarios representing pathways through which the U.S. can achieve carbon neutrality by 2050, and (2) evaluating potential impacts of future U.S.

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solar development on corridors with high connectivity value between large protected areas and in regions with varied microclimates that will support climate-change-induced species migration.

2. MATERIALS AND METHODS

To explore potential solar-driven land-cover change, we performed an impact assessment on five distinct scenarios of projected solar energy development by 2050 produced by the Net-Zero America Project[33] (NZAP) using the 2019 National Land Cover Database (NLCD).[34] Next, we used two peer-reviewed datasets of landscape-scale movement-relevant data to assess the effects of potential PV solar development on: (1) corridors that connect and facilitate movement between large protected areas, and (2) climate-resilient landscapes (i.e., regions with varied habitats and micro-climates likely to support a broad cohort of species forced to migrate due to warming temperatures across the U.S.).[35,36]

Potential Land-cover Change across Solar Energy Development Scenarios. The NZAP models multiple scenarios through which the U.S. could achieve carbon neutrality by 2050. Their modeling framework consists of four main components: (1) projecting the demand for various services that require energy, (2) using the EnergyPATHWAYS model to specify particular technologies that can be used by consumers to meet that demand, (3) using the RIO model to identify a mix of energy supply technologies that can provide enough energy to meet that demand at the lowest possible cost, and then (4) using the results from EnergyPATHWAYS and RIO to model finer scale considerations (including the siting of renewable energy facilities) at the state and sub-state level. Five scenarios are publicly accessible. Four are project pathways based on varying assumptions that ultimately arrive at national net-zero goals, while one is a reference scenario representing business as usual practices where the U.S. does not reach national net-zero goals. We used all five in this analysis (Table 1; Supporting Information 1). The scenarios with base land-use assumptions (BLUA) relied upon 60 spatial datasets to exclude land based on techno-economic and environmental considerations (Supporting Information 1). Scenarios with constrained land-use assumptions (CLUA) operated along more stringent land-use exclusions, removing prime soils and intact landscapes from consideration to better preserve areas with high value for environmental protection, adaptation, and restoration while still reaching a net-zero target by 2050.

The NZAP modeling framework includes spatially explicit projections of renewable energy development by 2050 for each of the five available scenarios. We acquired these projections and filtered them to include only the potential footprints of solar energy facilities, and then uploaded them to Google Earth Engine. Through Google Earth Engine, we also accessed the 2019 release of the NLCD dataset and selected the 30 meter resolution land cover product for the U.S. contained within that release. We used this release of the NLCD rather than a model of future land-use and land-cover change to assess potential changes from a current baseline. The current extent of unaltered land that best supports biodiversity is likely to be greatest in the present as continued development across sectors contributes to habitat loss and fragmentation, and our goal is to understand how PV solar expansion may potentially impact such areas.

Table 1. Attributes of the Five NZAP Scenarios Used in This Study[a]

NZAP scenario	scenario description
reference	This scenario is based on the data found in the U.S. Energy Information Administration's 2019 Annual Energy Outlook. Modeling based on these data does not allow for new energy policies and maintains low projections for the price of oil. Under this scenario, the U.S. does not reach net-zero goals by 2050.
high electrification (E+) base and constrained land use	The assumptions of this scenario include near-total electrification of the transport and building sectors by 2050 and the additional electricity production that would be needed to supply this increased demand. Two versions of this scenario are assessed in this analysis: a base land-use scenario (BLUA) with fewer restrictions on where renewable energy can be deployed, and a more limited constrained land-use scenario (CLUA). Under these scenarios, the U.S. does reach net-zero goals by 2050.
100% renewable (E+ RE+) base land use	Like E+, this scenario includes the near-total electrification of the transport and building sectors, but explores a more aggressive pathway where the vast majority of electricity supply comes from renewable sources and fossil fuel electricity generation is eliminated in its entirety by 2050. Under these scenarios, the U.S. does reach net-zero goals by 2050.
constrained renewable (E+ RE−) base land use	This scenario is similar to the E+ RE+ scenario but constrains the total growth rate of renewable energy sources while employing more carbon capture to balance a slower transition away from fossil fuels while still achieving carbon neutrality by 2050. Under this scenario, the U.S. does reach net-zero goals by 2050.

[a]Additional information can be found in Supporting Information 1.

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Table 2. Aggregated National Totals of Total Nameplate Capacity (Gigawatts [GW]), Land Footprint (km^2), and Projected Area (km^2) of Solar Energy Development that Intersects with High-Value Corridors, and RCL for Each NZAP Scenario[a]

NZAP scenario	projected solar capacity by 2050 (GW)	projected solar footprint by 2050 (km^2)	projected area of land in high-value corridors converted to solar (km^2)	projected area of land in RCL converted to solar (km^2)
reference, BLUA	157.82	3116.21	520.06 (proportion of projected footprint: 16.69%) (proportion of national area in high-value corridors: 0.2%)	798.70 (proportion of projected footprint: 27.04%) (proportion of national area in RCL: 0.1%)
RE−, BLUA	643.26	14,661.32	2453.07 (proportion of projected footprint: 16.73%) (proportion of national area in high-value corridors: 0.96%)	4609.91 (proportion of projected footprint: 33.18%) (proportion of national area in RCL: 0.48%)
E+, CLUA	1483.96	39,040.63	2917.34 (proportion of projected footprint: 7.47%) (proportion of national area in high-value corridors: 2.55%)	11,367.99 (proportion of projected footprint: 30.7%) (proportion of national area in RCL: 1.29%)
E+, BLUA	1500.66	40,694.41	4399.31 (proportion of projected footprint: 10.81%) (proportion of national area in high-value corridors: 2.65%)	13,032.80 (proportion of projected footprint: 32.37%) (proportion of national area in RCL: 1.4%)
RE+, BLUA	2756.89	63,166.63	6157.20 (proportion of projected footprint: 9.75%) (proportion of national area in high-value corridors: 4.12%)	19,606.91 (proportion of projected footprint: 32.6%) (proportion of national area in RCL: 2.09%)

[a]The proportion (%) of development ("projected footprint') projected to occur on land in high-value corridors and on RCL is reported below the projected area of land, as is the proportion (%) of national total area of high-value corridors and RCL that is projected to be converted by solar energy development.

To align the spatial resolutions of NLCD land cover data (30 m) and the spatial projections for each NZAP scenario (500 m), we reprojected the NLCD dataset to a resolution of 500 m using the mode—in other words, the land-cover category in the NLCD dataset that best represented each 500 m sampling window became the land-cover category assigned to that 500 m window. We then calculated the area of each resampled NLCD land-cover category found within solar energy facility footprint polygons for each NZAP scenario using a grouped reducer within the reduceRegions() function. Next, we summed the area of each land-cover category within the polygons of each NZAP scenario to determine the extent of projected solar-driven land-cover change by 2050, under the assumption that any land located within the boundary of a polygon would be converted to an abiotic industrial land-cover associated with conventional solar energy facilities. This was done for the continental U.S. and each of the 48 contiguous states.

Movement-relevant Change across Potential Solar Facility Footprints. We then applied a similar workflow to two datasets of landscape-scale, movement-relevant data to assess the effects of potential solar development on corridors and climate-resilient landscapes. The first dataset, published by Belote et al., represents land that is potentially of high value for connecting large protected areas in the U.S., of the mid-2010s. Specifically, the authors delineated "corridors" using findings of several connectivity models, each of which was constructed with assumptions on the extent to which human alteration of the land influences landscape connectivity.[36] As far as we are aware, this is one of the only peer-reviewed studies that has produced a national spatially explicit estimate of connectivity between protected areas. The final composite corridor map was published as a continuous raster where each pixel represents the mean composite value of that land as a corridor. In their analysis of this raster, the authors binned this continuous raster into deciles where higher deciles represent higher value for animal movement, a step we reproduced. We then took this binned raster and converted it into a binary image, which was clipped to the geographic boundary of the continental U.S. The binary image represented the bottom 80% of corridors (the bottom eight deciles) as a "0" and the top 20% of corridors (the top two deciles) as a "1". The top 20% of corridors are hereafter referred to as high-value corridors.

Next, we calculated the total area of each binary class for the U.S. and each state using a grouped reducer within the reduceRegions() function. From this we derived the total area of land in high-value corridors nationally, and in each state. We also calculated the total area of each binary class within the projected footprints of the five NZAP scenarios using the same reducer. From this, we derived the proportion of projected solar development that may occur on areas in high-value corridors nationally, and in each state.

We then used The Nature Conservancy's Resilient and Connected Landscapes (RCL) data to assess the effects of solar energy development on the potential movement of species owing to climate change. This dataset, first published for the eastern U.S. in 2014[35,37] and recently expanded nationwide, identifies well-connected areas characterized by an array of microclimates as of the late 2010s that are likely to provide buffers against a changing climate. As far as we are aware, this is one of the only national studies of landscape potential to support climate-change-induced migration. Each pixel in this categorical dataset represents an area that has: (1)

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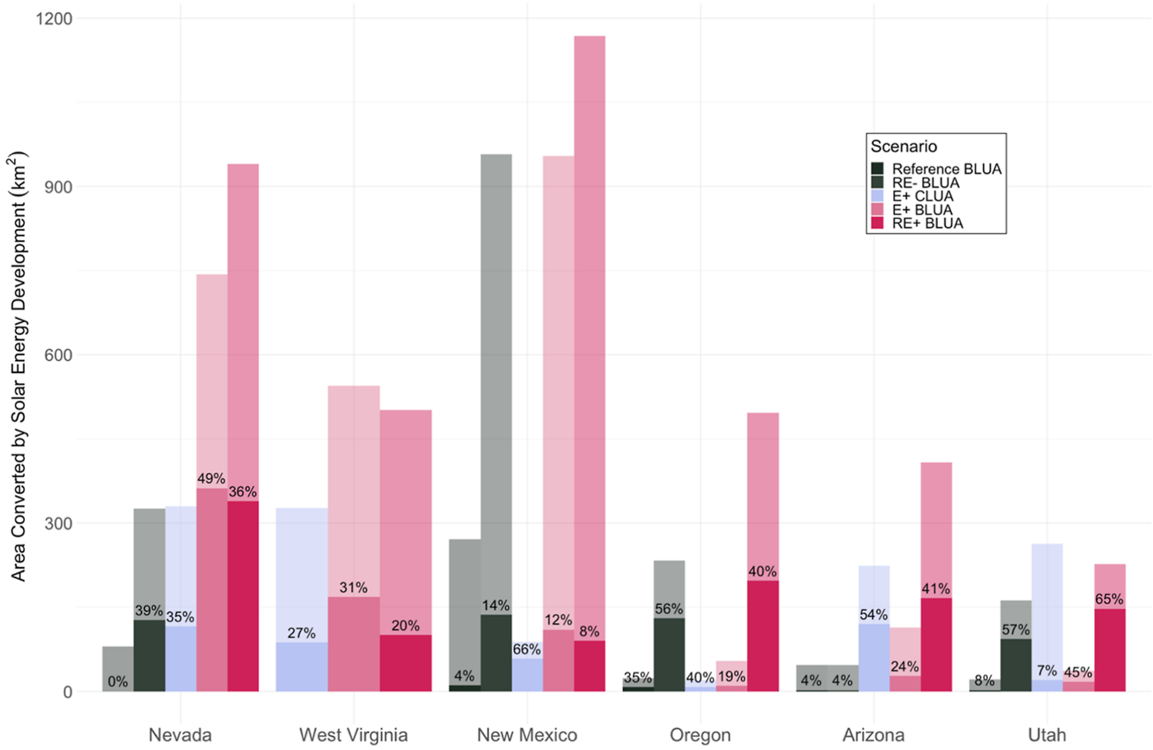

Figure 2. Projected area converted by solar energy development across six highly impacted states in the U.S. Pale bars represent the total area (km^2) projected to be converted by solar energy development by 2050 across the five NZAP scenarios. Dark portions of each bar represent the area (km^2) of high-value corridors that is projected to be converted. Percentages describe proportion (%) of state land projected to be converted to solar energy that overlaps with high-value corridors. These six states were chosen due to their relatively high proportions of solar development projected to occur on high-value corridors, as well as their variation between scenarios. Data for all states can be found in Supporting Information 4.

diverse microclimates (2) a narrow corridor (e.g., a riparian area), within which climate-induced movement is likely to occur for some species, or (3) a larger area (e.g., a forest) through which climate-induced movement is likely to occur for some species. We joined all RCL classes into a single layer, excluding the Excluded Tribal Lands class—while the RCL dataset is publicly available, The Nature Conservancy withholds data that might be considered sensitive from such public releases, including spatial data pertaining to tribal land. We thus removed all projected solar footprints overlapping with tribal lands from our analysis of solar development occurring on RCL. The total area removed from this analysis included 23 km^2 for the reference scenario, 282 km^2 for RE−, BLUA, 790 km^2 for E+, CLUA, 436 km^2 for E+ BLUA, and 1026 km^2 for RE+, BLUA. We then created a binary image using the same methodology described for the high-value corridor image. This image represented land in the U.S. that was not identified as RCL (assigned a "0") and land that was identified as RCL (assigned a "1"). We analyzed this image using the same methodology described above for the corridor image.

RESULTS AND DISCUSSION

We found that the reference scenario, which does not provide a pathway for the U.S. to reach net-zero goals by 2050, projects that business-as-usual practices will result in slightly less than 160 GW of installed solar energy capacity across more than 3000 km^2 of land (Table 2). The other four scenarios that do achieve net-zero goals predict between 485 and 2599 GW of capacity and 14,661.32−63,166.63 km^2 will be deployed by 2050—up to 20× the land area projected by the reference scenario. The net-zero scenarios project at least a fourfold increase in area of solar energy development projected to occur on high-value corridors; the proportion of total development occurring on such land in the net-zero scenarios exceeds that of the reference only once, and by a small margin (Table 2). The opposite is true for projected development on RCL, where the reference scenario projects the lowest proportion of solar development occurring on RCL of the five scenarios examined here.

Reference Scenario. The reference, BLUA scenario projects 158 GW of solar energy capacity development by 2050 (approximately 64 GW more than the total U.S. solar capacity as of 2021[19]) with a spatial footprint slightly above 3000 km^2 (Table 2). Approximately 17% of this footprint is projected to be on land within high-value corridors, while 27% is projected to be on RCL. In this scenario, over 40% of solar energy development in the U.S. state of Texas will occur on high-value corridors—the greatest among U.S. states (Figure 2). In Oregon, Washington, and California, over 20% of development will occur on such land. In Maine, New Mexico, and Oklahoma, over 40% of solar energy development under this scenario will occur on RCL, while nine other states (IL, LA, MS, MO, FL, CA, CT, IA, and OR) are projected to host over 20% of development on such land (Figure 3). Shrub/scrub, pasture/hay, and cultivated crops are all projected to be converted to solar energy across more than 400 km^2 (Figure 4), but no land-cover category is expected to be converted to solar energy across more than 0.2% of its total U.S. area.

RE−, BLUA Scenario. Projected U.S. solar energy development through 2050 under the RE−, BLUA scenario includes 643 GW of solar energy capacity across a footprint of 14,661 km^2. This represents an increase of 485 GW of capacity

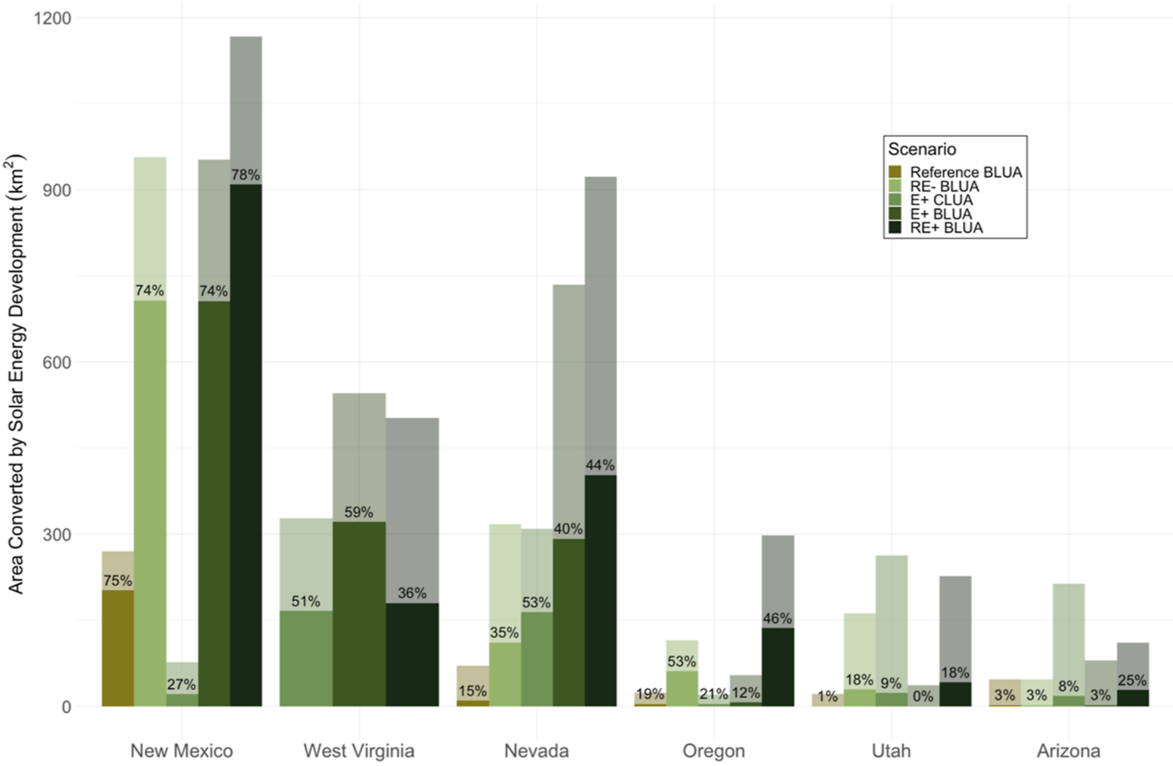

Figure 3. Projected area converted by solar energy development across six highly impacted states in the U.S. Pale bars represent the total area (km^2) projected to be converted by solar energy development by 2050 across the five NZAP scenarios. Dark portions of each bar represent the area (km^2) of RCL that is projected to be converted. Percentages describe proportion (%) of state land projected to be converted to solar energy that overlaps with RCL. These six states were chosen due to their relatively high proportions of solar development projected to occur on RCL, as well as their variation between scenarios. Data for all states can be found in Supporting Information 5.

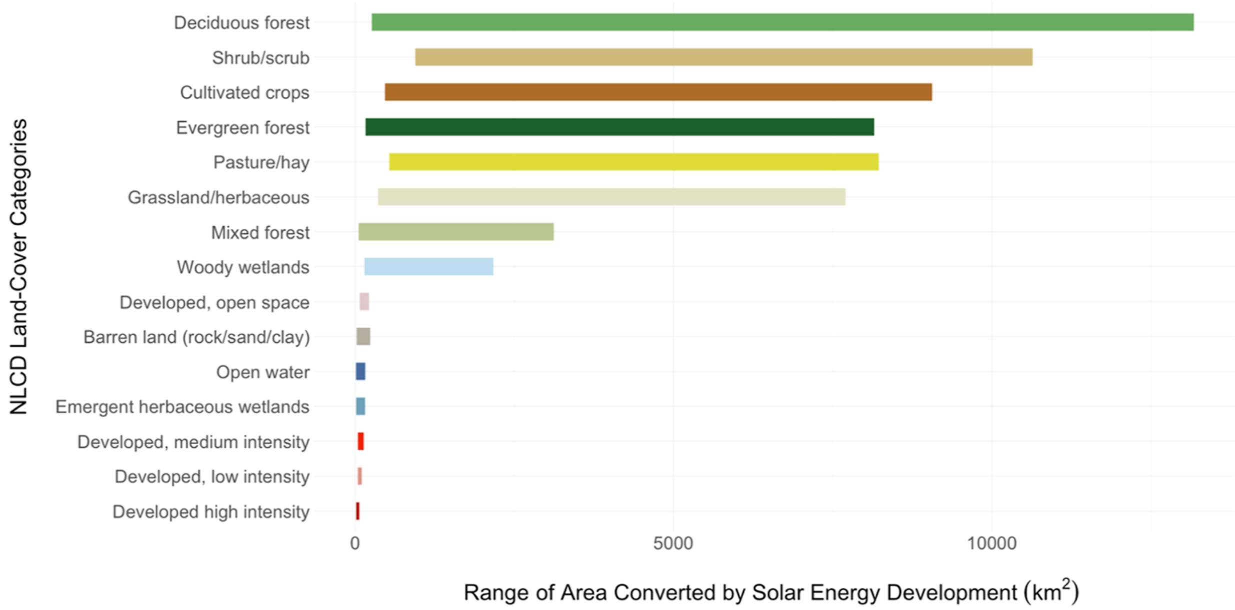

Figure 4. Range of potential land-cover change by 2050 for each National Land Cover Database category across the five NZAP scenarios in the U.S.

and more than 11,500 km^2 of land area compared to the reference scenario (Table 2). The proportion of land projected to be developed for solar that is on high-value corridors is approximately the same as the reference scenario (17%), while the proportion of development on RCL is approximately 33% of the total (~6% greater than the reference scenario). Over half the footprint of solar energy development in Utah and Oregon is projected to occur on high-value corridors, as is more than 30% of the footprint in five other U.S. states (NV, TX, WY, WA, and CA). Under RE−, BLUA, more than 50% of projected solar development is expected to occur on RCL in seven states (MA, NM, CO, OR, AL, CT, and NJ), while over

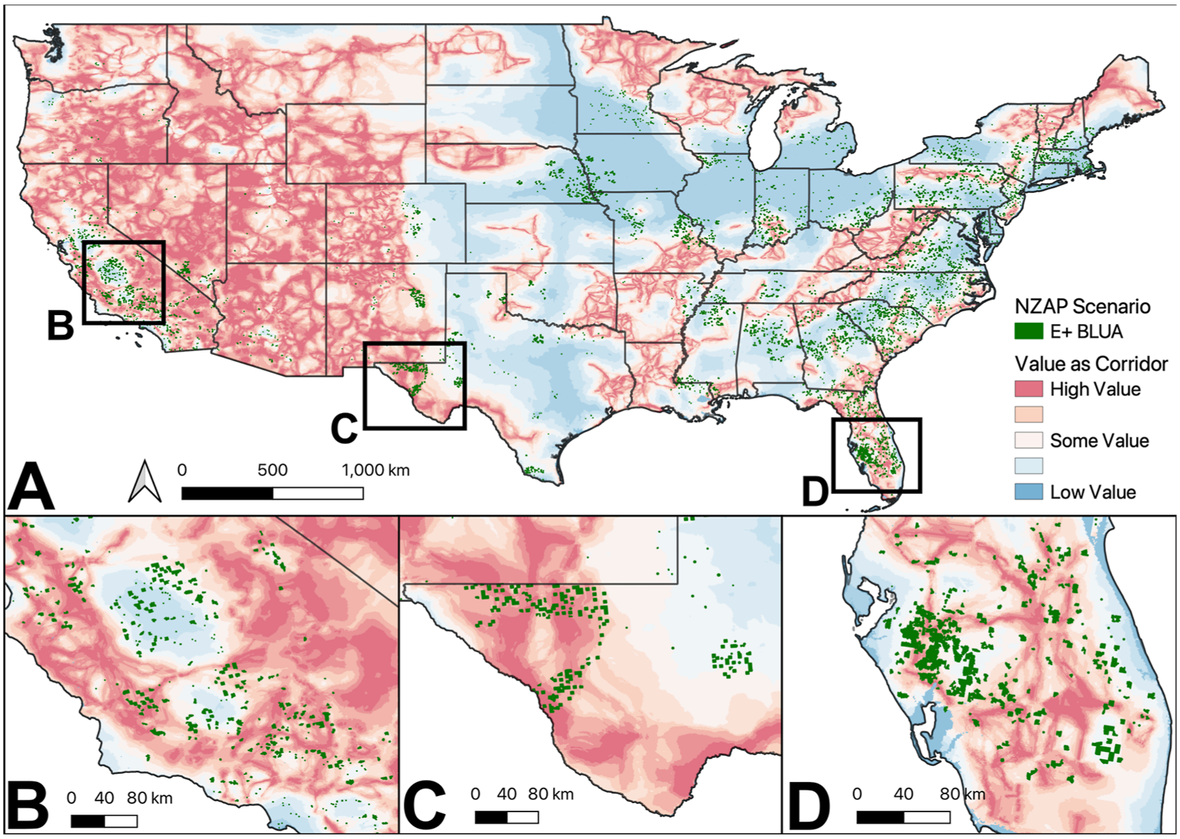

Figure 5. Maps show overlap between projected solar energy development by 2050 (from the E+, BLUA NZAP scenario) and high-value corridors in the United States. (A) Solar energy development projected under the E+ BLUA scenario is concentrated in the desert southwest and the eastern seaboard, with some expansion into Texas and the Midwest. Examples of overlap between the E+, BLUA scenario and high-value wildlife corridors include (B) southern California, (C) eastern Texas, and (D) central Florida.

20% of projected development is expected to occur on RCL across 21 states. Under the RE−, BLUA scenario, nearly 30% of solar energy development is projected to occur on shrub/scrub, 15% on deciduous forest, and 13% on cultivated crops in the U.S (Supporting Information 3). No U.S. land-cover category is projected to be converted to solar across more than 0.3% of its national area, but six categories are projected to see over 1000 km^2 of conversion to solar (Figure 4).

E+, CLUA Scenario. The E+, CLUA scenario projects more than double the capacity (1484 GW) and associated spatial footprint (39,041 km^2) of U.S. solar energy by 2050 compared to the RE−, BLUA scenario. Of all five scenarios, E+, CLUA projects the lowest proportion of U.S. solar development occurring on high-value corridors (7.47%) and second lowest on RCL (30.7%). The area of projected solar development occurring on high-value corridors in this scenario is 2917 km^2, which is 464 km^2 more than that of the RE−, BLUA scenario. Over half of the solar energy development in New Mexico and Arizona is projected to occur on high-value corridors, while at least 20% of development will occur on high-value corridors in five other states (OR, WA, NV, WV, and LA). Over 60% of solar energy development under this scenario will occur on RCL in four states (VT, NH, KS, and MA), while more than half of states in the continental U.S. are projected to host over 20% of total solar development on RCL. In the E+, CLUA scenario, 22% of development is projected to occur on deciduous forest, 18% on cultivated crops, and 14% on grassland/herbaceous (Supporting Information 3). Nationally, over 1% of deciduous forest is projected to be converted to solar energy under this scenario, representing over 8500 km^2. No other land-cover categories are projected to have over 1% of their national area converted to solar (Supporting Information 3).

E+, BLUA Scenario. The E+, BLUA scenario projects 1500 GW of solar capacity across 40,694 km^2, an increase of 17 GW of capacity and 1654 km^2 compared to the E+, CLUA scenario. The projected proportion of land developed for solar on high-value corridors under this scenario is 3% higher than the E+, CLUA scenario, representing an additional 1482 km^2 (Figure 5). The projected difference in development occurring on RCL is approximately 2% between the E+ scenarios. In the E+, BLUA scenario, over 20% of solar development is projected to occur on high-value corridors across six states (NV, UT, WV, TX, AZ, and CA). Over 50% of solar development under this scenario is expected to occur on RCL in nine states (NH, NM, VT, WV, CO, PA, CA, MA, and ME), while more than half of the states in the continental U.S. are projected to host over 20% of development on RCL. In terms of land-cover categories, 22% of development in this scenario is projected to occur on deciduous forest, 17% on shrub/scrub, and 16% on cultivated crops (Supporting Information 3). Only 10% is projected to occur on grassland/herbaceous. Like the E+, CLUA scenario, deciduous forest is the only land-cover type projected to be converted to solar across more than 1% of its national area (Supporting Information 3).

RE+, BLUA Scenario. Solar energy expansion is projected to reach 2757 GW and occupy 61,167 km^2 by 2050 under the RE+, BLUA scenario. This scenario projects a lower

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proportion of solar energy development occurring on high-value corridors compared to the E+, BLUA scenario, but a higher proportion than that of the E+, CLUA scenario. It also projects the second highest proportion of solar energy development occurring on RCL after the RE−, BLUA scenario. In Utah, 65% of solar energy development is projected to occur on high-value corridors, while at least 20% of development is projected to occur on high-value corridors in Arizona, Oregon, Nevada, California, and West Virginia. Seven states are projected to host over 60% of solar development on RCL (NM, RI, CT, OK, NH, VT, and CO)—31 states are projected to host over 20% of development on RCL. In this scenario, 21% of development is projected to occur on deciduous forest, 17% on shrub/scrub, and 14% on cultivated crops (Supporting Information 3). Deciduous forest, pasture/hay, and mixed forest are projected to be converted to solar energy across more than 1% of their national area, over more than 24,500 km^2 combined (Supporting Information 3).

From Projections to Planning. Less than 1% of the total U.S. land area is projected to be converted to solar energy development under even the most liberal NZAP scenario prediction, representing a relatively small driver of land-cover change relative to other land-use types such as agriculture and urban development.[10] Within that footprint, however, our results show a substantial overlap of projected solar energy development with high-value land for animal movement. Across projections, 7−17% of total solar development is anticipated on high-value corridors between large protected areas, while 27−33% of total development is expected on RCL. Furthermore, some land-cover categories more likely to support animal movement may be converted by solar development across more than 1% of their total national area.

The intersection between projected solar energy development and high-value land for animal movement is more prominent at the sub-national level, varying dramatically between states. For example, the proportion of California's solar development that is projected to occur on high-value corridors ranges from 13% of total development in the E+, CLUA scenario to 30% of total development in the RE−, BLUA scenario. Texas is projected to have only 9% of its total solar development occur on high-value corridors under the E+, CLUA scenario, while in the RE−, BLUA scenario that proportion rises to 37%. Utah's range is even greater, from 7% in the E+, CLUA scenario to 65% in the RE+, BLUA scenario. Collecting and utilizing empirical movement data at fine spatial scales will be essential to avoid, minimize, and mitigate impacts in those states with variable and substantial projected overlaps between solar energy development and land important for animal movement.

One successful example of how local data can guide regional solar energy development was facilitated by the U.S. Bureau of Land Management (BLM), which promoted solar energy development within specifically delineated Solar Energy Zones across six western states in the 2010's.[38] These zones were identified as being conducive to solar development after extensive spatial analysis accounting for various technical considerations and resource conflicts. Habitat connectivity and other critical ecological considerations featured prominently in the development of these zones. This type of careful solar facility siting based on local data and stakeholder engagement is likely the most important and effective means of avoiding negative impacts of solar development on animal movement.

At the national scale, three forest categories in the NLCD (deciduous, evergreen, and mixed) ranked among the top five land-cover categories in the proportion of their national area converted to solar energy across the four net-zero scenarios. Deciduous forest ranked first in all four, ahead of human-altered landscapes like cultivated crops and pasture/hay—in three of those scenarios, that proportion of conversion exceeded 1% of the national total area of deciduous forest. Even in the E+, CLUA scenario, development on deciduous forest comprised the largest proportion of impact across all land-cover categories. The conversion of forest land-cover categories and others that represent less altered land (including shrub/scrub and grassland/herbaceous) over those already altered by humans or with less value for animal movement (such as developed, open space or barren land) represents a concerning ecological trade-off.

While the two E+ scenarios differ in what land can be considered for solar energy development, the BLUA result in only a slight increase in deployed solar energy capacity and its associated footprint when compared to the CLUA. However, the CLUA appear to reduce the amount of development projected to occur on areas with more value for animal movement, particularly for high-value corridors. This holds for the direct comparison between the two E+ scenarios, but also across scenarios with different assumptions. For example, the E+, CLUA scenario projects solar expansion with double the capacity and footprint of the RE−, BLUA scenario, while also projecting nearly 10% less solar development on high-value corridors.

Research gaps pertaining to solar energy infrastructure's influence on the movement of individual species persist,[39] and solar energy development is likely to impact different species in different ways.[18,40] Some are less likely to be affected—volant species, for example, can fly above or around facilities and may be less at risk for PV-driven disruption of their movement or migration. However, mortality of volant species due to direct impacts with solar energy infrastructure has been observed.[41] Large mammals could lose access to all or portions of their home range and have migratory pathways disrupted,[32] and are thus more likely to experience adverse effects from solar development. There may even be species that benefit from solar development and make use of these novel spaces to avoid predation or access previously unavailable resources.[42] Mitigation strategies (e.g., constructing facilities with corridors to facilitate movement) may increase movement for certain species in some landscapes, but few have been assessed at solar energy facilities outside anecdotal reports or grey literature forums (but see refs 40, 43, and 44). A more specific focus on the species most likely to be affected will clarify what siting configurations, facility designs, and mitigation interventions are most effective across broader geographic scales.

Future renewable energy movement ecology research may choose to focus on (1) species most likely to be affected, (2) siting practices and configurations that can avoid the negative impacts of solar energy on wildlife movement, and (3) testing mitigation strategies such as corridor development to allay negative effects of solar development on animal movement. However, conservation organizations, state wildlife agencies, and policymakers should not be dissuaded from taking action now to align solar energy development goals with those of wildlife conservation. There is an extensive literature in landscape, movement, corridor, disturbance, roadway, and fence ecology that is applicable to renewable energy ecology.

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This early phase of solar energy development can be guided by the lessons gleaned from these disciplines and later refined by the research described above to fill in the most pressing gaps.

The U.S. is on the precipice of dramatic changes to its national energy portfolio, with solar energy technology poised to become a substantial contributor over the next 30 years. This is a positive development for the decarbonization of that portfolio, but also represents a substantial planning challenge. Among dozens of other considerations, solar energy development must begin to explicitly account for concerns regarding the preservation of animal movement or risk exacerbating the "green-versus-green dilemma" to the point where the goals of solar development and wildlife conservation risk decoupling. As solar energy's footprint burgeons, it is likely to add pressure to landscapes already altered by dozens of other considerations. A transition is imminent and ongoing, but there is still time to execute a national response that balances goals for climate change mitigation and the preservation of biodiversity.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c00578.

> Information on NZAP scenarios, data sources and formats, computed areas of land-cover change driven by NZAP projections of solar development, at the national and state levels, computed areas of alteration to land with high-value as corridors between large protected areas driven by NZAP projections of solar development, at the national and state levels, computed areas of alteration to RCLs driven by NZAP projections of solar development, at the national and state levels (PDF)

AUTHOR INFORMATION

Corresponding Author

Michael O. Levin − *Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, New York 10027, United States;* orcid.org/0000-0003-4831-2567; Email: mol2112@columbia.edu

Authors

Elizabeth L. Kalies − *The Nature Conservancy, Durham, North Carolina 27701, United States;* orcid.org/0000-0001-7749-6647

Emma Forester − *Department of Land, Air & Water Resources and Center for Wild Energy, University of California, Davis, Davis, California 95616, United States*

Elizabeth L. A. Jackson − *Columbia University, New York, New York 10025, United States*

Andrew H. Levin − *University of Rochester, Rochester, New York 14627, United States*

Caitlin Markus − *The Nature Conservancy, Durham, North Carolina 27701, United States*

Patrick F. McKenzie − *Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, New York 10027, United States*

Jared B. Meek − *Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, New York 10027, United States;* orcid.org/0000-0001-8191-4266

Rebecca R. Hernandez − *Department of Land, Air & Water Resources and Center for Wild Energy, University of California, Davis, Davis, California 95616, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.3c00578

Author Contributions

M.O.L. conceived and designed the research and collected data; M.O.L., R.R.H., and ELK wrote the manuscript; M.O.L., E.F, E.L.A.J., A.H.L., C.M., P.F.M., and J.B.M. analyzed data; all authors contributed to manuscript drafts. All authors have given approval to the final version of this manuscript.

Notes

The authors declare no competing financial interest.

All Javascript and R code used in these analyses are documented and publicly accessible via a Dryad repository (https://doi.org/10.5061/dryad.mw6m90628). The raw results derived from the spatial analyses described in this manuscript are available in the Dryad repository as well. The assets used to conduct the spatial analyses are all publicly available, and their sources (along with links to download each asset) can be found in Supporting Information 1.

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ABBREVIATIONS

AZ	Arizona
CA	California
CO	Colorado
CT	Connecticut
KS	Kansas
LA	Louisiana
LUIE	land use intensities of energy
MA	Massachusets
ME	Maine
NH	New Hampshire
NM	New Mexico
NV	Nevada
NZAP	Net-Zero America Project
OK	Oklahoma
OR	Oregon
PA	Pennsylvania
PV	photovoltaic
RCL	Resilient and Connected Landscapes
RI	Rhode Island
TX	Texas
U.S.	Continental United States
UT	Utah
VT	Vermont
WA	Washington
WV	West Virginia

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