Model the Hidden Cost of China's 2060 Carbon Neutrality: Potential Biodiversity Impacts of Wind and Solar Energy Expansion

By

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Executive Summary

Renewable energy development is considered a key solution to mitigate climate change, but it can also have potential negative impacts on biodiversity. As China seeks to expand its renewable energy facilities to meet its ambitious "2060 Carbon Neutrality" goals, it is important to assess the potential conflicts between renewable energy development and biodiversity conservation. This master project assessed the potential impacts of large-scale wind and solar energy expansion on biodiversity conservation in China, in light of the country's ambitious "2060 Carbon Neutrality" goals. Using suitability analysis and biodiversity mapping, the study identified areas of potential conflict between renewable energy development and biodiversity conservation. The results showed that while the expansion of renewables tended not to encroach on areas of high priority for biodiversity conservation, certain regions without the strictest protection were still at risk, as illustrated by case studies of the Qilianshan-Qinghaihu Region and Hainan Province.

The study highlights the need for careful planning and management to ensure that renewable energy development is sustainable and does not come at the cost of biodiversity conservation. The study also emphasizes the importance of considering the spatial scale and resolution of analyses when assessing potential conflicts between renewable energy development and biodiversity conservation. Future research efforts should prioritize the development of high-resolution, comprehensive data on both renewable energy potential and biodiversity value to provide more detailed and accurate information. The study's findings provide important insights for policymakers, conservation practitioners, and renewable energy developers in China and beyond. By taking a proactive, integrated approach to renewable energy and biodiversity planning, we can ensure a sustainable future for both energy production and biodiversity conservation.

Abstract

Large-scale renewable energy deployments, as urgent solutions to mitigate climate change and its consequences, are reshaping the landscape in the human-environment nexus. Albeit promoted as pathways to bend the curve of biodiversity loss through their emission reduction and habitat restoration potential, renewables require significant land assets per unit energy and could impose high cost to ecosystems, triggering potential conflicts between global climate mitigation and biodiversity conservation. As China expanding its landscape of large-scale wind and solar energy facilities to fulfill its ambitious "2060 Carbon Neutrality" goals, an assessment of the potential areas of such concerns at a high resolution can provide insights for stakeholders to effectively manage biodiversity impacts of renewable power transitions. This project used suitability analysis to identify and predict the potential land use conflict between wind and solar energy expansion and biodiversity conservation in China under the 2060 announced pledge scenario in contrast to the biz-as-usual model of renewables expansion rate. We also quantify the biodiversity impacts of such expansion scenarios by estimating the mean richness and rarity scores, along with ecosystem service values and conflicting zones with Key Biodiversity Areas. Although our results indicated the renewables expansion under China's ambitious goals tend not to encroach a high ratio of prioritized areas for biodiversity, the potential impacts in regions without the strictest protection are still worth investigation, as illustrated in our case studies for the Qilianshan-Qinghaihu Region and Hainan Province. The study provides insights for decision-makers to develop renewable energy facilities while protecting biodiversity and ecosystem services.

Keywords:

renewable energy; carbon neutrality; biodiversity conservation; land use conflict; China

Word Count (*abstract only*): 250

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1. Introduction

Renewable energy sources have emerged as a key component of the global transition to a sustainable energy system, with wind and solar energy gaining increasing attention and investment in recent years as critical technologies for reducing greenhouse gas emissions and mitigating climate change. Global investment in renewable energy is expanding and is unlikely to halt in the next decades. Clean energy investment is predicted to exceed $1.4 trillion by 2022, indicating a considerable increase following several years of lackluster development. It currently accounts for about three-quarters of total energy investment growth and has increased at a 12% annual pace since 2020 (International Energy Agency, 2022). However, the rapid development of wind and solar energy facilities can pose significant land use conflicts and threaten biodiversity conservation, as these facilities require more space than traditional energy sources and may become barriers to biological corridors, drivers of habitat fragmentation, and other impacts (Agha et al., 2020; Hernandez et al., 2015). Therefore, it is crucial to assess the potential conflicts between renewable energy development and biodiversity and identify effective strategies to mitigate them.

In China, wind and solar energy have a massive contribution to the country's efforts to transition to a low-carbon economy. As the world's largest emitter of carbon dioxide, China has made significant progress in expanding its renewable energy capacity in recent years, driven by advancements in technology, policy support, and resource availability. Renewable energy development in China has been expanding rapidly in recent years, with wind and solar power leading the charge as the country seeks to meet ambitious carbon neutrality goals. China's wind and solar power capacity reached a historical high in 2022, with new installations (capacity) exceeding 120 million kilowatts, bringing the total renewable energy capacity to over 1.2 billion kilowatts. Renewable energy accounted for 76.2% of the country's newly installed capacity, making it the main driver of new power installations. Major renewable energy projects made significant progress, including the construction of large wind and solar power bases in desert, Gobi, and other barren areas (National Energy Administration, 2023). This expansion has been driven by a combination of policy support, technological innovation, and economic incentives (International Energy Agency, 2020). At the same time, China's development of renewable energy has made positive contributions to global emission reductions. In 2022, China's renewable energy generation was equivalent to a reduction of about 2.26 billion tons of domestic carbon dioxide (CO_2) emissions, while the export of wind and solar products reduced CO_2 emissions in other countries by about 573 million tons, totaling a reduction of 2.83 billion tons, accounting for 41% of the global carbon reduction from renewable energy during the same period (National Energy Administration, 2023). China has become an active participant and important contributor to global efforts to address climate change.

On the other hand, China is also home to some of the world's most biologically diverse ecosystems, which face significant threats from habitat loss and fragmentation (Xu et al., 2009; Li and Pimm, 2016). Some regions with abundant renewable energy resources are not only restricted or prohibited from development according to China's main functional zone planning, but they are also key areas for ecological and species protection. These areas have important and irreplaceable ecological values, such as biodiversity conservation value, soil and water conservation value, and ecological function value, etc. Previous studies have shown that the construction and operation of centralized wind and photovoltaic power generation projects can potentially have negative impacts on local climate and local ecological functions and species diversity (Miller and Keith, 2018; Matthies et al, 2015; Alam et al, 2016). Considering the 20-30 year operation cycle of wind and photovoltaic power generation, if the construction planning and site selection are inappropriate, it may cause long-term negative impacts on the ecosystem functions and biodiversity. As the expansion of those renewable energy sources often requires large amounts of land, which may lead to potential land-use conflicts with important habitats and ecosystems, ensuring the sustainable and responsible site selection and implementation of renewable energy is critical to minimize these impacts and maintain biodiversity and ecosystem services (Stoms et al., 2013; Allison et al., 2014).

Under the context of ecological civilization in China, to avoid the old path of "pollute first and then treat, destroy first and then protect" regarding the potential negative ecological impacts of renewable energy development, it is essential to coordinate the development of renewable energy with ecological protection during the planning and site selection stages. As a result, there is a growing need to understand the potential impacts of renewable energy development on biodiversity in China to ensure long-term sustainability and integrated development.

A few studies have investigated the trade-offs between renewable energy development and biodiversity conservation, particularly in the context of wind and solar energy expansion. For example, Thaxter et al. (2017) and Choi et al. (2020) assessed the impact of wind energy facilities on bird and bat populations with synthesized evidence from existing data sets and studies. They found that, on average, larger turbine capacity increased collision rates, but deploying a smaller number of large turbines with greater energy output reduced total collision risk per unit energy output. However, the authors also noted that impacts varied widely depending on location, species, and seasonality. Other studies have also highlighted the potential negative impacts of wind and solar energy development on wildlife and their habitats (Jones and Pejchar, 2013; Lovich and Ennen, 2017; Chock et al., 2020).

While there has been a significant amount of research on the impacts of renewable energy development on biodiversity, few studies have used spatial suitability analysis and scenario-based planning to explore these issues in the context of China's ambitious carbon neutrality goals. Recognizing the potential impacts of renewable energy development on biodiversity is crucial to ensure sustainable and responsible implementation. This does not mean that renewable energy and biodiversity are inherently incompatible, but rather that we need to prioritize rational and appropriate planning and policy frameworks to guide and supervise the implementation process.

To address this issue, this study conducts a suitability analysis and predict the potential land areas needed for wind and solar energy expansion to examine the potential conflicts between renewable energy development and biodiversity conservation in China. Using scenario-based planning to explore the impact of ambitious 2060 carbon neutrality goals at both national and provincial scales, the study seeks to provide insights that can inform more effective policymaking and management strategies. By comparing the results at multiple scales and from various land-use filters, the study aims to provide a comprehensive understanding of the trade-offs between renewable energy development and biodiversity conservation in China, and to identify areas where careful planning and management are necessary to mitigate conflicts and promote sustainable development.

2. Materials and Methods

2.1 *Study Area and Analysis Framework*

The study used suitability analysis and grid-by-grid allocation at both national and provincial scales to simulate the site selection process under multiple renewable energy expansion scenarios of China. The purpose of this work is to assess the potential conflicts between renewable energy development and biodiversity conservation in China with spatial perspectives. The spatial overlap is crucial in understanding the potential impacts of energy development on natural ecosystems. In this study, we aim to examine the spatial overlap between wind/solar energy suitability and biodiversity to identify areas where renewable energy development may pose a threat to biodiversity conservation.

To achieve this goal, we assessed the distribution of wind/solar energy suitability and biodiversity across the country and compared the two spatial patterns to determine the degree of overlap, or the potential conflict, by tabulating the overlay region with statistics featuring the estimated impacts on biodiversity metrics (if land use is converted). We explored the richness and range-size rarity of crucial species for conservation. We then developed three scenarios of wind and solar energy expansion, ranging from conservative to aggressive, with three land-use filters restricting potential land development in accordance with technical or policy feasibility, and conducted a resource allocation algorithm using the targets from all three scenarios under each of the three land-use filters, based on the produced suitability score layers. We also compared the overlay between chosen cells for wind or solar energy development by the allocation algorithm and ecological data layers such as ecosystem services values (Xie et al, 2013), area-of-habitat, range-size-rarity, and key biodiversity areas (BirdLife International, 2017). The major steps of this project are shown in Figure 1 and documented in detail in the following sub-sections. A detailed description of data used in this project is listed in *S1. Data Description*.

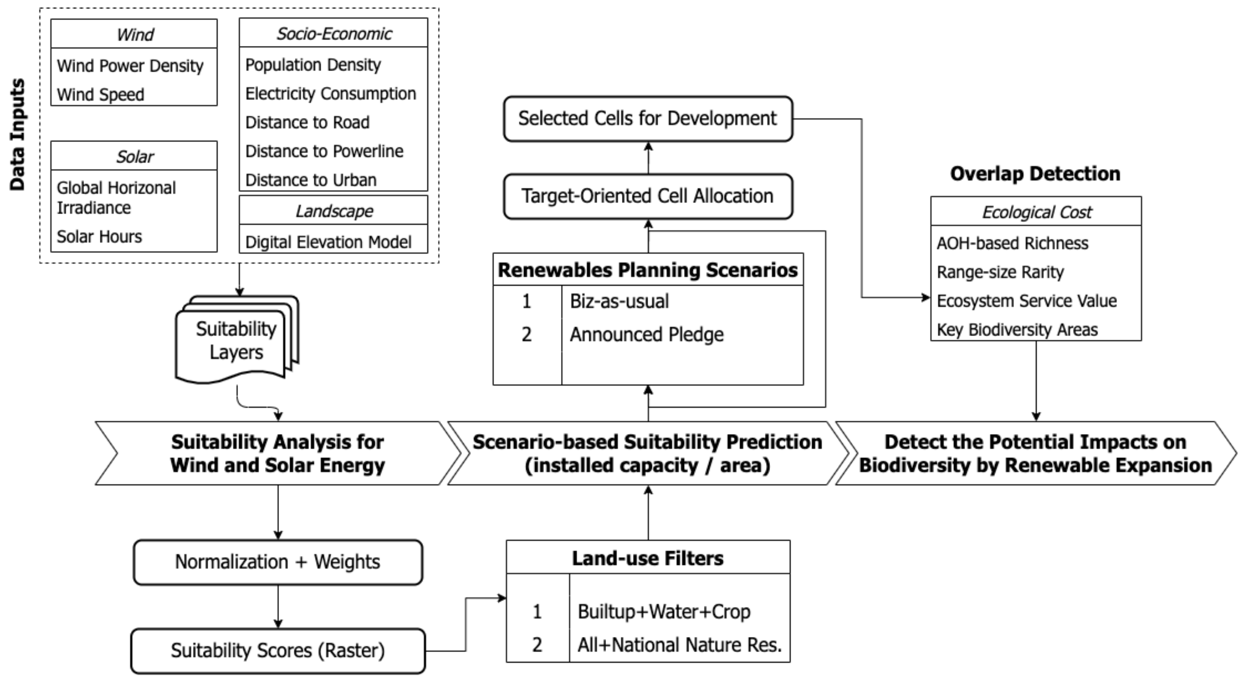


Figure 1 An overview of the analysis framework of the project.

The project defines its scope of analysis within the terrestrial boundary of China, including the 31 continental province-level administrative regions. The study employed the Krasovsky_1940_Albers Projected Coordinate System, a widely used reference system suitable for China (Guo et al., 2022) and measured in meters. We conducted the spatial analysis at the resolution of 250 meters in accordance with the energy data sets retrieved from the Global Wind Atlas and Global Solar Atlas. A potential issue with conducting a spatial analysis at a finer scale for the selection of renewable energy sites is whether the cell size can accommodate the standard requirements of energy projects in terms of their area. With reference to the latest versions of *Land Quota of Photovoltaic Wind Power Station Project* (2012) and the *Land Quota of Photovoltaic Power Station Project* (2022) approved by the P.R.C. Ministry of Natural Resources, we calculated the land use index, *aka*, the area needed per unit amount of installed capacity of wind and solar energy, to fit our fine cell resolution. In terms of either energy sources, our 250-meter land unit area (6.25 hectares) is comparable to the standard land use index of wind energy sites of 400 Mega Watts composing of 3-Kilo-Watt wind turbines, or solar energy sites of 10 Mega

Watts composing of 10-Kilo-Volt photovoltaic facilities at the technical efficiency of 30%. We predicted the potential land use in accordance with the type of facilities.

2.2 *Suitability Analysis*

To locate regions with high suitability for wind or solar development, the study produced maps of wind power density, solar power density, and integrated nine additional variables affecting the site selection of utility-scale wind and solar facilities, including average wind speed, sunshine hours, electricity consumption, population density, distance to urban regions, distance to major roads, distance to electricity transmission infrastructure, and slope (Deveci et al., 2021; Goh et al., 2022; Hise et al., 2022; Rediske et al., 2019; Rediske et al., 2021) to produce the maps for wind and solar energy suitability, respectively. At this stage of analysis, we also conducted a preliminary examination of spatial conflict between renewable energy development and biodiversity protection by visualizing the overlapped regions of the top-quantile areas in terms of wind or solar suitability and the composite of top-quantile biodiversity richness and rarity. We compute the quantiles by the natural-breaks statistics.

The study analyzed the paired combinations of planning scenarios, land use restrictions, and planning approach for renewable energy deployment in China. The three planning scenarios included a business-as-usual scenario and a scenario based on the announced pledge of carbon neutrality. Each scenario featured a particular rate of growth for wind and solar installed capacity in China, and the final targets were set as the accumulated amount in GW ($1GW = 10^6 KW$) up to the year of 2060, taking the 2020 statistics as the basis (both countrywide and provincial-wide), as shown in Table 1.

- Scenario#1: Biz-as-usual Scenario is based on the annually averaged wind and solar installed capacity growth rate between 2021 and 2022 in China.
- Scenario#2: Announced Pledge Scenario is based on IEA's report on China's renewable energy forecast (IEA, 2021)

Table 1 Scenarios and planning targets for wind and solar energy facilities (installed capacity measured in Giga Watts, GW).

Targeting Installed Capacity measured in Giga Watts	**Wind**		**Solar**	
	Annual Growth	**Total (2060)**	**Annual Growth**	**Total (2060)**
Biz-as-usual Scenario	37.63	1796.01	87.41	3715.57
Announced Pledge Scenario	56.10	2516.34	200.80	8137.78

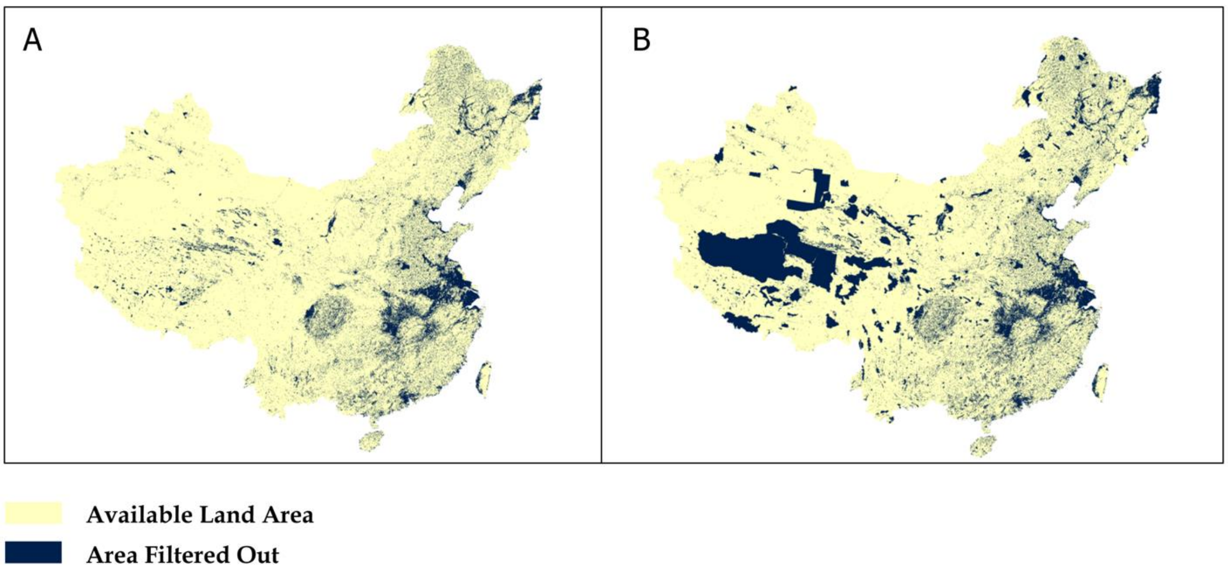


Figure 2 Map of available land areas in China after applying the land-use filters. (A) Mask#1: Filtered out water, built-up, and agriculture land cover, with 77.40% of land areas available. (B) Mask#2: Filtered out water, built-up, agriculture, and land within the National Nature Reserves of China (NNR), with 68.15% of land areas available.

2.3 *Prediction of Land Use Conflict*

When it comes to resource allocation, we set up two land use filters remove different land use types from the available area for potential expansion of wind and solar energy facilities based on current land cover and land use map of China (Xu et al., 2018):

- Filter #1: Removing water, built-up, and farmlands.
- Filter #2: Removing water, built-up, farmlands, and National Nature Reserves.

Using the filtered land areas (错误!未找到引用源。) as the base layers, we employed a scenario-based planning approach at both national and provincial scales. At the national scale, we allocated cells from the top-ranked (in terms of suitability) nationally, while at the provincial scale, we allocated cells within the extent of each province and then merged them into one map at the national scale. Each land unit contains information on both its wind and solar suitability, as well as the maximum installed capacity it can support in ideal conditions. During the allocation process, we accumulated the installed capacity of each selected unit area and stopped at the last needed unit area to achieve the nation's or each province's renewable energy targets under the conditions of the two scenarios and land use filters described above.

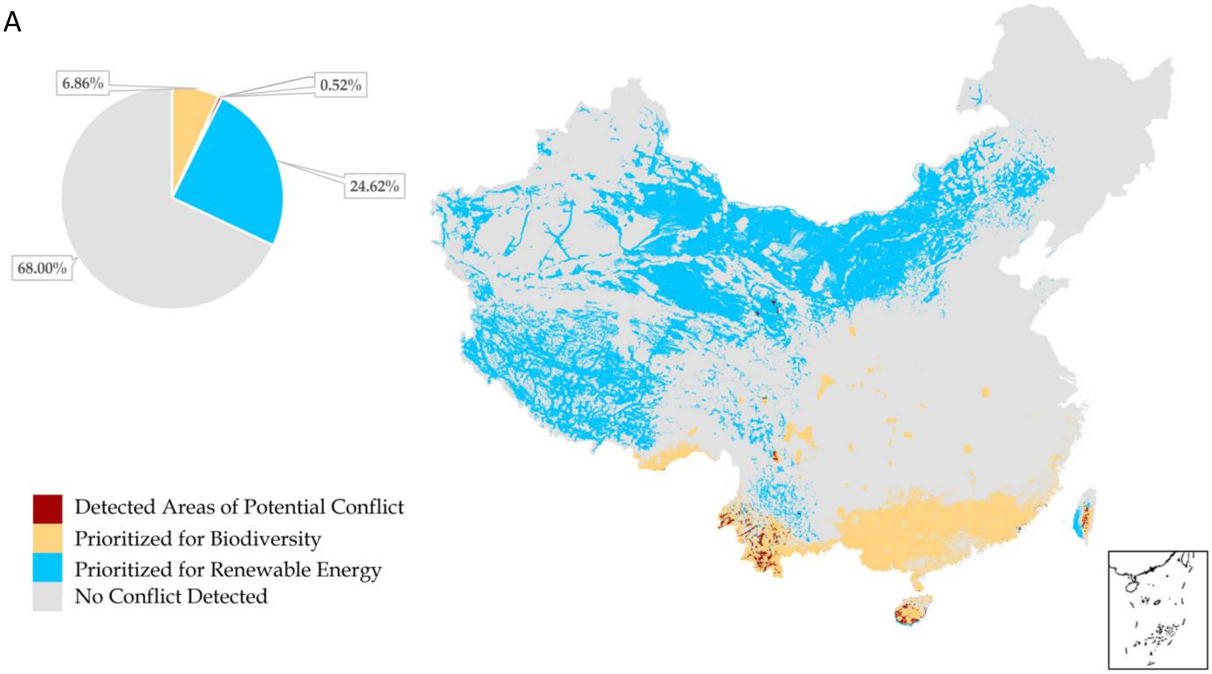
In this study, we aimed to assess the potential biodiversity cost of resource allocation decisions by following a two-step process. Firstly, we identified potential patches through resource allocation simulations. Then, we overlaid these patches with various biodiversity-themed layers, such as ecosystem services value, key biodiversity areas (KBAs), and richness and range-size-rarity for threatened species in China. Our objective was to identify any conflicts between resource allocation decisions and biodiversity conservation goals.

All the analysis were carried out in ArcGIS Pro Model Builder and RStudio.

3. Results

3.1 *Spatial Conflict of Areas Prioritized for Renewable Energy and for Biodiversity*

A



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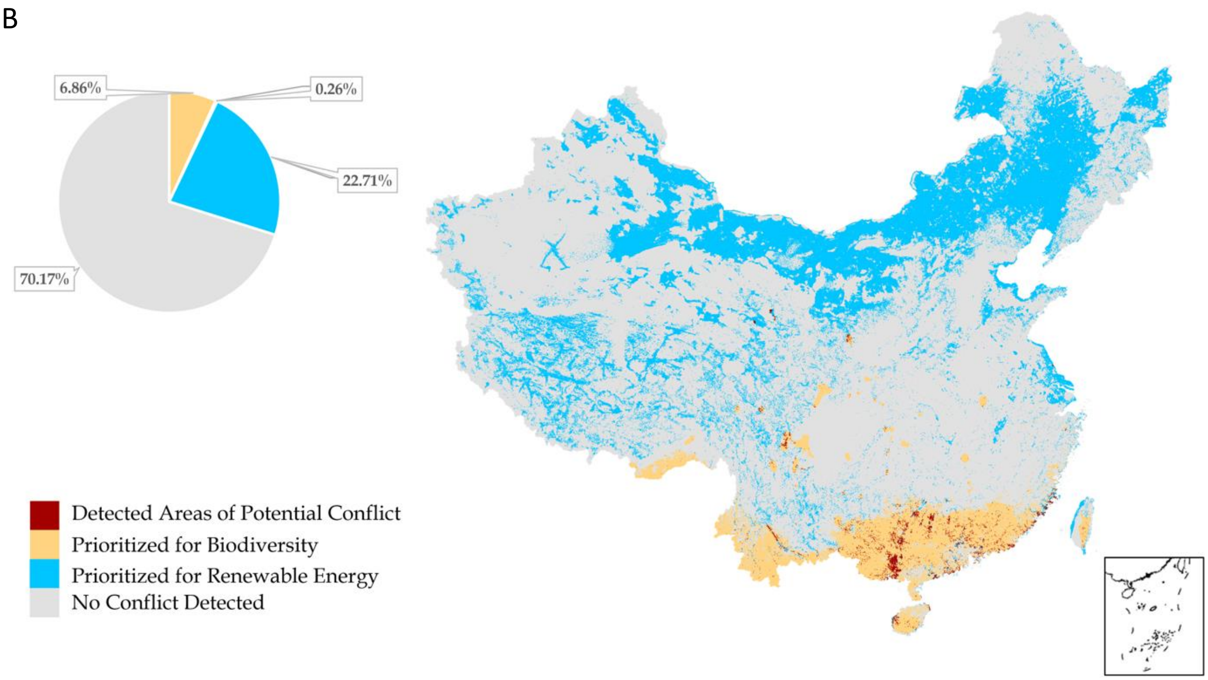

Figure 3 Potential area of conflict detected with suitability analysis between prioritized areas for (A) Wind and (B) Solar development and prioritized areas with highest biodiversity richness or rarity scores,

classified by natural breaks (top-quantile).

The results of the suitability analysis indicate potential areas of conflict between prioritized areas for wind and solar development and areas of high biodiversity richness or rarity in China (Figure 3). The identification of potential conflicts between wind and solar development and areas of high biodiversity richness or rarity is crucial for informing sustainable land-use planning decisions. Specifically, our analysis highlights the need for careful consideration of the location and scale of renewable energy development projects to minimize potential negative impacts on biodiversity. The results suggest that the southern part of China, including the Hengduan, Nanling, and Gaoligong Mountains, and the hilly regions in Hainan Province, are particularly vulnerable to conflicts between renewable energy development and biodiversity conservation. These areas are known to support a high concentration of threatened and endemic species, highlighting the need for careful management and mitigation measures. Moreover, the analysis reveals differences in the patterns of potential conflict between wind and solar development. While areas with high potential for wind development overlap more with areas of low biodiversity richness or rarity in the northwestern part of China, the areas with high potential for solar development tend to lean more into the northeastern regions. These regional variations in the patterns of potential conflict underscore the need for tailored and context-specific approaches to sustainable land-use planning. In conclusion, this study provides a valuable contribution to the understanding of the potential land-use conflicts between renewable energy development and biodiversity conservation. The results can inform policy and decision-making processes aimed at achieving sustainable development goals while safeguarding biodiversity.

Building upon the suitability analysis, we utilized a resource allocation algorithm to identify the land areas required to meet the renewable energy targets while minimizing potential conflicts with biodiversity conservation goals. The algorithm considered both wind and solar suitability information and theoretical maximum capacity of each land unit. The output of the algorithm was a map of prioritized land units, which were then selected to achieve the renewable energy targets while accounting for the scenarios and land use filters described in the methods section.

3.2 *Detected Areas Demanded to Fulfill the 2060 Carbon Neutrality Goals in China*

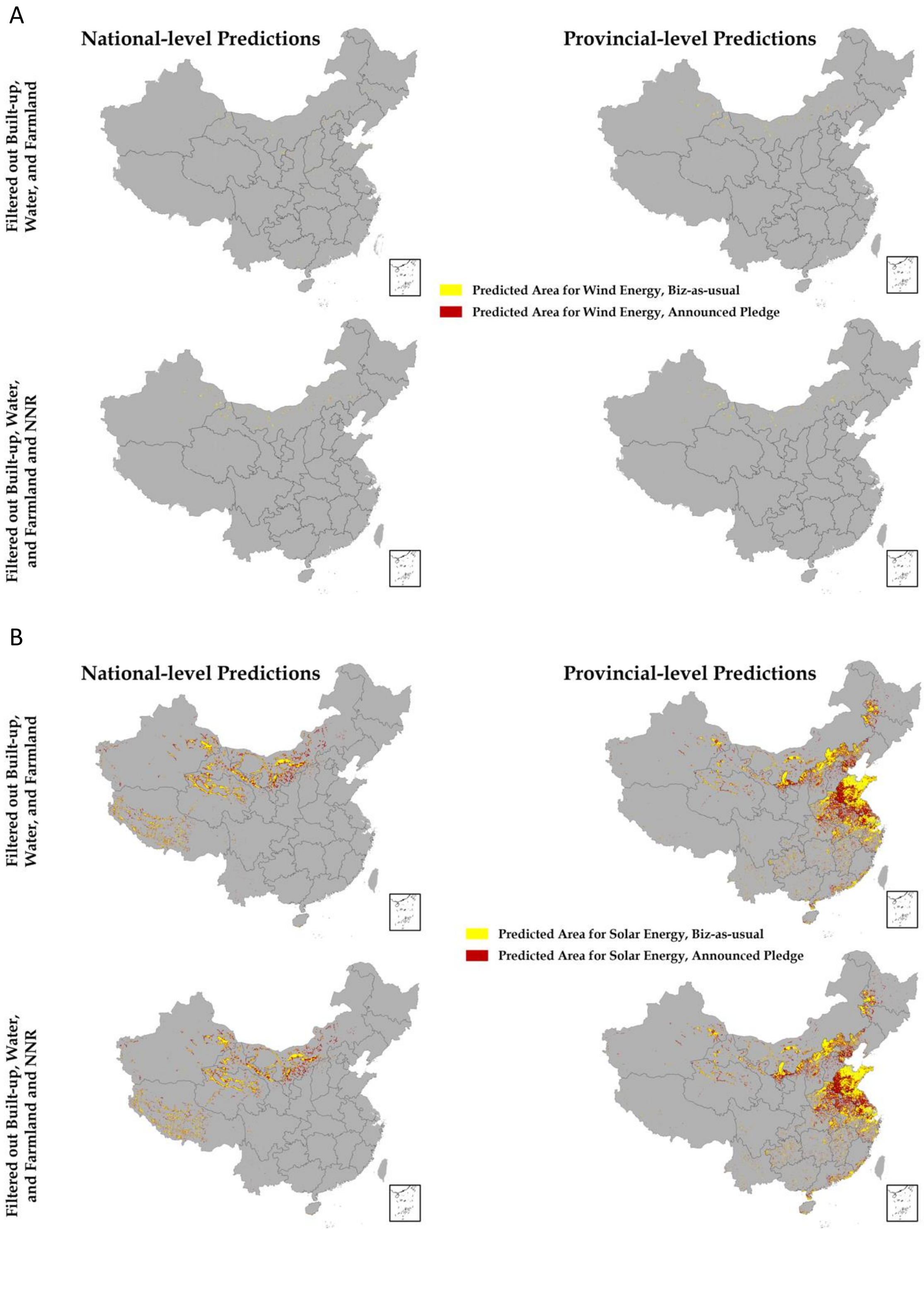

Figure 4 National-level and provincial-level predicted land areas for (A) wind energy and (B) solar energy development under Biz-as-usual and announced pledge scenarios.

Based on the results of our suitability analysis, we observed that the areas with the highest potential for wind energy development at the national level were primarily situated in the northwestern region of the country. On the other hand, the predicted areas for solar energy development were mainly concentrated in both the northeastern and northwestern regions. At the provincial level, our analysis revealed that the provinces with the highest demand for potential land areas for wind energy development were Ningxia, Jiangsu, and Shanghai, despite none of these provinces exceeding 0.1% of the total areas under the 2060 carbon neutrality target. The wind expansion predictions demonstrated the high efficiency of wind energy's land use in terms of facilities or total land use change. It's worth noting that our analysis did not account for any potential issues that could arise from cables or transmission lines blocking the landscape. For solar energy development, our analysis showed that Shanghai, Jiangsu, and Shandong would sacrifice the highest percentage of potential areas under the 2060 carbon neutrality target and the strictest land use scenario and even lead to land use deficits (see Table S 1).

Also, the predicted land areas to be used for wind energy development (Figure 4-A) were found to be relatively scattered and dispersed throughout the study area, making it difficult to discern any clear patterns or clusters at the current scale of analysis. Further zooming in or using a finer resolution may be necessary to better visualize the distribution of these areas and any potential conflicts with biodiversity conservation goals. As to examine the potential impacts on biodiversity of renewable energy, in the most technically realistic situations, in the following sections, we would focus on the prediction results based on the full land use filter (excluding water, built-up, farmland, and National Nature Reserves), and present the results of solar energy only due to the hardness in visualizing the results for much scattered wind prediction results.

3.3 *Detected Conflict in Fulfilling the 2060 Carbon Neutrality Goals*

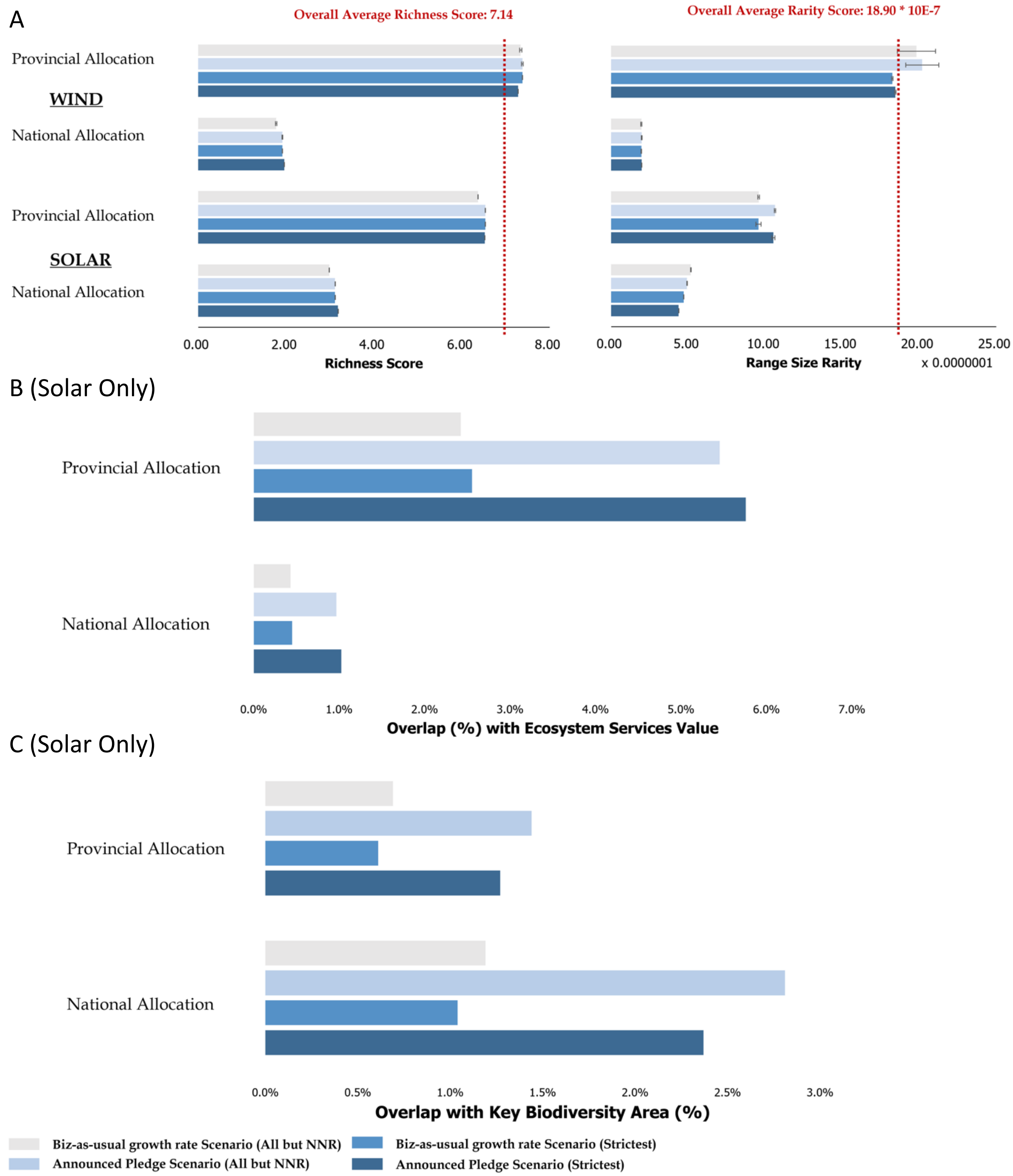

Figure 5 Overview of detected conflicts between renewable energy expansion and biodiversity. (A) Average richness and rarity conditions in wind and solar expansion areas; (B) The sum of ecosystem services values within the predicted land areas to be used by solar energy expansion; (C) The area ratio of potentially threatened key biodiversity areas contained in the predicted land areas for solar expansion, compared with the total land area designated as key biodiversity areas in China.

Our analysis showed that the average richness and rarity scores for wind and solar expansion areas were generally lower than the national average, except for the predicted wind energy expansion under the provincial scale analysis (Figure 5-A). This suggests that wind energy expansion in certain provinces may have a higher potential to impact biodiversity than in other regions at the national level. However, overall, our results indicate that there may be potential conflicts between renewable energy expansion and biodiversity conservation in China. This is supported by the fact that the species used to calculate the richness and rarity score are either threatened or protected species, highlighting the importance of balancing renewable energy development with biodiversity conservation.

It is worth noting that both national and provincial scale predictions for wind energy expansion would threaten less than 0.1% of total ecosystem service values and key biodiversity areas, thus not included in the charts above (Figure 5-B, C).

The results for ecosystem services values and key biodiversity areas are noteworthy. We found that the national scale predictions had lower ESV scores than the provincial scale predictions, indicating that there may be a trade-off between renewable energy expansion and ecosystem services at the national level. However, the national scale predictions had higher overlapped or potentially conflicting areas with KBA than the provincial scale predictions, suggesting that there may be a greater potential for conflicts between renewable energy expansion and biodiversity conservation at the national level. Another aspect of concern is that we found a slightly larger area of potential conflict with key biodiversity areas when using the strictest land use filter, which removed the current National Nature Reserves, compared to the filter that only excluded water, built-up, and farmland areas. Although protected areas are important for minimizing potential conflicts between renewable energy expansion and biodiversity conservation, we have concerns that areas not under the strictest protection may be subject to land use change by renewable energy expansion. Conversely, avoiding renewable energy development in unprotected areas may also lead to missed opportunities for clean energy expansion. Therefore, a balanced approach is needed to address both renewable energy development and biodiversity conservation in China.

Further analysis of the changes in ecosystem service values and key biodiversity areas under different scenarios will be conducted in future studies. A brief preview of this phenomenon can be seen in the following case studies (see *Case Studies of Key Biodiversity Areas*).

4. Discussion

4.1 *Patterns of Detected Land Use Conflicts*

The results of our study reveal a clear pattern of potential land use conflicts between renewable energy development and biodiversity conservation in China. Our suitability analysis shows that there are areas with high potential for wind and solar energy development that also overlap with regions of high biodiversity richness or rarity scores. This finding, in terms the magititude of spatial conflicts, echoes with the concerns of previous studies highlighting the importance of considering biodiversity conservation in renewable energy planning (Dunnet et al., 2022), though this study starts planning at land area level from scratch and could not provide comparison to the exact amount of land area to be expanded under the predictions of Rehbein et al. (2020) and Zalk et al. (2018).

The highest density of conflicts is found in the southern provinces of China, particularly in Hainan, Yunnan, and Guangxi, which are known for their high biodiversity value. Our analysis also reveals some conflicts in the northern provinces, particularly in the Qilianshan and Qinghaihu region. These areas, while having lower biodiversity richness and rarity scores than the southern provinces, are still critical habitats for species of concern, including the snow leopard and Tibetan antelope. Our study also highlights the potential trade-offs between achieving renewable energy targets and conserving biodiversity in China. While the government has set ambitious renewable energy targets, our analysis suggests that achieving these targets may require development in areas with high biodiversity value. As such, it is crucial for decision-makers to carefully balance the need for renewable energy development with the need to protect and conserve biodiversity.

4.2 *Case Studies of Key Biodiversity Areas*

The identification of potential conflicts between renewable energy development and biodiversity conservation in China highlights the need for careful planning and management of renewable energy projects. Specifically, our analysis indicates that there is a risk that new solar facilities may be built in internationally recognized Key Biodiversity Areas (KBAs) that are not currently listed in China's National Nature Reserves (NNRs). This finding is concerning because KBAs are globally important areas for biodiversity conservation and are recognized as such by international organizations such as the International Union for Conservation of Nature (IUCN).

Our analysis suggests that if new solar facilities are built in KBAs, there is a risk of significant biodiversity loss, as well as potential conflicts with local communities and indigenous peoples. In addition, the construction of solar facilities in KBAs could damage the ecological connectivity of these areas, which is important for maintaining healthy ecosystems and supporting migratory species. Therefore, it is important for decision-makers to consider the potential impacts of renewable energy projects on KBAs and to carefully evaluate alternative locations that would minimize negative impacts on biodiversity.

To better exemplify the potential impacts of predicted renewable energy development on biodiversity, we selected two areas where there is clear overlap between the projected solar development and the Key Biodiversity Areas in China.

4.2.1 *Qilianshan-Qinghaihu Region*

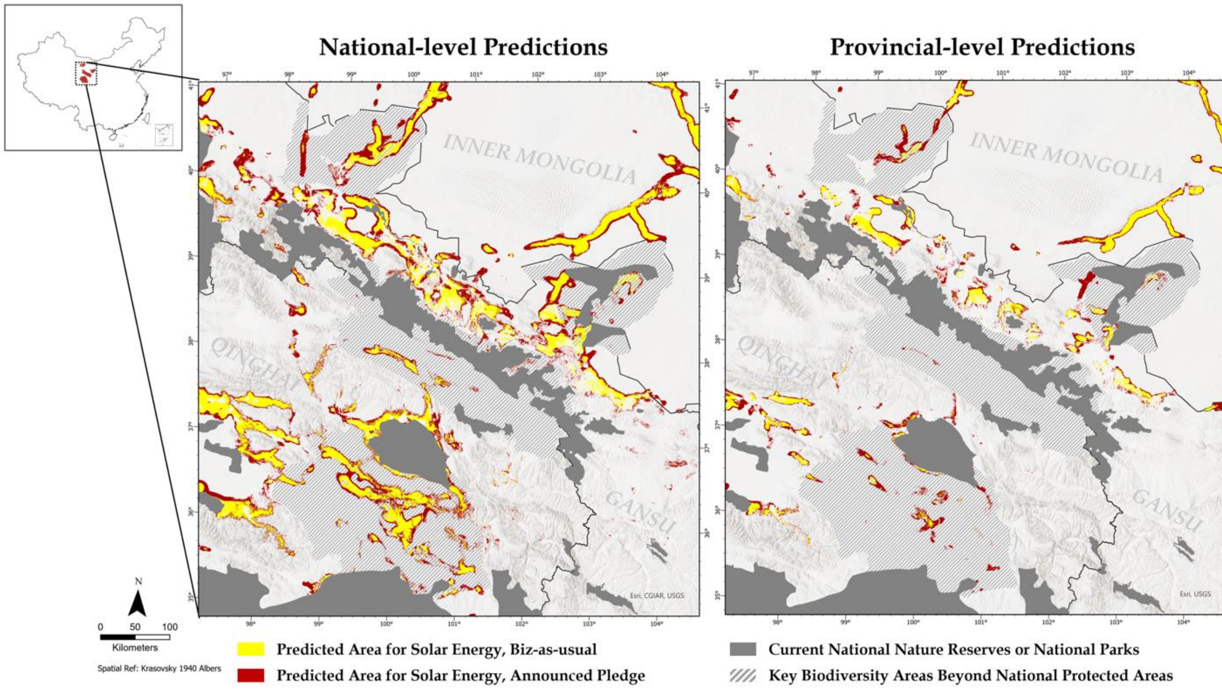

Figure 6 Predicted solar expansion near Qilianshan and Qinghaihu

The first is the Qilianshan-Qinghaihu region (Figure 6), which has relatively low species richness and rarity scores but supplies important habitats for some species of concern. In national-scale predictions, the Qilianshan-Qinghaihu region supplied a large magnitude of land areas for solar expansion, while the Gansu Province and Qinghai Province themselves demanded much less land areas to fulfill their provincial targets. The close distribution of predicted areas for solar development on the edge of Qilianshan and Qinghaihu National Nature Reserves may raise concerns about potential impacts on the biodiversity and ecosystem services of these protected areas. It is important to carefully evaluate the potential risks and benefits of renewable energy expansion in such areas, taking into account the ecological sensitivity of the region and the potential impacts on local communities. Policy makers may need to consider alternative locations for renewable energy development that minimize potential conflicts with protected areas while still meeting the needs for energy production.

The vast region around Qilianshan and Qinghaihu, despite having relatively lower richness and rarity scores compared to the biodiversity hotspot regions in the southern part of China, serves as a crucial habitat for species of concern. though in relatively richness score and rarity score, provides important habitat for species of concern, including Snow Leopard (*Panthera uncia*), Tibetan Wild Yak (*Bos mutus*), Tibetan Antelope (*Pantholops hodgsonii*), Tibetan Gazelle (*Procapra picticaudata*), Tibetan Argali (*Ovis ammon hodgsoni*), Kiang (*Equus kiang*), and Black-necked Crane (*Grus nigricollis*), just to name a few.

4.2.2 *Hainan Province*

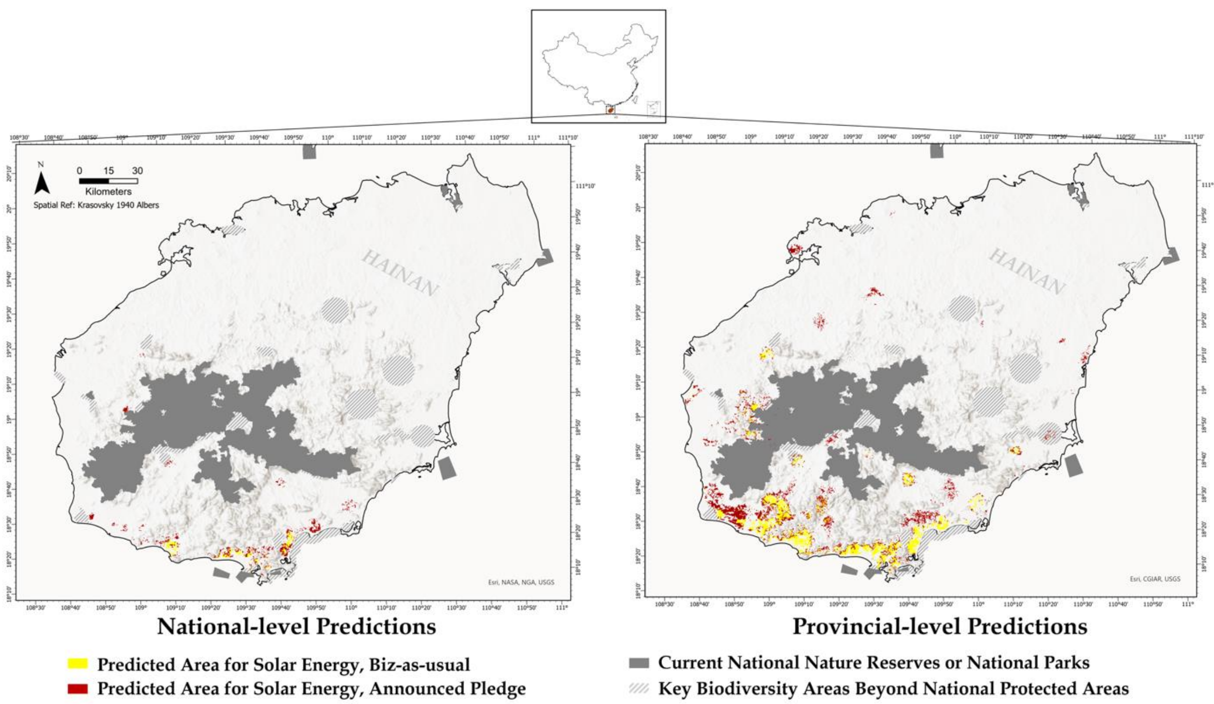

Figure 7 Predicted solar energy expansion in Hainan Province, China.

The second case study area is the Hainan province (Figure 7), which has high species richness and is also a priority area for conservation, but Hainan would demand a higher amount of land areas to supply its own solar energy targets to ensure China could reach the national carbon neutrality goal in 2060. In the case of Hainan, we have identified around 5% of land areas predicted for solar expansion located within key biodiversity areas. Additionally, a certain amount of these key biodiversity areas is located within protection areas at lower administrative levels such as provincial or county levels, and not within national nature reserves or the Hainan Rainforest National Park. It highlights the need for conservation efforts to extend beyond just national nature reserves and protected areas to also include lower administrative levels such as provinces and counties. This could involve increasing the coverage and effectiveness of existing protected areas at these levels or establishing new protected areas in regions of high biodiversity value. It also emphasizes the importance of considering biodiversity conservation in land use planning for renewable energy expansion projects.

Hainan, the southernmost province of China, is a region of exceptional biodiversity with a high richness and rarity score. The tropical rainforests in Hainan are home to numerous terrestrial endemic species, including Hainan Gibbon (*Nomascus hainanus*), Hainan Peacock-pheasant (*Polyplectron katsumatae*), and Hainan Eld's Deer (*Elaphodus cephalophus hainanus)*, which are all classified as critically endangered on the IUCN Red List. However, the overlap between predicted solar development and key biodiversity areas in Hainan highlights the potential for conflicts between renewable energy expansion and biodiversity conservation efforts in this region.

In short, our case study provides important insights into the potential conflicts between renewable energy development and biodiversity conservation in China. Another reason for including the two case studies is that both regions contain more than 30% of internationally recognized key biodiversity areas not yet covered by the strictest protection in China, *aka*, not included in the National Nature Reserves, the Qilianshan National Park Pilot, or the newly established Hainan Rain Forest National Park. Our analysis suggests that careful planning and management of renewable energy projects is needed to ensure that they do not have negative impacts on globally important areas for biodiversity conservation. As China continues to expand its renewable energy infrastructure, it will be important to monitor the potential impacts of these projects on biodiversity and to adopt a precautionary approach to decision-making.

4.3 *Limitations of the Study and Future Pathways*

This study is subject to several limitations that could affect the interpretation of its findings. First, the analysis may have missed certain sensitive species or habitats that could be impacted by renewable energy development. Future research could incorporate more detailed data on species distributions and habitat requirements to provide a more accurate assessment of potential impacts. Additionally, the suitability analysis relied on available literature and expert opinion, which may be incomplete or biased. Alternative models or data sources could be used to provide a more comprehensive assessment of potential impacts on biodiversity. In addition to the limitations already mentioned, there are several other potential limitations of this geospatial study. One limitation is the potential for errors in the input data used to create the suitability models, such as errors in land use classifications or inaccuracies in environmental data sources. Additionally, the study may not account for other factors that could affect the impacts of renewable energy development on biodiversity, such as the specific technologies used for energy production, the intensity of land use change, or the presence of invasive species. Furthermore, the study assumes a static and homogeneous landscape, which may not be the case in reality, as the spatial distribution and diversity of species and habitats may change over time. Finally, the study does not consider the potential indirect impacts of renewable energy development, such as changes in water availability or soil quality, which could have secondary effects on biodiversity.

This study has some limitations that could affect the interpretation of its findings. One limitation is the lack of ground-truth data, which could impact the identification of impacts of existing power plants that are not included in this analysis. To address this, further remote sensing-based classification could be used to provide a more accurate assessment of potential impacts on biodiversity. Another limitation is that this analysis is based on current land use data and does not account for future projections. As renewable energy development continues to expand, there may be additional impacts on biodiversity that are not captured in the current analysis. To address this, future research could incorporate future land use projections to provide a more comprehensive assessment of potential impacts on biodiversity. It is also important to note that the suitability analysis relied on available literature and expert opinion, which may be incomplete or biased. Alternative models or data sources could be used to provide a more comprehensive assessment of potential impacts on biodiversity. Lastly, the visualization and suitability criteria used to simulate the decision-making process of wind and solar energy site selection could benefit from more interactive and participatory elements. Developing a web-based suitability and allocation application with Google Earth Engine could be an important future step in making the analysis more accessible and transparent - which is not currently incorporated as a part of this Master Project submission. It could be an important future step in making the analysis more accessible and transparent. However, it is important to note that the application is still under construction and requires further refinement and testing before it can be used effectively for decision-making purposes. However, further refinement and testing of the application is necessary before it can be effectively used for decision-making purposes.

To address the potential impacts of renewable energy development on biodiversity conservation, a multi-faceted approach is required that considers the specific ecological context of the project area, as well as social, economic, and political factors that may affect the planning process. Several key strategies can be employed to minimize negative impacts on biodiversity, including:

- Conducting thorough ecological assessments: It is crucial to conduct comprehensive ecological assessments of the project area before initiating any renewable energy project. This assessment should identify and understand potential impacts on local biodiversity, including rare or endangered species, as well as sensitive habitats or ecosystems.
- Avoiding high conservation value areas: In cases where renewable energy development is likely to have significant negative impacts on biodiversity, it may be necessary to avoid high conservation value areas altogether. This may require the

identification of alternative project sites or the development of new technologies that can minimize ecological impacts.

- Minimizing land use impacts: The expansion of renewable energy sources often involves significant land use changes, such as clearing of forests or other natural habitats. To minimize these impacts, alternative land use options such as degraded or marginal lands, as well as innovative land management practices like agroforestry or ecological restoration, should be considered.
- Implementing best practices for construction and operation: Construction and operation of renewable energy facilities can have significant impacts on local ecosystems, such as noise pollution, habitat fragmentation, and disturbance to wildlife. Best practices for construction and operation can help minimize these impacts, such as careful site selection, noise abatement, and the use of low-impact construction techniques.
- Collaborating with local communities and stakeholders: Collaboration with local communities and stakeholders is vital to ensuring that renewable energy development is both socially and ecologically sustainable. This may involve engaging in dialogue with local communities to identify potential impacts and concerns, as well as developing mechanisms for community participation in decision-making and benefit-sharing.

5. Conclusion

In conclusion, our study identified potential conflicts between renewable energy development and biodiversity conservation in China. Using suitability analysis and biodiversity mapping, we found that a certain proportion of areas identified as highly suitable for wind and solar energy development also overlapped with areas of high biodiversity richness or rarity scores. These results suggest that there is a need for careful planning and management to ensure that renewable energy development does not come at the cost of biodiversity conservation. Our study also highlights the importance of considering the spatial scale and resolution of analyses when assessing potential conflicts between renewable energy development and biodiversity conservation. We found that finer-scale spatial analyses provided more detailed and accurate information on potential conflicts, but also required more detailed and accurate data inputs. This suggests that future research and planning efforts should prioritize the development of high-resolution, comprehensive data on both renewable energy potential and biodiversity value. Overall, our study contributes to the growing body of literature on renewable energy development and biodiversity conservation, and provides important insights for policymakers, conservation practitioners, and renewable energy developers in China and beyond. By taking a proactive, integrated approach to renewable energy and biodiversity planning, we can ensure a sustainable future for both energy production and biodiversity conservation.

Reference

1. Agha, M., Lovich, J. E., Ennen, J. R., & Todd, B. D. (2019). Wind, sun, and wildlife: do wind and solar energy development 'short-circuit' conservation in the western United States?. Environmental Research Letters, 15(7), 075004. https://doi.org/10.1088/1748-9326/ab8846
2. Aho, K., Derryberry, D., Peterson, T. (2014), "Model selection for ecologists: the worldviews of AIC and BIC", Ecology, 95 (3): 631–636, doi:10.1890/13-1452.1, PMID 24804445.
3. Alam M, Dupras J, Messier C. (2016). A framework towards a composite indicator for urban ecosystem services. Ecological Indicators, 60: 38-44.
4. Allison, T.D., Root, T.L., & Frumhoff, P.C. (2014). Thinking globally and siting locally: renewable energy and biodiversity in a rapidly warming world. Climatic Change, 126, 1-6. doi: 10.1007/s10584-014-1127-y.
5. Arderne, C., Zorn, C., Nicolas, C., Srebotnjak, T., & Adamson, K. (2020). Predictive mapping of the global power system using open data. Scientific Data, 7(1), 19. https://doi.org/10.1038/s41597-019-0347-4
6. BirdLife International. (2017). The World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Re:wild, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. Available at www.keybiodiversityareas.org. [Accessed 12/21/2022)].
7. BirdLife International and Handbook of the Birds of the World (2021). Bird species distribution maps of the world. Version 2021.1. Available at http://datazone.birdlife.org/species/requestdis. [Accessed 12/21/2022)].
8. Brooks, T. M., Pimm, S. L., Akçakaya, H. R., Buchanan, G. M., Butchart, S. H. M., Foden, W., Hilton-Taylor, C., Hoffmann, M., Jenkins, C. N., Joppa, L., Li, B. V., Menon, V., Ocampo-Peñuela, N., & Rondinini, C. (2019). Measuring Terrestrial Area of Habitat (AOH) and Its Utility for the IUCN Red List. Trends in Ecology & Evolution, 34(11), 977–986. https://doi.org/10.1016/j.tree.2019.06.009
9. Buchhorn, M., Lesiv, M., Tsendbazar, N. - E., Herold, M., Bertels, L., & Smets, B. (2020). Copernicus Global Land Cover Layers-Collection 2. Remote Sensing, 12(6), 1044. doi:10.3390/rs12061044
10. Burkhard B, Kroll F, Nedkov S, et al. (2012). Mapping ecosystem service supply, demand and

budgets. Ecological Indicators, 21(3): 17-29.
11. Center for International Earth Science Information Network - CIESIN - Columbia University. (2020). Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11 [Data set]. NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H49C6VHW.
12. Chen, J. D., & Gao, M. (2021). Global 1 km × 1 km gridded revised real gross domestic product and electricity consumption during 1992–2019 based on calibrated nighttime light data [Data set]. Figshare. https://doi.org/10.6084/m9.figshare.17004523.v1
13. Choi, D. Y., Wittig, T. W., & Kluever, B. M. (2020). An evaluation of bird and bat mortality at wind turbines in the Northeastern United States. PloS one, 15(8), e0238034.
14. Chock, R. Y., Clucas, B., Peterson, E. K., Blackwell, B. F., Blumstein, D. T., Church, K., Fernández-Juricic, E., Francescoli, G., Greggor, A. L., Kemp, P., Pinho, G. M., Sanzenbacher, P. M., Schulte, B. A., & Toni, P. (2021). Evaluating potential effects of solar power facilities on wildlife from an animal behavior perspective. Conservation Science and Practice, 3(2), e319. https://doi.org/10.1111/csp2.319
15. Deveci, M., Cali, U., & Pamucar, D. (2021). Evaluation of criteria for site selection of solar photovoltaic (PV) projects using fuzzy logarithmic additive estimation of weight coefficients. Energy Reports, 7, 8805–8824. https://doi.org/10.1016/j.egyr.2021.10.104 https://doi.org/10.1126/sciadv.abc3436
16. Dunnett, S., Holland, R. A., Taylor, G., & Eigenbrod, F. (2022). Predicted wind and solar energy expansion has minimal overlap with multiple conservation priorities across global regions Proceedings of the National Academy of Sciences, 119(6), e2104764119. https://doi.org/10.1073/pnas.210476411
17. Faith, D. P. (2021). Valuation and Appreciation of Biodiversity: The "Maintenance of Options" Provided by the Variety of Life. Frontiers in Ecology and Evolution, 9. https://www.frontiersin.org/articles/10.3389/fevo.2021.635670
18. Goh, H. H., Li, C., Zhang, D., Dai, W., Lim, C. S., Kurniawan, T. A., & Goh, K. C. (2022). Application of choosing by advantages to determine the optimal site for solar power plants. Scientific Reports, 12(1), Article 1. https://doi.org/10.1038/s41598-022-08193-1
19. Guo, B., Yang, F., Fan, J., & Lu, Y. (2022). The changes of spatiotemporal pattern of rocky desertification and its dominant driving factors in typical karst mountainous areas under the background of global change. Remote Sensing, 14(10), 2351. https://doi.org/10.3390/rs14102351.

20. Hernandez, R. R., Hoffacker, M. K., Murphy-Mariscal, M. L., Wu, G. C., & Allen, M. F. (2015). Solar energy development impacts on land cover change and protected areas. Proceedings of the National Academy of Sciences, 112(44), 13579–13584. https://doi.org/10.1073/pnas.1517656112
21. Hise, C., Obermeyer, B., Ahlering, M., Wilkinson, J., & Fargione, J. (2022). Site Wind Right: Identifying Low-Impact Wind Development Areas in the Central United States. Land, 11(4), Article 4. https://doi.org/10.3390/land11040462
22. International Energy Agency – IEA (2020). China's net-zero ambitions: the next Five-Year Plan will be critical for an accelerated energy transition, IEA, Paris https://www.iea.org/commentaries/china-s-net-zero-ambitions-the-next-five-year-plan-will-be-critical-for-an-accelerated-energy-transition
23. International Energy Agency – IEA (2021). An energy sector roadmap to carbon neutrality in China, IEA, Paris. https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china.
24. Inman, R. H., Pedro, H. T., & Coimbra, C. F. (2013). Solar forecasting methods for renewable energy integration. Progress in energy and combustion science, 39(6), 535-576.
25. IUCN. (2016). A global standard for the identification of Key Biodiversity Areas: Version 1.0. https://portals.iucn.org/library/node/46259
26. Jarvis, A., Reuter, H.I., Nelson, A., & Guevara, E. (2008). Hole-filled SRTM for the globe Version 4. Available from the CGIAR-CSI SRTM 90m Database. http://srtm.csi.cgiar.org
27. Jiang, D., Wang, D., Fu, J., Zhang, C., Li, L., & Zhang, J. (2020). Assessment of potential of renewable energy to be produced on unused land in Inner Mongolia Autonomous Region. Science & Technology Review, 38(11), 60-69.
28. Jones, N. F., & Pejchar, L. (2013). Comparing the ecological impacts of wind and oil & gas development: A landscape scale assessment. PloS one, 8(11), e81391. https://doi.org/10.1371/journal.pone.0081391
29. Jordaan, S. M., Lee, J., McClung, M. R., & Moran, M. D. (2021). Quantifying the ecosystem services values of electricity generation in the US Chihuahuan Desert: A life cycle perspective. Journal of Industrial Ecology, 25(4), 1089–1101. https://doi.org/10.1111/jiec.13111
30. Jung, M., Dahal, P. R., Butchart, S. H. M., Donald, P. F., De Lamo, X., Lesiv, M., Kapos, V., Rondinini, C., & Visconti, P. (2020). A global map of terrestrial habitat types. Scientific Data, 7(1), Article 1. https://doi.org/10.1038/s41597-020-00599-8
31. Kazem, H. A., & Chaichan, M. T. (2019). The effect of dust accumulation and cleaning methods on PV panels' outcomes based on an experimental study of six locations in Northern Oman.

Solar Energy, 187, 30–38. https://doi.org/10.1016/j.solener.2019.05.036

32. Keith, D. W., DeCarolis, J. F., Denkenberger, D. C., Lenschow, D. H., Malyshev, S. L., Pacala, S., & Rasch, P. J. (2004). The influence of large-scale wind power on global climate. Proceedings of the National Academy of Sciences, 101(46), 16115–16120. https://doi.org/10.1073/pnas.0406930101
33. Kikuchi, R. (2008). Adverse impacts of wind power generation on collision behaviour of birds and anti-predator behaviour of squirrels. Journal for Nature Conservation, 16(1), 44–55. https://doi.org/10.1016/j.jnc.2007.11.001
34. Li, B. V., & Pimm, S. L. (2016). China's endemic vertebrates sheltering under the protective umbrella of the giant panda. Conservation Biology, 30(2), 329-339.
35. Li, S., Gao Q., Wang X., et al. (2016). Characteristics of vegetation and soil property changes by photovoltaic plant Interference in Alpine Desert Steppe. Journal of Soil and Water Conservation, 30(6): 325.
36. Lorenz, E., Hurka, J., Heinemann, D., & Beyer, H. G. (2009). Irradiance forecasting for the power prediction of grid-connected photovoltaic systems. IEEE Journal of selected topics in applied earth observations and remote sensing, 2(1), 2-10.
37. Lovich, J. E., & Ennen, J. R. (2011). Wildlife conservation and solar energy development in the desert southwest, United States. BioScience, 61(12), 982-992. doi: 10.1525/bio.2011.61.12.8
38. Lumbierres, M., Dahal, P. R., Di Marco, M., Butchart, S. H. M., Donald, P. F., & Rondinini, C. (2022). Translating habitat class to land cover to map area of habitat of terrestrial vertebrates. Conservation Biology, 36(3), e13851. https://doi.org/10.1111/cobi.13851
39. Lumbierres, M., Dahal, P. R., Soria, C. D., Di Marco, M., Butchart, S. H. M., Donald, P. F., & Rondinini, C. (2022). Area of Habitat maps for the world's terrestrial birds and mammals. Scientific Data, 9(1), Article 1. https://doi.org/10.1038/s41597-022-01838-w
40. Matthies B D, Kalliokoski T, Ekholm T, et al. (2015). Risk, reward, and payments for ecosystem services: A portfolio approach to ecosystem services and forestland investment. Ecosystem Services, 16: 1-12.
41. Meijer, Huijbregts, Schotten, & Schipper. (2018). Global patterns of current and future road infrastructure - Supplementary spatial data (Version 4 - 2018) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.6420961
42. Miller, L.M. & Keith, D.W. (2018). Observation-based solar and wind power capacity factors and power densities. Environmental Research Letters, 13(10), 104008.
43. Papathanasopoulou E, Beaumont N, Hooper T, et al.2015. Energy systems and their impacts on

marine ecosystem services. Renewable and Sustainable Energy Reviews, 52: 917-926.
44. Pimm, S. L., Jenkins, C. N., & Li, B. V. (2018). How to protect half of Earth to ensure it protects sufficient biodiversity. Science advances, 4(8), 2616.
45. P.R.C. National Development and Reform Commission (NRDC). (2021). The 14th Five-Year Renewable Energy Development Plan of the People's Republic of China. Retrieved from https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202206/t20220601_1326719.html?code=&state=123
46. P.R.C. National Development and Reform Commission (NRDC) & The Nature Conservancy. (2017). China's Eco-Friendly Spatial Layout for Renewable Energy Development (2016-2030) Retrieved from https://tnc.org.cn/edm/0611.pdf
47. P.R.C. National Energy Bureau (NEB). (2022). The National Energy Administration held a press conference to release the grid connection of renewable energy in 2021 and answer questions. Retrieved from http://www.gov.cn/xinwen/2022-01/29/content_5671076.htm
48. P.R.C. Ministry of Natural Resources (2012).
49. P.R.C. Ministry of Natural Resources (2022).
50. Rediske, G., Burin, H. P., Rigo, P. D., Rosa, C. B., Michels, L., & Siluk, J. C. M. (2021). Wind power plant site selection: A systematic review. Renewable and Sustainable Energy Reviews, 148, 111293. https://doi.org/10.1016/j.rser.2021.111293
51. Rehbein, J. A., Watson, J. E. M., Lane, J. L., Sonter, L. J., Venter, O., Atkinson, S. C., & Allan, J. R. (2020). Renewable energy development threatens many globally important biodiversity areas. Global Change Biology, 26(5), 3040–3051. https://doi.org/10.1111/gcb.15067
52. Rocky Mountain Institute (RMI). (2017). A review of solar PV benefit & cost studies 2nd edition. Retrieved from https://rmi.org/wp-content/uploads/2017/05/RMI_Document_Repository_Public-Reprts_eLab-DER-Benefit- Cost-Deck_2nd_Edition131015.pdf
53. Shamshirband, S., Mohammadi, K., Yee, L., Petković, D., & Mostafaeipour, A. (2015). A comparative evaluation for identifying the suitability of extreme learning machine to predict horizontal global solar radiation. Renewable and sustainable energy reviews, 52, 1031-1042.
54. Stanek, W., Czarnowska, L., Gazda, W., & Simla, T. (2018). Thermo-ecological cost of electricity from renewable energy sources. Renewable Energy, 115, 87–96. https://doi.org/10.1016/j.renene.2017.07.074
55. Stoms, D.M., Dashiell, S.L., & Davis, F.W. (2013). Siting solar energy development to minimize biological impacts. Renewable Energy, 57, 289-298. https://doi.org/10.1016/j.renene.2013.01.055

56. Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H. M., Newbold, T., Green, R. E., Tobias, J. A., Foden, W. B., O'Brien, S., & Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. Proceedings of the Royal Society B, 284(1862), 20170829. https://doi.org/10.1098/rspb.2017.0829
57. Villa, F., Bagstad, K. J., Voigt, B., Johnson, G. W., Portela, R., Honzák, M., & Batker, D. (2014). A Methodology for Adaptable and Robust Ecosystem Services Assessment. PLOS ONE, 9(3), e91001. https://doi.org/10.1371/journal.pone.0091001
58. Wiedmann T O, Suh S, Feng K S, et al. (2011). Application of hybrid life cycle approaches to emerging energy technologies-the case of wind power in the UK. Environmental Science & Technology, 45(13): 5900-5907.
59. Xie, G., Zhang, C., Zhen, L., & Zhang, L. (2017). Dynamic changes in the value of China's ecosystem services. Ecosystem Services, 26, 146–154. https://doi.org/10.1016/j.ecoser.2017.06.010
60. Xu, H., Tang, X., Liu, J., Ding, H., Wu, J., Zhang, M., Yang, Q., Cai, L., Zhao, H., & Liu, Y. (2009). China's Progress toward the Significant Reduction of the Rate of Biodiversity Loss. BioScience, 59(10), 843–852. https://doi.org/10.1525/bio.2009.59.10.6
61. Xu, X., Liu, J., Zhang, S., Li, R., Yan, C., & Wu, S. (2018). China's multi-temporal land use remote sensing monitoring dataset (CNLUCC). Resource and Environmental Science Data Center, DOI, 10.12078/2018070201.
62. Yahdjian L, Sala O E, Havstad K M. (2015). Rangeland ecosystem services: Shifting focus from supply to reconciling supply and demand. Frontiers in Ecology and the Environment, 13(1): 44-51.
63. Zalk, V.J., & Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. Energy Policy, 123, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023
64. Zhou, M., Wang X. (2019). Influence of photovoltaic power station engineering on soil and vegetation: Taking the Gobi Desert Area in the Hexi corridor of Gansu as an example. Science of Soil and Water Conservation, 17(2): 132-138.

Supplementary Materials

S1. Data Description

Renewable Energy Data

- *Global Horizontal Irradiance (GHI)*. This layer provides data on the amount of solar radiation that reaches a horizontal surface at a particular location, measured in kilowatt hours per square meter per year (kWh/m^2), and is a key parameter for assessing the potential for solar energy generation (Lorenz et al., 2009; Inman et al., 2013). We used the long-term averaged annual GHI data for China from Global Solar Atlas at 250-meter resolution.
- *Sunshine Hours*. This layer provides the number of hours of sunlight that a particular location receives over the course of a year, retrieved from the open data set of National Ecosystem Science Data Center (http://www.nesdc.org.cn/) at 1-km resolution. This information is often used as a relative indicator of the richness of solar energy availability (Shamshirband et al., 2015).
- *Wind Power Density.* This layer, from Global Wind Atlas at 250-meter resolution, provides data on the amount of power that can be generated by a wind turbine at a particular location. It considers factors such as wind speed and air density and is typically measured in watts per square meter (W/m^2).
- *Wind Speed at 100m height.* This layer, also from Global Wind Atlas at 250-meter resolution, provides data on the speed and direction of wind at a particular location. It is an important factor for assessing the potential for wind energy generation. On the contrary, strong winds and the carried dusts can cause damage to solar panels and their support structures (Kazem and Chaichan, 2019).
- *Existing Power Plants.* Provided by the World Resource Institute (), this layer contains data on the location and type of existing power plants in the area of interest. Each power plant is geolocated, and the database provides detailed information about each plant, including its capacity, generation, ownership, and fuel type. In China the data set contains utility-scale plants with an installed capacity higher than 1 Mega

Watts. This information is useful for assessing the potential for renewable energy development in the region, as well as for identifying potential sites for new installations that can leverage existing infrastructure.

Biodiversity and Ecosystem Data

To represent biodiversity in our study, we utilized the distribution range data for terrestrial species including mammals, birds, reptiles, and amphibians, collected from the International Union for Conservation of Nature (IUCN) Red List. A cell size of 250m by 250m was used across terrestrial ecosystems in China. Based on the protection and endangered status of species with reference to the appendix of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), IUCN Red List, and the List of key protected wild animals in China, the selected list of important species included 607 species in total, with 128 amphibians, 222 birds, 160 mammals, and 97 reptiles. The data was filtered based on the presence and original status of each listed important species in China, limiting the final ranges to include species extant or possibly extinct, and native or reintroduced only. In addition, we also included the Key Biodiversity Area (KBA) data to visualize the potential impact range of wind and solar energy expansion in China.

- *Richness under the Area-of-Habitat (AOH) scheme*. The area-of-habitat (AOH) approach refers to the habitat available to a species within its range. It is used to complement a geographic range map by showing the potential occupancy of the species and reducing commission errors. The AOH approach takes into account the quantity and quality of available habitat, aka, the suitable habitat type and elevation range, etc., and can help identify areas that are critical for the survival and persistence of a species. With IUCN data for species ranges, suitable elevation ranges, and terrestrial habitat type data (Jung et al., 2020; Lumberre et al., 2021), we computed the AOH-based richness data set for the 607 species.
- *Range-size Rarity (RSR)*. To indicate the potential irreplaceability of habitat patches, we calculated rarity-weighted richness for each taxon to prioritize regions that harbor high numbers of limited range species. The rarity-weighted richness was calculated

using the following equation, with i representing the ith species in the region of analysis, and n standing for the total number of species in the region. r_i is the range size (area) of each species i. Therefore, each cell of the RSR output would represent the ratio of the cell's area to the total area of the species' ranges.

$$RSR = \sum_{i}^{n} \frac{1}{r_i}$$

- *Ecosystem Services Value*. We retrieved the grid-based ecosystem services value data set (Xie et al., 2017) from the Resource and Environment Science and Data Center (RESDC), Chinese Academy of Sciences, to compute the possible ecological cost in terms of ecosystem service value loss due to renewable energy expansion overlap. The data set is at 1km resolution with each cell measured in a monetary unit of 10 thousand RMB.
- *Key Biodiversity Area*. Key Biodiversity Areas (KBA) are sites that significantly contribute to the survival of biodiversity in various ecosystems, including terrestrial, freshwater, and marine ecosystems. The identification of KBAs follows globally recognized criteria outlined in the Global Standard for the Identification of Key Biodiversity Areas (IUCN, 2017).

Socio-economic Data

The inclusion of socio-economic datasets is crucial for understanding the feasibility of renewable energy projects and their potential interactions with the local population's demand. In this study, four key socio-economic datasets were included to inform our suitability analysis for wind and solar energy facilities in China. The first dataset is grid-based population density, which provides information on the distribution of human populations across the project area and helps to identify areas with high demand for energy. The second dataset is electricity consumption, which measures the amount of electricity consumed in the region and helps to identify areas with high energy needs. The third dataset is transmission infrastructure, which provides information on the existing electrical grid, including power lines and substations, and is critical for assessing the feasibility of renewable energy projects. Finally, the study also included road infrastructure data, which shows the existing road network and is important for transportation and construction logistics during the development of renewable energy projects. Including these datasets in our suitability analysis enabled the project to gain a more comprehensive understanding of the potential impacts of renewable energy projects on local communities and infrastructure.

- *Grid-based Population Density*. Population density data provides information on the distribution of human populations across the project area and can be used to identify areas with high demand for energy. The study used the fourth version of the Gridded Population of the World (GPWv.4) representing modelled data on the distribution of human population (Center for International Earth Science Information Network, 2020).
- *Electricity Consumption*. Electricity consumption data measures the amount of electricity consumed in the region and can help to identify areas with high energy needs. The data is retrieved from Chen et al. (2021) at 1-km resolution.
- *Transmission Infrastructure*. Transmission infrastructure data provides information on the existing electrical grid, including power lines and substations, which is critical for assessing the feasibility of renewable energy projects, retrieved from
- *Road Infrastructure*. Road infrastructure data shows the existing road network, which is important for transportation and construction logistics during the development of renewable energy projects. The road dataset as linear infrastructure was retrieved from the Global patterns of current and future road infrastructure (GRIP) database for region 6 – Asia (Meijer et al., 2018) and extracted by the project analysis extent.

Land Conditions

The assessment of land conditions is essential for both the sustainability and biodiversity analysis in this project. First, land use patterns across China were incorporated using land use filters inspired by Liu et al. (2022) and Jiang et al. (2020). Second, the Copernicus land cover classification dataset was employed to generate area-of-habitat maps for key species based on the approach of transferring land cover to habitat types (Lumberries et al., 2021; Lumberries et al., 2022). Additionally, elevation and slope profiles derived from the SRTM digital elevation models were utilized in both habitat mapping and suitability analysis.

- *Land Use in China.* The China National Land Use/Cover Dataset (CNLUCC) is a thematic database of China's national scale multi-temporal land use/cover based on manual visual interpretation using Landsat remote sensing images as the primary information source. The dataset adopts a two-level classification system, with the first level consisting of six categories: cropland, forestland, grassland, water, built-up land, and unused land, and the second level further dividing into 25 types based on the first level. The dataset used in this study is the latest version, updated in 2020 (Xu et al., 2018). The 1-km resolution land use data set is provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn).
- *Land Cover for Habitats*. The Copernicus Global Land Service (CGLS) is a multi-purpose service component that provides a range of bio-geophysical products on the status and changes in land surface at a global scale. The Dynamic Land Cover map at 100 m resolution (CGLS-LC100) provides a global land cover map as a valuable dataset for this project's analysis of land cover patterns for habitat classification.
- *Digital Elevation Model (DEM)*. The project includes a 250-m resolution DEM dataset from the SRTM project. The SRTM 90m Digital Elevation Database v4.1 is a publicly available digital elevation dataset that provides high quality elevation data for large portions of the tropics and other areas of the developing world (Jarvis et al., 2008).
- *Map of National Nature Reserves (NNR).* The project used a compiled NNR dataset with openly available data from the World Database of Protected Areas (WDPA, https://www.protectedplanet.net) and some were manually adjusted with reference to the more complete data set by Pimm et al. (2018).

S2. Full Results for Wind and Solar Energy Development Prediction

Table S 1 Predicted results for wind suitability by scenarios and land use filters. Each table cell value represents the remaining percentile of land areas after achieving the designated energy development targets. "All But NNR" filters out water, built-up, and farmlands. "Full Filter" also excludes National Nature Reserves (NNR) of China as well.

Percentiles (%) of Land Area Remained	**Biz-as-Usual Scenario**		**Announced Pledge Scenario**	
	All But NNR	**Full Filter**	**All But NNR**	**Full Filter**
Anhui	99.99706	99.99706	99.99590	99.99590
Beijing	99.99848	99.99848	99.99810	99.99810
Chongqing	99.99833	99.99833	99.99772	99.99772
Fujian	99.99520	99.99520	99.99326	99.99326
Gansu	99.99677	99.99677	99.99548	99.99548
Guangdong	99.99463	99.99463	99.99248	99.99248
Guangxi	99.99749	99.99749	99.99649	99.99649
Guizhou	99.99737	99.99737	99.99631	99.99631
Hainan	99.99928	99.99928	99.99892	99.99892
Hebei	99.98920	99.98920	99.98488	99.98488
Heilongjiang	99.99852	99.99852	99.99793	99.99793
Henan	99.99110	99.99110	99.98751	99.98751
Hubei	99.99691	99.99691	99.99566	99.99566
Hunan	99.99696	99.99696	99.99575	99.99575
Inner Mongolia	99.99722	99.99722	99.99611	99.99611
Jiangsu	99.98264	99.98264	99.97569	99.97569
Jiangxi	99.99738	99.99738	99.99633	99.99633
Jilin	99.99722	99.99722	99.99611	99.99611
Liaoning	99.99408	99.99408	99.99170	99.99170
Ningxia	99.97763	99.97763	99.96873	99.96873
Qinghai	99.99897	99.99897	99.99856	99.99856
Shaanxi	99.99602	99.99602	99.99444	99.99444
Shandong	99.99005	99.99005	99.98608	99.98608
Shanghai	99.98914	99.98914	99.98449	99.98449
Shanxi	99.98919	99.98919	99.98489	99.98489
Sichuan	99.99913	99.99913	99.99878	99.99878
Tianjin	99.99109	99.99109	99.98742	99.98742
Tibet	99.99999	99.99999	99.99999	99.99999
Xinjiang	99.99882	99.99882	99.99835	99.99835
Yunnan	99.99816	99.99816	99.99742	99.99742
Zhejiang	99.99720	99.99720	99.99613	99.99613
Provincial Average	99.99488	99.99488	99.99283	99.99283
National	99.99724	99.99724	99.99613	99.99613

Table S 2 Predicted results for solar suitability by scenarios and land use filters. Each table cell value represents the remaining percentile of land areas after achieving the designated energy development targets. "All But NNR" filters out water, built-up, and farmlands. "Full Filter" also excludes National Nature Reserves (NNR) of China as well.

Percentiles (%) of Land Area Remained	**Biz-as-Usual Scenario**		**Announced Pledge Scenario**	
	All But NNR	**Full Filter**	**All But NNR**	**Full Filter**
Anhui	94.47	94.47	87.89	87.89
Beijing	96.85	96.85	93.10	93.10
Chongqing	99.68	99.68	99.29	99.29
Fujian	99.14	99.14	98.12	98.12
Gansu	98.43	98.43	96.57	96.57
Guangdong	97.98	97.98	95.58	95.58
Guangxi	99.53	99.53	98.97	98.97
Guizhou	97.50	97.50	94.53	94.53
Hainan	98.65	98.65	97.04	97.04
Hebei	90.29	90.29	78.74	78.74
Heilongjiang	98.94	98.94	97.67	97.67
Henan	95.41	95.41	89.95	89.95
Hubei	97.74	97.74	95.06	95.06
Hunan	99.16	99.16	98.15	98.15
Inner Mongolia	98.99	98.99	97.78	97.78
Jiangsu	91.17	91.17	0.00	0.00
Jiangxi	97.84	97.84	95.27	95.27
Jilin	98.54	98.54	96.80	96.80
Liaoning	97.73	97.73	95.03	95.03
Ningxia	84.93	84.93	66.98	66.98
Qinghai	98.77	98.77	97.31	97.31
Shaanxi	96.73	96.73	92.85	92.85
Shandong	88.37	88.37	0.00	0.00
Shanghai	90.74	90.74	0.00	0.00
Shanxi	94.67	94.67	88.32	88.32
Sichuan	99.82	99.82	99.62	99.62
Tianjin	90.76	90.76	79.77	79.77
Tibet (Xizang)	99.95	99.95	99.89	99.89
Xinjiang	99.43	99.43	98.75	98.75
Yunnan	99.62	99.62	99.17	99.17
Zhejiang	92.74	92.74	84.09	84.09
Provincial Average	96.28	96.28	84.27	84.27
National	98.63	98.63	96.99	96.99

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Salute, me familia. To the island of cakes, ice creams, coconuts, and bananas – in a sustainable future!