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Perspective

Climate-Smart Siting for renewable energy expansion

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SUMMARY

A massive expansion of renewable energy (RE) is underway to meet the world's climate goals. Although RE serves to reduce threats from climate change, it can also pose threats to species whose current and future ranges intersect with RE installations. Here, we propose a "Climate-Smart Siting" framework for addressing potential conflicts between RE expansion and biodiversity conservation. The framework engenders authentic consultation with affected and disadvantaged communities throughout and uses overlay and optimization routines to identify focal areas now and in the future where RE development poses promise and peril as species' ranges shift in response to climate change. We use this framework to demonstrate methods, identify decision outcomes, and discuss market-based levers for aligning RE expansion with the United Nations Global Biodiversity Framework now and as climate change progresses. In the face of the climate crisis, a Climate-Smart Siting strategy could help create solutions without causing further harm to biodiversity and human communities..

INTRODUCTION

The global community faces a crucial moment in tackling the dire consequences of climate change and biodiversity decline.[1] In the coming decades, unprecedented growth of renewable energy (RE) capacity is anticipated to mitigate climate change alongside a rapid evolution of RE technology, market forces, and regulatory policy. However, relatively little attention is placed on how growth in RE interacts with goals seeking to protect and restore nature. Globally, RE production rose 7% in 2021, resulting in a record-breaking increase of 522 TWh[2] and an unprecedented 28.7% of total global electricity generated from renewable sources.[3] Nearly 90% of this growth came from new wind and photovoltaic (PV) solar energy installations. Renewable energy is projected to surge by nearly 2,400 GW from 2022 to 2027, constituting over 90% of global electricity capacity expansion from 2022.[4] The expansion of RE can positively and negatively impact biodiversity, depending on the specific technology and location. In addition, socio-economic impacts on frontline communities can also be observed as negative consequences of RE implementation.[5]

Although increases in RE development are crucial for mitigating climate change via fossil fuel use reduction, individual solar or wind energy power plants and their supporting infrastructure (e.g., transmission corridors, and energy storage) can aggravate the other global environmental crisis, which is the loss of biodiversity. For logistical, financial, and socio-political reasons, wind and solar energy power plants are commonly constructed in natural environments (e.g., forests, deserts, prairies, and seashores),[6,7] a trend that will likely continue through 2050.[8,9] Although RE installations can reduce greenhouse gas emissions associated with the production and consumption of fossil fuels, they can occupy comparatively large physical footprints and cause significant land-use and land-cover change where they are sited.[10–13] Habitat destruction and increased ecological stress are troublesome, especially when the power plant's footprint harbors resident or migratory species or species that play crucial ecological roles.[14–17] Large, ground-mounted solar and wind energy power plants typically have operational lifespans of 25–40 years, and their impacts will likely continue for decades beyond the period of active production.[13] Researchers have also begun to document how RE installations can affect human ecosystems, including the physical, socio-economic, and/or cultural well-being of nearby communities.[18–21]

Solar and wind energy power plants can be designed to reduce negative ecological consequences and neutral or even beneficial effects.[22–28] Understanding and minimizing the negative effects of RE systems on their surroundings in creative and informed ways to protect nature is an important element in reducing the unintended harmful consequences of RE development on recipient environments. The industry has the potential to grow with ecologically informed regulatory policy and market-based incentives so that new facilities will serve to simultaneously address both crises and advance environmental justice (EJ) in the next few decades. EJ refers to the fair treatment and meaningful involvement of all people in decision-making processes, regardless of race, ethnicity, income, or other socio-economic factors.

Spatial planning practices vary across different regions but often incorporate strategies to prevent conflicts and protect sensitive areas in alignment with regulation.[29] We introduce a systematic model-based approach to address these challenges. While previous studies[30–33] have explored aspects of RE development, our framework stands out for its integration of multiple models and calculation of diverse scenarios and

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perspectives with the inclusion of species range shifts and EJ. We recognize the need to situate our methodological approach within the broader context of spatial planning frameworks to enhance its transferability to other contexts worldwide. Here, we aim to contribute to the discourse on sustainable RE development beyond national boundaries and promote a more comprehensive understanding of the challenges and opportunities in this field.

We present a holistic "Climate-Smart Siting" framework for identifying RE siting pathways that will minimize potential harm and maximize the benefits of each energy installation to its local surroundings. Unlike traditional approaches that focus on economic, geographic, and arbitrary criteria for biodiversity considerations based on datasets static in time, the framework proposes the use of comprehensive spatiotemporal optimization, integrating current datasets and future scenarios of solar and wind energy potential, land-use and land-cover change considerations, critical infrastructure, target species (including current and future species range shifts) and protected area expansion, and socio-ecological consequences, whether harmful or beneficial. For example, the exclusion of current protected areas is common in RE planning but, as of yet, there is little active anticipation of how RE installations will interplay with the expansion of protected areas proposed under global initiatives. For example, the United Nations' Kunming-Montreal Global Biodiversity Framework targets, which include the call for the protection of at least 30% of Earth's land and oceans by 2030, underscores the need for strategic planning to balance conservation efforts with RE development and emphasizes the importance of siting projects in areas that minimize ecological disruption and maximize biodiversity conservation.[34,35] Thus, there is an need for a framework that integrates a holistic assessment of potential wind and solar energy sites by considering multiple spatiotemporal dimensions of energy production, EJ, and climate-induced species range shifts simultaneously.

A key element of this framework is the inclusion of meaningful engagement of all stakeholders and rightholders in the siting process, especially people who live near prospective RE power plant sites. Industry and government engaging in authentic, two-way communication with the local community can reveal their needs and concerns and incorporate those into siting decisions. Participation of stakeholders in mapping, frequent consultation with community leaders, and workshops to inform community members about the siting decision process, the plans for construction and operation, and the expected positive, neutral, and negative impacts ensure that concerns and preferences of local communities, tribal nations, environmental groups, and other relevant stakeholders are heard, which fosters social acceptance and may reduce RE siting opposition.[36,37]

The "Climate-Smart Siting" framework emphasizes the identification of the best places to build RE projects while protecting nature. Unlike other methods, Climate-Smart Siting considers future climate changes, how different species might move, and how communities can become an integral part of the decision-making process to make RE development more sustainable and more beneficial for everyone involved.

CONTEXT: CURRENT DECISION-MAKING PRACTICES AND CONSEQUENCES

In the past, resource availability, land availability, and profit projections have driven most RE siting decisions; as a result, ecosystems and human communities have suffered negative consequences. During construction, habitat damage and fragmentation occur due to road construction, vegetation clearance, soil discing, grading, compaction, and noise and dust pollution.[25,38–40] Operation of facilities, such as spinning turbine blades and heat-concentrating solar power towers, harms a wide range of organisms, including resident and migratory birds, bats, reptiles, other mammals, plants, and pollinators.[41–43] A striking example is observed in the construction of RE projects within the Mojave Desert, which has had adverse effects on long-lived shrub and cacti species[25] and has significantly impacted the desert tortoise (*Gopherus agassizii*).[44] The advent of wind farms in certain regions has also elicited concerns regarding their potential impact on bird populations, including iconic species like the bald eagle (*Haliaeetus leucocephalus*).[45] These concerns emphasize the importance of considering the broader ecological implications and seeking innovative solutions for sustainable RE development.

When informed by knowledge about ecosystem services, critical species, and the needs of adjacent communities, RE development can be neutral and in some cases beneficial, when siting spares land for nature (e.g., rooftop solar) or is "stacked" with ecological restoration.[46–50] In California, where conversion to farmland has previously destroyed California prairie habitat, installation of PV power plants can support native wildflowers and, to a lesser extent, grass species, which once proliferated in the Central Valley.[51,52] In Egypt, PV sited on top of shallow, constructed water bodies and canals may significantly lower the temperature of the water below, reducing evaporation and the need to convert other land for energy development.[47,53,54] Studies at offshore wind farms, such as the Princess Amalia Wind Farm off the Dutch coast, seek to assess if siting and construction practices can successfully minimize disturbance to avian, marine, and benthic life.[55–57]

Within the United States (US), existing efforts for RE siting such as the wind risk assessment map by the American Bird Conservancy (ABC),[58] the Desert Renewable Energy Conservation Plan (DRECP), and mapping done by the U.S. Fish and Wildlife Service (FWS) provide valuable insights into the landscape of RE siting assessments.[59] ABC's assessment map primarily focuses on bird collision risk with wind turbines, providing a valuable resource for understanding avian vulnerability. Similarly, the DRECP aims to balance RE development with conservation goals in the California desert region. Additionally, the FWS mapping initiative focuses on identifying wildlife and habitat risks associated with land-based wind energy projects. While these efforts contribute to understanding the impacts of RE development on biodiversity currently, our Climate-Smart Siting framework embodies a comprehensive approach that integrates multiple factors beyond just current wildlife impacts. We emphasize the incorporation of EJ considerations, community engagement, and climate change impacts on biodiversity into RE siting decisions. By reviewing existing efforts and identifying gaps and strengths, we refine the framework to aggregate strengths and address identified gaps, ensuring a more holistic and inclusive approach to RE siting assessments. The scale of the problem varies depending on the species, as illustrated by the overlapping territories of endangered species such as the Mohave ground

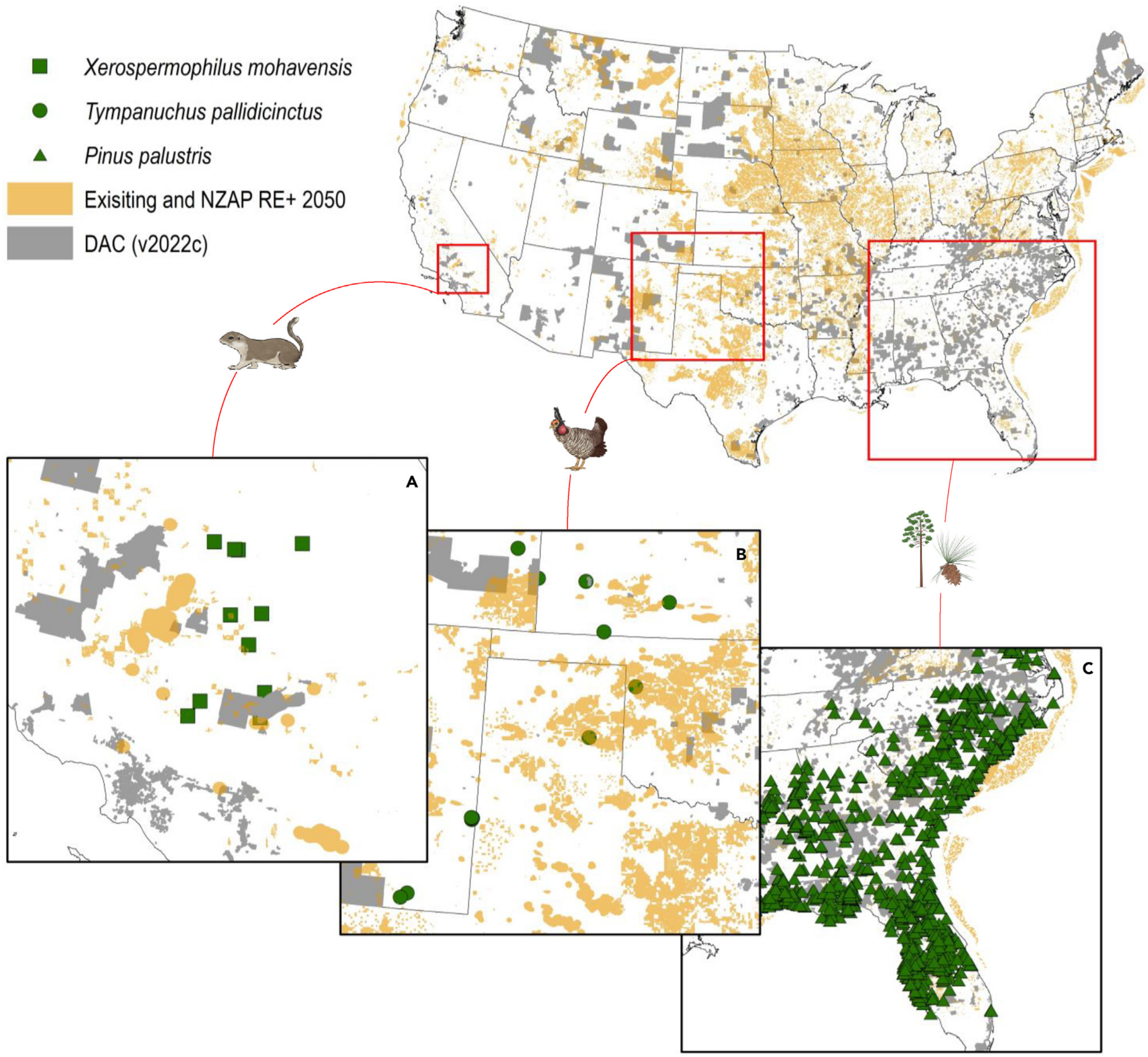

Figure 1. Intersection of biodiversity, renewable energy (RE), and disadvantaged communities

(A) The occurrences of the endangered Mohave ground squirrel (*Xerospermophilus mohavensis*) overlap with existing and NZAP RE+ (Net-Zero America Project 100% Renewable),[60,61] as well as areas populated by disadvantaged communities (DAC).[62]

(B) The occurrences of the lesser prairie chicken (*Tympanuchus pallidicinctus*) intersect with existing renewable energy (RE) sites, along with areas populated by disadvantaged communities.

(C) The occurrences of the longleaf pine (*Pinus palustris*) intersect with existing RE sites, along with regions populated by disadvantaged communities. The national boundaries for United States (US) are downloaded from US Geological Survey.[63]

squirrel (*Xerospermophilus mohavensis*) in California and the lesser prairie chicken (*Tympanuchus pallidicinctus*) in the mid-US, with both existing and projected RE sites by 2050 (Figure 1). These RE sites intersect with areas inhabited by disadvantaged communities, underscoring the complexity of the challenges.

CHALLENGE: THE NEED FOR A HOLISTIC APPROACH

Although awareness of the need to consider the ecological consequences of RE is on the rise, knowledge gaps remain, and regulatory bodies and industry have failed to achieve the majority of previously established Aichi Targets for biodiversity.[64] Hence, the call by the United Nations' Kunming-Montreal Global Biodiversity Framework's new 23 targets for 2030 to achieve a world living "in harmony with nature" by

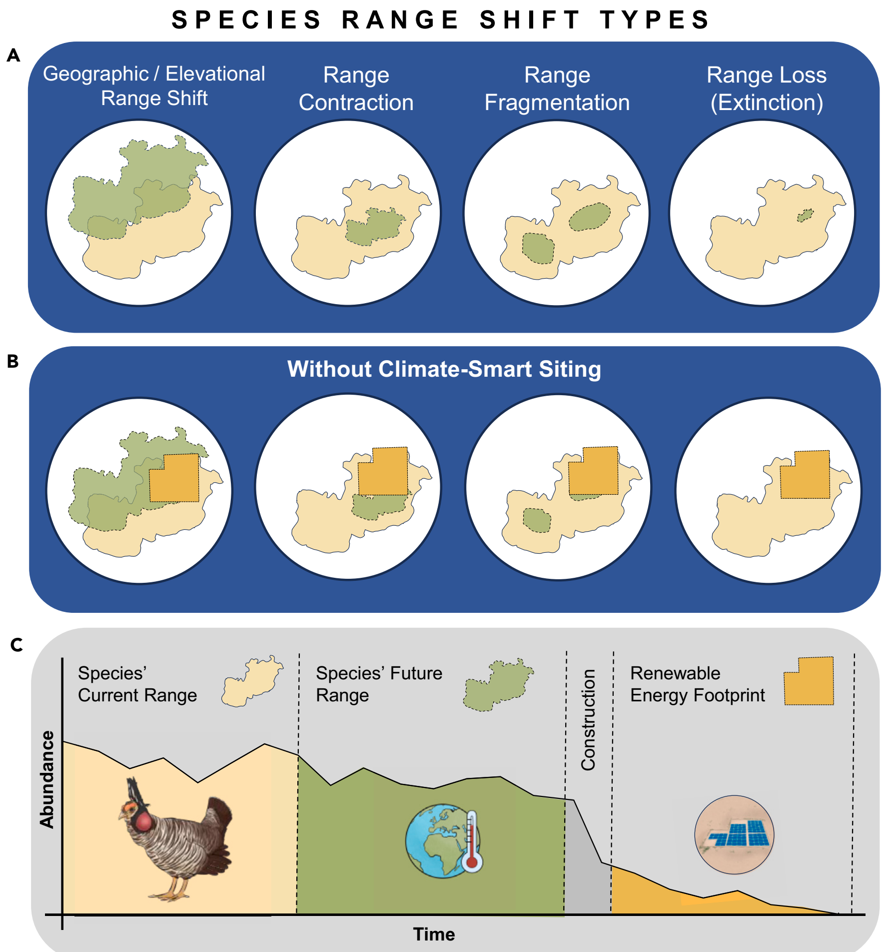

Figure 2. Climate-driven species range shift types and potential outcomes without Climate-Smart Siting

(A) Four primary climate-driven species range shift types: contraction, shifts, fragmentation, and total range loss (extinction).

(B) Hypothetical scenarios depicting RE expansion without "Climate-Smart Siting," resulting in overlap with the future climate refugia (green shaded polygons) of the climate-vulnerable species.

(C) Illustration depicting the decline in abundance of the climate-vulnerable species over time, including potential impacts over the lifespan of a renewable energy project lacking "Climate-Smart Siting".

2050.[65] In a systematic review of ∼160 research papers from the energy and sustainability science literature, Ashraf et al. (2023) found that <15 solar and wind energy studies have documented the impact of climate change on biodiversity.[66] Further, while it is becoming more common to account for present ranges of endangered and ecologically important species in siting decisions, current research, practices, and policies ignore the future, climate-change-driven ranges of critical species[67] (Figure 2).

Although RE development could mitigate climate change for society at large, poor siting decisions and the absence of fair and equitable consideration of communities living in the vicinity can reduce public acceptance and worsen socio-economic disparities.[25,68–70] For example, wind energy development can improve air quality by replacing fossil fuel-based power generation but, depending on the scenario, RE build-outs can actually exacerbate racial and socio-economic disparities because better-off communities enjoy more benefits from cleaner air.[71] While cleaner air resulting from RE development benefits all communities, disparities may arise due to existing socio-economic factors, such as access to healthcare and environmental resources. Further, in the US and Canada, opposition to wind farms was greater in Whiter and wealthier communities, respectively.[72] Disparities in opposition may direct RE development toward poorer communities who lack socio-economic power to advocate for siting concerns related to local air pollution (e.g., dust, soil-bourne diseases) as well as concerns related to loss of local natural capital.[73] Thus, while RE projects contribute to overall air quality improvement, the disparity between communities in experiencing these benefits may widen due to other sources of air pollution disproportionately affecting low-income areas.

In the US, wind energy development associated with renewable portfolio standards in 2014 led to $2.0 billion in health benefits through improved air quality, though only 29% and 32% of these benefits reached racial/ethnic minority and low-income populations.[71] Inequitable siting decisions have also affected cultural resources.[74] For example, the construction of the Blythe concentrating solar power project

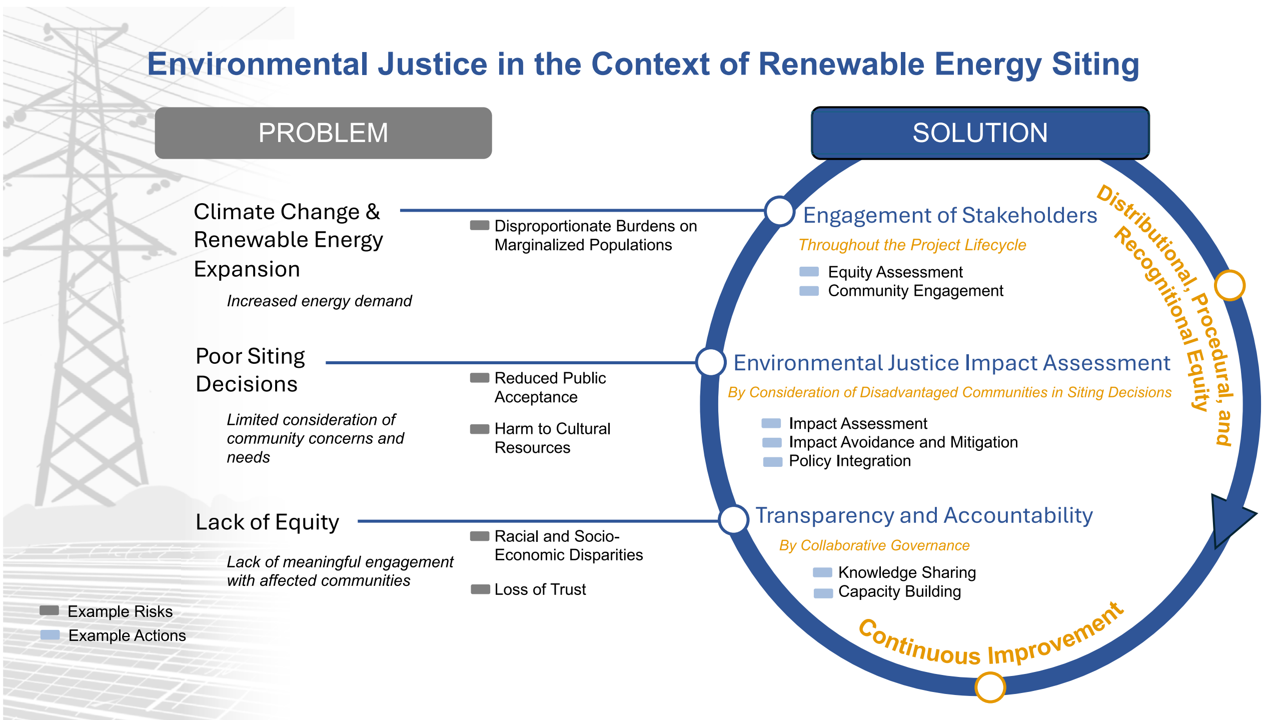

Figure 3. Challenges and proposed solutions related to environmental justice, community engagement, and consultation in the context of renewable energy (RE) siting

Environmental justice-related challenges include disparities in the distribution of environmental burdens on host communities and disadvantaged communities (DACs), insufficient host community involvement in decision-making processes, and a lack of consideration of socio-economic factors (left, "Problem"). Climate-Smart Siting seeks to address these issues through equity assessments, meaningful community engagement, impact assessments, mitigation strategies, policy integration, transparency and accountability measures, collaborative governance structures, capacity-building initiatives, knowledge-sharing mechanisms, and a commitment to continuous improvement. Together, these strategies aim to promote fair and equitable outcomes for all communities affected by RE development, fostering a more inclusive and sustainable approach to the energy transition (right, "Solution").

(California, US) resulted in the bulldozing of two Kokopelli geoglyph sites.[75] Quoted in The Los Angeles Times, a Tribal Elder noted it "disrupted the peace of our ancestors and our relationship with the land."[76] Authentic co-development with Tribal authorities in the early siting stage might have prevented this outcome. Further underscoring the importance of equity in RE siting, new 2021 federal rules in the US require that 40% of investments in clean energy be accrued by disadvantaged communities.[77] The problems encompass disparities in the distribution of environmental burdens, inadequate community involvement in decision-making processes, and a lack of consideration for socio-economic factors. These challenges underscore the need to address equity concerns and ensure that the benefits and burdens of RE development are fairly distributed among all communities (Figure 3).

Effective shaping of industry and policy will require that siting decisions be made with a holistic, multi-faceted approach, rather than piecemeal decisions driven by analysis of energy resources, land availability, and biodiversity constraints. An effective approach to siting would (1) consider complex tradeoffs between productivity, cost, ecology, and human communities; (2) incorporate accurate predictions of how each RE installation will affect its surroundings; (3) protect not only the current ranges and migratory pathways of critical species but also their future distributions; (4) address racial and socioeconomic disparities; (5) be based in good decision-making practices; and (6) drive the development of market-based incentives for the industry to make environmentally and ethically responsible decisions. The shift toward a more comprehensive approach to RE siting is a pressing challenge that requires immediate attention, with research, policy, and industry collaboration playing crucial roles in shaping the future of RE development.

SOLUTION: THE CLIMATE-SMART SITING FRAMEWORK

Here, we describe a framework for well-informed, thoughtful design and siting of RE systems. The framework is loosely modeled on efforts in other sectors in which holistic, Climate-Smart frameworks have been developed, such as infrastructure,[79] agriculture,[80] forestry,[81] and spatial planning.[82] These frameworks help create sustainable, future-proof solutions that reduce environmental impact, enhance resource efficiency, and contribute to the overall well-being of human society, including nature that supports it.

The siting framework has four components (*4Cs*) (Figure 4). These are (i) **C**ommunities: public engagement, collaboration, and consultation to support EJ, which includes authentic consultation with host communities, especially Indigenous peoples and those coping with

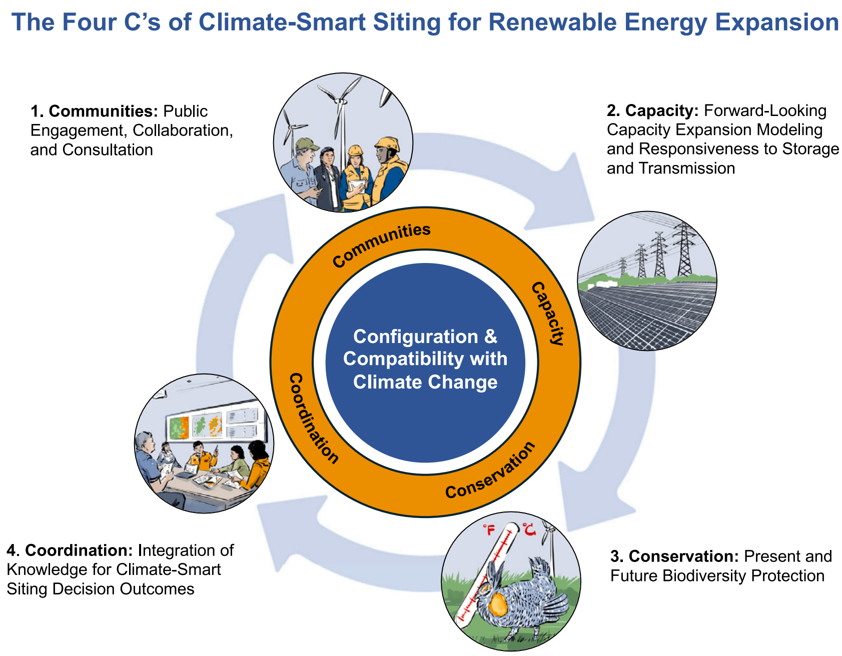

Figure 4. Major components of the Climate-Smart Siting framework

A Climate-Smart Siting framework emphasizes communities, capacity, conservation, and coordination while making renewable energy (RE) siting decisions. The Climate-Smart Siting Framework comprises the 4 Cs integrated throughout the life cycle of RE projects. (Modified from the 3 Cs of Landmark Solar Agreement by Stanford Woods Institute for Environment).[78]

socio-economic disadvantages; (ii) Capacity: forward-looking capacity expansion modeling and responsiveness to storage and transmission, i.e., mapping current and future areas suitable for RE expansion in terms of appropriate energy resources, economic, and geographic constraints, including land-use and land-cover change, and critical infrastructure (e.g., transmission, substations), but also in terms of socio-economic conditions and environmental constraints; (iii) Conservation: present and future biodiversity protection, i.e., comparison of those maps to the current and future ranges of target species (including the expansion of conservation areas); and (iv) Coordination: integration of knowledge for Climate-Smart objectives throughout the first three components that balance the needs for energy production, biodiversity conservation, and the health and economies of human communities. The integration of information can also guide policymakers in the regulation of the RE industry, including market-based incentives for developers to adopt such a framework and follow informed best practices. Additionally, a Climate-Smart Siting framework can inform decision support policy recommendations to ensure that future RE development pathways consider socio-environmental factors and promote conservation goals while achieving climate change targets (detailed steps (Figure 5)). By leveraging legislative, regulatory, and market-based strategies, the Climate-Smart Siting process could facilitate a just transition to a low-carbon future.

Communities (C1): Public engagement, collaboration, and consultation

Climate-Smart Siting emphasizes the engagement of a wide range of stakeholders and rightsholders in decision-making, including energy developers, financiers, and operators, federal and state agencies, Tribes and Indigenous groups, residents of nearby communities, universities and other research entities, environmental groups, non-governmental organizations, other landowners, and *trans*-border and multinational entities (e.g., the Mexican-US-Canadian Commission on Environmental Cooperation). Engagement can commence in both formal and informal settings and ideally will progress with authenticity, ensuring that considerations of attitudes, values, and EJ issues of the host and impacted communities remain paramount throughout the process. This includes involving residents in decision-making processes, seeking their input on project plans, and addressing their concerns and priorities. By actively involving communities in the siting process, RE developers can build trust, reduce conflicts, and ensure that projects align with community needs and preferences. Conducting equity assessments can help identify communities that may be disproportionately impacted by RE projects. Stakeholders and rightsholders outside the RE development industry can participate in mapping, community consultation, and engagement workshops that bring real and perceived possible impacts on host communities to light. Expectations for all stakeholders may be established early and in writing, including compensation for time and resources to facilitate participation and a plan to ensure an appropriate number and nature of liaisons between interested parties. Considering the concerns and preferences of as many stakeholders as possible fosters social acceptance and reduces conflicts and unintended harmful consequences. Following the design, development, and initial operation of new RE installations, documentation of the resulting consequences for relationships between stakeholders, socio-economics, and cultural values is very important. These data

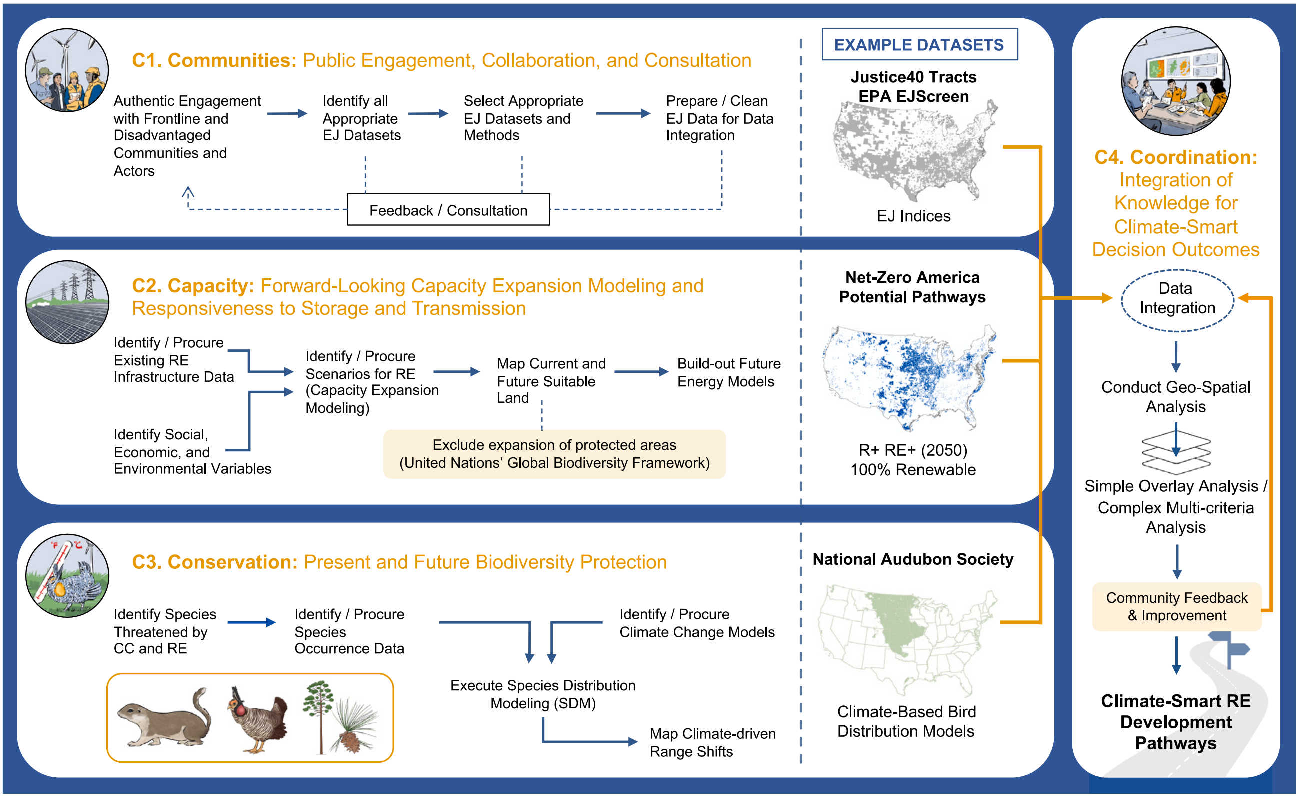

Figure 5. The Climate-Smart Siting framework addresses conflicts between biodiversity and renewable energy (RE) siting by offering an integrated workflow leading to spatiotemporally explicit solutions supporting the expansion of RE, shifts in species ranges, and the 23 targets embodied in the United Nations' Kunming-Montreal Global Biodiversity Framework

This example Climate-Smart Siting workflow highlights ecological, social, and economic research areas aimed at mitigating climate change while simultaneously addressing the challenges of RE siting and biodiversity conservation in the context of climate change. It consists of the following steps: C1. Assessing EJ implications across the framework's "four Cs." C2. Planning RE expansion by integrating forward-looking capacity expansion models with geographic methods to produce spatially-explicit buildout scenarios. Such buildout scenarios are poised to accommodate plans for protected area expansion as the United Nations' Kunming-Montreal Global Biodiversity Framework targets are operationalized. C3. Developing maps of climate-change (CC)-driven species range shifts. C4. Integration of criteria to achieve "Climate-smart siting" decision outcomes (Example Datasets: Justice40 Tracts,[83] Net-Zero America Project Potential Pathways,[60] Audubon's Climate Based Bird Distribution Models[84]).

and the lessons learned can then inform decisions, such that RE siting decisions will continue to improve in terms of maximal benefits and minimal harm.[85] Incorporating equity into RE projects involves identifying factors contributing to inequity, strengthening institutional and cultural elements to empower communities, collaboratively developing adaptive and inclusive governance and policy systems, and assessing metrics to monitor performance and progress.[86]

Spatially-explicit data on EJ (e.g., data on environment, socio-economics, access to opportunities, and physical health risks of disadvantaged communities) are more abundant than ever before globally[83,87,88] and can play a crucial role in guiding decisions regarding community involvement and engagement in various initiatives during RE projects. By analyzing EJ data,[62] decision-makers can identify communities that bear a disproportionate burden of environmental hazards and socio-economic disparities, thus highlighting the need for targeted mitigation and engagement efforts. Appropriate interpretation of EJ data enables stakeholders to prioritize communities most impacted by RE development and tailor mitigation and engagement strategies to address their specific concerns and needs effectively. Moreover, EJ data can inform decision-makers about the historical context of environmental injustices, and empower them to design equitable and inclusive engagement approaches that foster meaningful participation and collaboration with affected communities.

Ensuring a just transition to RE presents a multifaceted challenge, as RE projects represent potential economic benefits through increased property taxes and job opportunities, while also imposing real and perceived concerns related to visual impacts, industrialization of rural landscapes, and impacts on wildlife. The nuanced nature of community perspectives underscores the difficulty in making generalizations about desires or aversions toward RE initiatives. Navigating these concerns requires careful consideration of the broader socio-economic context in which they exist.[86] Universities are particularly poised in assisting in this process owing to expertise in EJ, community development, collaborative problem-solving, and multi-disciplinary experts (Figure 3).[89]

Capacity (C2): Forward-looking capacity expansion modeling and responsiveness to storage and transmission

Energy system models, specifically capacity expansion models (CEM), are a technological innovation on par with solar energy itself, but resulting findings lacked geographic specificity until recently.[90] Capacity expansion models are critical for an RE transition as they optimize the design and operation of power systems where RE contributes increasingly more power to the grid over time, balancing trade-offs among costs, system reliability, and carbon emissions.[91] Alongside the development of CEMs were transformative methodologies emerging from the discipline of geography that sought to identify areas suitable (and unsuitable) for future RE expansion at a high resolution. Such analyses often utilized satellite-based imagery and multiple criteria, including mapping areas according to solar irradiance resources, proximity to existing facilities (e.g., substations, transmission), and land availability, typically aiming to achieve favorable costs.

A step forward occurred as studies integrated outputs from CEMs with the multi-criteria geographic approaches employed in mapping RE potential (Figure 5 (ii)). For example, Wu et al. (2020) integrated the CEM RESOLVE with a four-tiered environmental compatibility matrix for 11 western US states to identify spatially-explicit buildout scenarios for wind, solar, and geothermal.[92]

Nonetheless, approaches to socio-environmental considerations in RE siting and CEMs continue to evolve, albeit often independently (but see Delafield et al., 2023[32]). Forward-looking CEMs may integrate multi-sector, long-duration energy storage,[91,93] a diversity of wind and solar energy sources, impacts of climate change on generation reliability over time (e.g., reduced flexible hydropower), hourly temporal resolutions, and multi-nodal transmission, including impacts from losses.[93] For example, Staadecker et al. (2023) use the CEM SWITCH to model how grid factors (including disallowing transmission expansion) drive long-duration energy storage outcomes across a 50-zone transmission network (>125 transmission zones) and 8,000 recipient sites for wind and solar energy development, the largest number for the US to date.[93] Importantly, they found that increased storage capacity through mandates up to 20 TWh decreases the need for transmission expansion, an often overlooked component of energy-driven land transformation that can reduce biodiversity and that is also typically perceived by local residents as negative.[94]

Despite their promise for the Climate-Smart Siting approach, existing CEMs emphasize centralized, investor-owned energy regimes (versus distributed options integrated within the built environment that spare land for conservation[95]); remain difficult to apply at the scale that planning and permitting commonly occur (i.e., local); are scarce outside the US[96,97]; and do not often consider appropriate ecological, socio-economic, and cultural factors that support a just transition.[32] Instead, forward-looking CEM outputs can be overlaid with the advanced multi-criteria analysis and forecasting routines (described in the following section) that appropriately integrate ecological, socio-economic, and cultural factors supporting a just transition across space and time. Importantly, this includes the consideration of current and anticipated future ranges of species requiring conservation attention, the expansion of conservation areas essential for realizing the United Nations' Kunming-Montreal Global Biodiversity Framework targets, including 30x30,[34,98] and how these factors intersect with environmentally disadvantaged communities.

Conservation (C3): Present and future biodiversity protection

Conservation of endangered, ecologically, or culturally important species requires the identification of those species, mapping of their geographic distributions, and consideration of the impact of RE on them during the entire life cycle of an installation. Species' distributions are not static — they can shift, fragment, shrink, or expand in time in response to climate change and changes in land cover and use. Thus, a sufficiently "smart" siting framework not only accounts for potential conflicts between species in the present but also in the future as ranges change (Figure 2). A key component of Climate-Smart Siting is the mapping of species' contemporary and potential future distributions.

Mapping of distributions, present and future, can be accomplished using species distribution modeling. Depending on data availability, climatically suitable habitat can be estimated by mechanistic models that account for physiological tolerances, resource use, habitat availability, demography, and genetics,[99–102] to correlative models that employ occurrence data obtained from museum and herbarium specimens, community science databases, and planned surveys to evaluate the kinds of environmental conditions favorable to a species[103] (Figure 5 (iii)). These models can then be used to map present-day and potential future ranges under future climate and land-use scenarios.[104,105] As species distribution models have become more sophisticated, they have come to yield actionable predictions for guiding conservation planning.[106]

When projected to future climate scenarios, models can identify shifts in the location of climatically suitable habitats, but the inhabitation of these areas requires a species to be able to disperse to them. Accounting for dispersal in these models remains an area of active research[107] and often requires underlying knowledge of dispersal capacities. Whether dispersal is natural or facilitated by humans, climatically areas to which a species successfully moves must also have a habitat that can support the species for new populations to establish. Thus, areas with current and potential future habitats must be preserved, perhaps as part of mitigation banking, to ensure species have areas to which to migrate.

Coordination (C4): Integration of knowledge for Climate-Smart decision outcomes

Decision support tools

Decision support tools that integrate spatial data, models, and visualization techniques can be used to achieve Climate-Smart Siting. These tools enable stakeholders and rightsholders to evaluate potential RE sites interactively, visualize the impacts of different criteria, and make informed decisions based on the framework's outcomes. Climate-Smart Siting enables decision pathways for future RE expansion through a range of spatial analyses, from basic overlays of RE expansion maps with species distribution data to more complex multi-criteria analyses (MCA).[108] Using multi-criteria decision-making methods such as the analytic hierarchy process or multi-objective optimization, an application

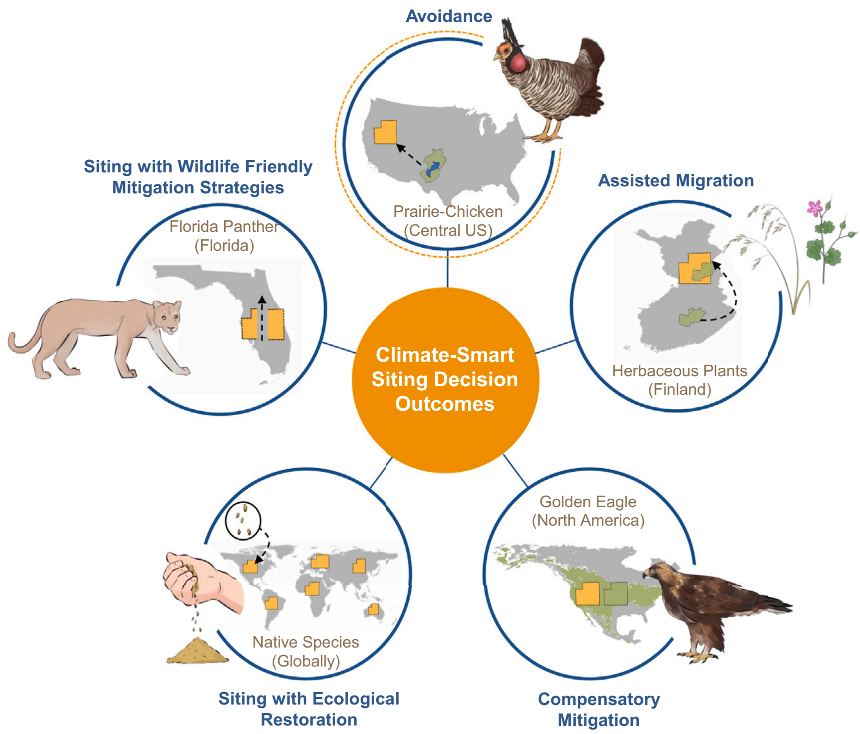

Figure 6. Examples of Climate-Smart Siting Decision Outcomes

Decision outcomes may include avoidance of the proposed site entirely, planned assisted migration for candidate species of interest, compensatory mitigation (e.g., establishment of mitigation banks), siting with ecological restoration, and siting with wildlife-friendly mitigation strategies tailored to reduce impacts and/or improve outcomes for target species.

of the Climate-Smart Siting framework emphasizes the evaluation and prioritization of potential sites based on various criteria concurrently. MCA considers technical, economic, and socio-ecological factors, including EJ and biodiversity conservation, to balance climate change goals and conservation needs. The framework proposes the generation of maps with intermediate data created along the framework workflow (Figure 2), such as current and future species ranges, Climate-Smart Siting scenarios, and EJ information, which can be shared with partners for feedback, aligning with EJ and transparent decision-making best practices and informing the final decision outcomes.[85,109] To enhance the framework's effectiveness, we can leverage available opportunities and tools to maximize benefits and minimize risks.

Climate-Smart Siting decision outcome types

Climate-Smart Siting uses results from these analyses to anticipate and, ultimately, select preferred decision outcomes. These outcomes encompass various strategies that aim to mitigate adverse impacts and enhance benefits associated with RE projects. For example, an **avoidance** outcome would proscribe development in areas impacting current and/or future critical habitat and migration routes of a species (Figure 6). Another outcome could include identifying RE development areas for **assisted migration**,[110] the human-assisted movement of species in response to climate change. For example, the construction of solar energy development in southern Finland – a region anticipated to shift from a climate with cold summers to one with mild warm summers by as early as 2070 – may include the seeding of a native, herbaceous mix of plant species that are threatened (in one or more southerly European country) and have poor dispersal ability (e.g., *Bromus benekenii*, *Carex pulicaris*, *Geranium lucidum*, *Sisymbrium supinum*).[111] A **compensatory mitigation** outcome would require investment in conservation actions in other parts of a species' range to achieve no net adverse impacts and/or loss of resources.[112,113] An example of compensatory mitigation is the preservation into perpetuity of habitat (''mitigation banking'') that is close in proximity and/or likeness to the RE site where habitat is lost. Offsite habitat-based compensatory measures may provide the best offsets for incidental bird and bat mortality (i.e., ''take'') by wind energy facilities.[114] Under climate change, offsite compensatory mitigation for RE may be uniquely prioritized for land representing both present and future species ranges.[115] RE installations may also afford opportunities for **ecological restoration**,[12,46,116] which could be third-party verified to ensure minimum, regional standards are met. Across the footprint of a solar energy project during an appropriate time of the construction phase (e.g., after poles or pylons are installed) and season, a developer may work with local restoration practitioners to establish native, low-stature plant communities, which pose no risks for panel shading and may simultaneously increase soil carbon and significantly reduce risk of fire compared to weedy, non-native species.[117–119] Field margins and hedgerows of taller native plants can also be established along the perimeter, inside and outside the site's fence line, enhancing carbon sequestration.[120,121] **Wildlife-friendly mitigation strategies** constitute on-site mitigation methods and technologies that reduce adverse impacts and/or provide benefits to biodiversity, including their range shifts. For example, chain-link fencing surrounding RE sites and new roads for access can block the movement of larger-bodied animals, such as the Florida panther (*Puma concolor coryi*), through landscapes that may need to be passable under future climate scenarios.[122] An on-site mitigation strategy may be to include custom welded or cut fence holes for RE sited on habitat comprising present and future panther corridors.[8,123,124] Fences may also be split such that a single RE site is divided into independently fenced areas, conferring a wildlife corridor between them. As roughly 70% of species have insufficient representation in protected areas globally,[125] safeguarding the passage of animal movement safely through RE-altered landscape is a necessary component of Climate-Smart Siting.[8]

These outcomes can be classified within the mitigation hierarchy, depending on specific needs and priorities.[126] By categorizing these outcomes within the mitigation hierarchy, decision-makers can prioritize actions based on their effectiveness in minimizing environmental harm and promoting conservation goals.

Climate-Smart Siting policy and market-based levers

Policy and market-based changes will be necessary for realizing the outcomes of a future-focused Climate-Smart Siting framework. For example, in the US, current regulatory and judicial interpretations allow (but do not require) impacts of climate change to be part of the decision on whether to list a species under the US Endangered Species Act (ESA). There is legal contention over whether potential future habitat would qualify for present-day consideration.[127] Similarly, anticipating range shifts in processes guided by, for example, the US National Environmental Policy Act, are also disallowed. Across many nations, state- and local-level regulations are often similarly hobbled by future-oriented accounting.[128] However, market-based certifications and guidance to enhance conservation-based outcomes in tandem with RE expansion are increasing. For example, a decision-support tool for enhancing ecosystem services on "solar parks" exists in the UK,[129,130] and a third-party audited Power-in-Pollinators certification program[131] in the US seeks to protect and restore pollinator habitat across electric utility-owned land assets. Overall, achieving the promise of Climate-Smart Siting will likely require a combination of legislative and regulatory policy revisions supported by innovative market-based strategies. In some places, meeting RE growth targets will simply be impossible without the holistic consideration of environmental consequences.

Integrating EJ considerations into RE siting may be facilitated through policy to promote Climate-Smart Siting. This may involve implementing measures to incentivize partnerships between RE developers and community-led RE projects in disadvantaged areas, the support of community-led RE policy incentives, EJ guidelines and protocols for RE development specific to unique, localized juristictions, and requests for the probative documentation of EJ-related impacts and outcomes in government-led finance applications (e.g., grants, loans) for RE projects. By embedding EJ principles into policy frameworks, governments can create an enabling environment for equitable RE development. Broadly, policy has demonstrated gains in addressing EJ and social issues through the improvement of participation (i.e., procedural justice), which RE siting decisions would benefit from, but this is but one facet of EJ and empirical studies on effective, appropriate EJ policy are limited.[132] Despite a relative lack of precedent, incorporating EJ considerations into policies and incentives impacting RE siting, measuring and reporting their efficacy can contribute to a broader scientific consensus and knowledge toward equitable benefits for all host communities of RE projects while minimizing adverse impacts on vulnerable populations.

CLIMATE-SMART SITING CASE STUDY: THREE VULNERABLE SPECIES IN THE US

We demonstrate the need for a Climate-Smart Siting framework by showing how species ranges and their response to climate change may overlap with RE expansion. Specifically, we use a case study focused on three climate-vulnerable species of the US: the Mohave ground squirrel[133] (candidate species for listing as threatened under the California ESA (ESA) and Near Threatened in the International Union for Conservation of Nature (IUCN) Red List), the lesser prairie chicken[134] (listed as threatened under the US ESA and Vulnerable under the Red List) and the longleaf pine[135] (*Pinus palustris*; listed as Endangered species under the Red List; Figure 3). These are but three of many species potentially affected by RE development in the different regions of the US, but they highlight the potential vulnerability of species, which any robust Climate-Smart exercise should consider.

Based on climatically suitable habitat projections for the period 2041–2070, considering moderate greenhouse gas emission pathways (Shared Socio-economic Pathways (SSP) 245), we found the Mohave ground squirrel is projected to experience a notable reduction in suitable habitat by 73% by 2041–2070 compared to the present (Figures 7A and 7D) (**Supplemental Information 1.0** for detailed methods). In addition to the challenges posed by climate change, the core habitat of the Mohave ground squirrel, primarily in California, is also anticipated to be a focal point for RE development under the Net-Zero America Project (NZAP) E + RE + Scenario 5, which aims for 100% renewable development by 2050. This dual pressure from climate change and RE development is likely to pose a significant threat to the Mohave ground squirrel population. Currently, the overlap area between the Mohave ground squirrel suitable habitat, and existing RE sites (both wind and solar) covers 4.2% of the suitable current habitat. However, this overlap is projected to increase to 7.5% in the future.

The combined intersection of all three Mohave ground squirrel habitats, existing RE sites, and disadvantaged communities cover 0.4% of the current suitable habitat. However, this overlap is projected to increase to 0.9% of current suitable habitat in the future (assuming no change in the distribution of disadvantaged communities[62] into the future).

Similarly, the lesser prairie chicken faces a significant challenge, as its projected suitable habitat declines by 82.4% by the 2050s due to climate change (Figures 7B and 7E). Consequently, further RE development within the remaining suitable habitat could potentially lead to a disproportionately adverse effect on the species.[134,136] Presently, the overlapping region among the lesser prairie chicken habitat, existing RE installations (comprising both wind and solar), and disadvantaged communities constitute 3.5% of the current habitat, increasing to 12.1%.

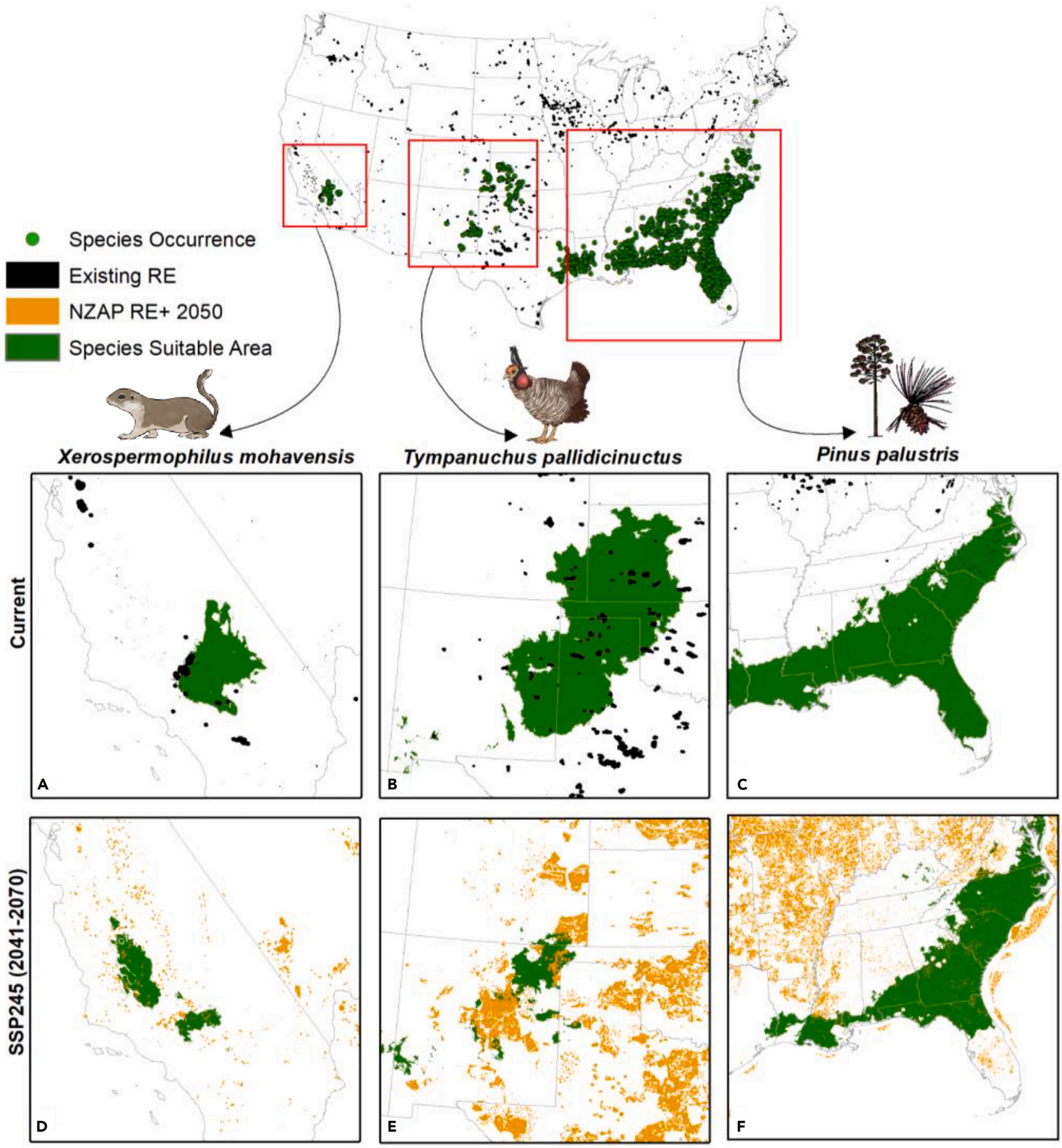

Figure 7. Current and future climatically suitable habitat of Mohave ground squirrel (*Xerospermophilus mohavensis*), lesser prairie chicken (*Tymanuchus pallidicinuctus*) and longleaf pine (*Pinus palustris*) highlighting the areas of overlap with renewable energy (RE)

We predicted the current and potential future climatically suitable habitat for three vulnerable species inhabiting different parts of the United States intersected with potential RE development.

(A–C) Map of the current potential distribution of three species with overlap of existing RE development, including wind and solar energy installations.

(D–F) Results of climatically suitable habitat with future (2041–2070) climate change under the medium pathway of greenhouse gas emissions (Shared Socio-economic Pathways (SSP) 245) intersecting with Net Zero America Project (NZAP) RE+ (100% renewable) 2050 maps.

The longleaf pine ecosystem encompasses a diverse range of natural communities characterized by the presence of its iconic species and a rich variety of understory grasses and herbs. This ecosystem historically extended over the majority of uplands throughout the southeastern coastal plain, spanning from Virginia to Texas, with additional stands located further inland.[137] Our species distribution analysis indicates that in relation to the species' current suitable habitat, there will be a 37.7% reduction in suitable habitat in the future (2041–2070) (Figures 7C and 3F). Presently, 0.02% of this area overlaps with existing RE installations, increasing to 2.4% in the future. This expansion of overlap arises from the shrinking suitable habitat for the species in the future.

These case studies of the Mohave ground squirrel, lesser prairie chicken, and longleaf Pine ecosystem reveal the potential challenges and opportunities associated with RE development in the context of climate change and species conservation and the need for a Climate-Smart Siting framework to ensure each species' persistence is guarded.

The first step in the Climate-Smart Siting framework, Community Engagement and Consultation (C1), is crucial for ensuring equitable decision-making in RE siting. The case of the Mohave ground squirrel in California underscores the importance of community engagement as the Central Valley hosts a diverse agricultural community already impacted by numerous environmental challenges–water scarcity, climate-exacerbated health risks on Latino farmworkers and disadvantaged communities[138,139]–requiring a delicate balance between economic livelihoods and species' protection.

For Forward-Looking Capacity Expansion Modeling (C2), we use secondary data from NZAP in the overlay analysis for three species to identify current and future areas suitable for RE expansion as these species' ranges shift. We identify a pressing need for advancements in capacity expansion modeling globally at different scales, to map current and future areas suitable for RE expansion in ways that also allow a diversity of storage, transmission, and land-sparing options that may safeguard species range shifts and optimize other environmental outcomes.[138–140] This approach enables the identification of areas where and how different types of RE development may overlap with critical habitats, potentially leading to conflicts. For instance, projections for the Mohave ground squirrel indicate a substantial reduction in suitable habitat due to climate change, exacerbated by the expansion of RE development. This highlights the importance of thorough planning and the implementation of mitigation measures to minimize adverse impacts on biodiversity and ecosystems.

Conservation and Biodiversity Protection (C3) necessitates the integration of conservation efforts into RE siting decisions to mitigate potential adverse impacts on vulnerable species and ecosystems. Through mapping climatically suitable habitats and identifying migration possibilities, critical habitats can be prioritized for habitat restoration initiatives. For instance, in the case of the lesser prairie chicken, conservation banks to offset potential impacts from wind energy may prioritize currently suitable habitats but ignore habitats where future ranges are anticipated, as well as the corridors that link them together. Given that less than 40,000 individuals remain, avian ecologists warn that a lack of habitat connectivity and guidance for wind siting is needed to avoid extinction.[141]

Coordination and integration (C4) demand the utilization of decision support tools and policy integration to harmonize the requirements of RE production, biodiversity conservation, and community well-being. Through the prioritization of areas with minimal environmental impact and the maximization of benefits for both humans and nature, decision-makers can attain more sustainable outcomes. The expansion of RE development within the longleaf Pine ecosystem underscores the imperative for concerted efforts. Restoration efforts of longleaf Pine have a history marked by collaboration; in 2009, America's longleaf Restoration Initiative commenced, comprised of 22 governmental agencies and implemented, in part, by local teams. Drawing from their success, the same collaborative inertia and best practices could be applied toward coordination to balance the need for "future-proof" longleaf pine habitat and RE development, in a holistic manner that considers ecological, socioeconomic, and cultural factors to guide equitable and sustainable RE transition for the US southeast.[142]

Overall, the application of the Climate-Smart Siting framework to these case studies demonstrates the importance of holistic approaches that consider EJ, climate change, and conservation goals in RE siting decisions. By incorporating stakeholder engagement, advanced modeling techniques, and conservation strategies, decision-makers can navigate the complex challenges of RE development while promoting sustainable outcomes for both people and nature.

OUTLOOK

Meeting the world's climate goals will likely require an immediate, massive expansion of RE systems. In the face of the interconnected challenges presented by climate change and biodiversity loss, prioritizing RE development with the greatest ecological advantages can minimize negative impacts while addressing energy needs, both in the present and for the future. The Climate-Smart Siting framework stands as a proactive approach to anticipate and mitigate the current and prospective impacts of RE siting scenarios. This is especially critical for safeguarding vulnerable populations and the human communities that coexist with them, all the while working toward a harmonized objective of climate mitigation, biodiversity conservation, and environmental justice. Active engagement with local host communities and stakeholders in the planning and development of RE projects is essential. Active engagement with local host communities and stake- and rightsholders in the planning development of RE projects can ensure that their perspectives and concerns are thoroughly considered.We propose a collaborative and inclusive approach to RE expansion that not only bolsters environmental protection but also contributes to the well-being of these communities while reducing the impacts of the climate change crisis.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.110666.

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AUTHOR CONTRIBUTIONS

All authors conceived the idea for this article. U.A. collected the data and conducted the analysis. U.A. and R.R.H. developed the figures and article text draft. R.R.H., T.L.M., and A.B.S. edited the article text and figures.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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