nature portfolio

Peer Review File

Land use impacts the environmental benefits of wind energy farms in China

Corresponding Author: Dr Jinfeng Chang

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Chang,

Your manuscript titled "Accounting for Land-Use Change Is Critical to Avoid Overstating the Climate Benefits of Wind Energy" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to
• address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid or relevant to the editorial threshold as outlined below)
AND
• meet our editorial thresholds as outlined below,

then we would be happy to look at a revised manuscript.

In the following, we list our minimum requirements for publication.

*** Present compelling new insight into the impact of wind farm expansion on land use change and greenhouse gas emissions

*** Provide a comprehensive overview of the related literature, methodological details, including all data and derivations used and scenario assumptions.

*** Provide an in-depth analysis of your scenarios and uncertainties, account for site-specific data related to wind energy production and dynamic vegetation change, and ensure your analysis robustly supports your claims.

If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

Link Redacted

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Martina Grecequet, PhD
Associate Editor,
Communications Earth & Environment
@CommsEarth

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements (Download the link to your computer as a PDF.)

For Manuscripts that fall into the following fields:
• Behavioural and social science
• Ecological, evolutionary & environmental sciences
• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.zip

For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review Communications Earth & Environment
This article seeks to quantify and compare the land use change greenhouse gas emissions impact of expanding wind farms, considering land use type and soil-vegetation type. The work is focused and takes a systematic approach, employing life cycle assessment (LCA) to analyse alternative lands expected to be placed into service for wind energy. The analysis is well developed and the authors build a strong case for the analysis based on prior studies of wind deployment. Dividing contributions to C emissions from loss in biomass, loss of soil organic carbon (SOC) and loss of C sink capacity, the authors found the greatest GHG emissions for forest wind farms (FWF), followed by grass wind farms (GWF) and finally by desert wind farms (DWF).
Results from this study present important data that should not be ignored in GHG accounts of renewable energy. While the findings are quite small compared with GHGs from coal and other fossil fuel, they are important to consider when planning wind onshore farms.
The methods applied by the authors appear to be robust in applying the LCA framework and gathering data from three specific locations (Fig. 7) and LUC-land cover change from the Century model. But how can the results remain robust for wind capacity for electricity generation in other locations? What is the expected variability in wind capacity together with LUC-GHG effects for other extreme locations suitable for wind power? The authors should address this point in their sensitivity analysis.
Other Comments:
1. Although the introduction offers a very focused case on LUC in energy via LCA approaches, it did not do a broad survey of how others have analyzed land and GHG emissions for other forms of energy. Potentially, this work takes some inspiration from studies of biofuels, which have examined the LUC-GHG footprint from direct emissions (e.g., doi:10.1126/science.1152747) and indirect emissions (10.1186/s13068-017-0877-y). Furthermore, other studies have also examined these effects for unconventional oil and gas (see, 10.1021/es1013278). Some survey of this kind of literature and its relevance to wind would be beneficial.
2. Table 1 data have too many significant digits; this needs correction.

3. Overall, the paper is clearly written; however, there are numerous awkward phrasings and use of incorrect prepositions and articles: lines 21 and 48, remove “the” before “climate”; line 58, missing “are”;

Reviewer #2 (Remarks to the Author):

This study conducted a life cycle carbon emission study on wind energy in China, focusing on the impact of land use change caused by wind energy. This study could potentially contribute to the regionalized life cycle assessment and the life cycle inventory availability of the directly impacted land of wind farms.
The main issue of the manuscript is that it was conducted on a small scale without enough depth of analysis or effort in data collection. The study was conducted at a relatively small scale, with only three wind farms; the life cycle assessment is not supported by a sufficient number of primary data, and the result analyses also do not include sufficient details/depth.
The only primary data is the manually annotated land use data. Key parameters, such as the amount of electricity generation, the value and the changes in capacity factor, and the land reclaiming process, are not impractical to collect for a small-scale analysis like this one, but in the study, the authors used simplified assumptions. As a result, the analysis is weak, especially since the key parameters of wind energy are sensitive to time.
Typically, the authors did not consider the changes in electricity generation during the lifetime of a turbine. The turbine performance (i.e., the capacity factor) is impacted by the maintenance of the turbines, and previous studies have shown that this can be dependent on energy policy (Hamilton et al. Joule. 2020).
The authors did not quantify the original land use during the construction of wind power projects, and the quantification procedure is not consistent among the three wind farms. It looks like the authors have recognized the partial reclaim process of the cable area between turbines (Figure 7c). However, the authors only included part of them (i.e., for typical turbines). The authors have not clarified why they addressed these differently. Additionally, the land use data is also not consistent. In Figure 7c, part of the cable areas is annotated, whereas no corresponding areas have been annotated for Figure 7 a and Figure 7b. Also, there are no images showing the whole picture of the wind farms. So it is hard to determine if a long access road is needed. Recent studies on wind in the US show that wind farms may require a long access road when they are located in a remote area. So, it is reasonable to guess that in China similar situation happens, especially in the forest case.
The authors considered all the annotated land use as permanent land use in the baseline scenario and they did not consider the impact of turbine size, which combined shows that the authors lack of understanding of the land use of wind farms. After the installation, the circular clearings, the cable area, and other disturbances will undergo a vegetation recovery process, which indicates using remote sensing imagery only captures a typical time point. The authors have also not tried incorporating this process as part of the baseline scenario. In the “Large-scale turbine deployment scenario,” the authors only considered the impact of material use but neglected the effect of land use change of a larger turbine. This scenario does not look valid. Larger turbines need larger space to site them.

Some minor comments.
Line 39. Please consider changing * to \cdot
Line 74. Please revise the citation (too many names)
Fig. 6. 1) Is wind considered a resource input or resource depletion? (Wind is currently listed as an input); 2) could you please try to separate the assemble stage and the onsite-installation stage? The current workflow sounds misleading and is not consistent with the description in the supporting material.
Line 447. Please consider revising “Life cycle interpretation” to something similar to “result interpretation.”
Uncertainty analysis. Please provide a list of uncertainty sources in the entire analysis.
Supporting Materials.
1. Please consider adding the time construction of the projects and provide more information regarding the turbine models (if they are not confidential).
2. The lifetime of a wind farm with 20- 25-year-old turbines looks small for modern turbines. The use of Denmark may lack representativeness as turbines there are older.
3. It looks to me that a land recovery scenario should be included in a baseline scenario.

Reviewer #3 (Remarks to the Author):

This is a well written and organized manuscript that used LCA to simulate carbon dynamics at wind farms. The concept is quite good and I agree with the authors that the work is relevant and needed. I do not know if the paper was limited by page constraints, but there is simply not enough detail in the methods to fully assess the work and I’m concerned some of the assumptions made, and the structure of the scenarios call the results into question. I have a few general statements then provide some line by line comments.

In the introduction, the authors sometimes use citations that are not the best fit for their statements and make overly broad, vague statements about wind energy impacts that simply are not yet supported though may be in the future.

The methods are not well-explained and this leads me to a number of concerns.
First, I’m concerned the ‘baseline’ scenario, that is the focus of the main results and conclusions of the paper is unrealistic and over-estimates carbon losses. The main analysis seems to assume the land change at wind farm is permanent for all 20 years and there is no recovery of the vegetation/carbon dynamics. The authors don’t explain this clearly, but scenario 5 is

land recovery. Land recovery will happen naturally, and in some systems (like grasslands) it can be very fast if there is enough rainfall. Furthermore, in forest systems, the disturbed land will often convert to either grasslands or shrublands depending on the environment and how the vegetation is managed. It is entirely unrealistic to assume vegetation recovery and carbon dynamics are static after construction. The “baseline” scenarios should all include some amount of ecological succession (a fundamental concept) and temporal patterns in carbon dynamics. This should be the basis of analyses.
Second, The scenarios are not explained at all and need to be. 468-474 is simply not enough detail.
Third, the energy production analysis using wind Ninja and Merra is not explained. This work is detailed and should include uncertainty that does not seem to be input into the LCA. Its very confusing.

Detailed comments

57. This is a better citation. It uses better methods than older papers and shows “of 148 specimens that onshore wind farms are the second most dilute source for power generation based”. Nøland, J. K., Auxepaules, J., Rousset, A., Perney, B. & Falletti, G. Spatial energy density of large-scale electricity generation from power sources worldwide. Sci Rep 12, 21280 (2022).

60. “large amount” is quite vague. Diffendorfer et al, suggested ~2% loss of undeveloped land around wind facilities but not (I did not see it) calculate a capacity density. Some might consider their 2% small. It might be better here, to find papers that project the amount of land that may be required for new wind energy. I believe papers by Rebecca Hernandez’s lab may have some of these. I’m less aware of such projections outside of North America but feel I’ve seen one from agroup in the UK. I cannot find it right now!
63. “large” again. See. https://doi.org/10.1016/B978-0-12-819727-1.00018-2. This is done by leading wind meteorologists (much more knowledgeable then Keith..whose paper has been criticized). They state: “Despite increasing number of research efforts, our assessment of potential WF impacts is still very limited. Although the WF impacts are mostly local and limited to the near-surface ABL, this is the layer where we live and plants grow. Hence, more studies are needed to improve our understanding of WT-atmosphere-surface interactions and our capability to model and project the weather, climatic and ecological impacts of large WFs.”
Figure 6. typo. Ramoval change to removal.

397. How did you do this? Custom code, does renewable.ninja do it for you? Did you use the WRF? There are lots of assumptions and methods here that are not explained. There should be lots of uncertainty in these models and these could be fed into the LCA to better characterize the overall uncertainty in total carbon budget.

** Visit Nature Research's author and referees' website at www.nature.com/authors for information about policies, services and author benefits**

Communications Earth & Environment is committed to improving transparency in authorship. As part of our efforts in this direction, we are now requesting that all authors identified as ‘corresponding author’ create and link their Open Researcher and Contributor Identifier (ORCID) with their account on the Manuscript Tracking System prior to acceptance. ORCID helps the scientific community achieve unambiguous attribution of all scholarly contributions. You can create and link your ORCID from the home page of the Manuscript Tracking System by clicking on ‘Modify my Springer Nature account’ and following the instructions in the link below. Please also inform all co-authors that they can add their ORCIDs to their accounts and that they must do so prior to acceptance.
https://www.springernature.com/gp/researchers/orcid/orcid-for-nature-research

For more information please visit http://www.springernature.com/orcid

If you experience problems in linking your ORCID, please contact the Platform Support Helpdesk.

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Chang,

First of all, please allow me to apologise for the delay in sending a decision on your manuscript titled "Accounting for Land-Use Change Is Critical to Avoid Overstating the Climate Benefits of Wind Energy". It has now been seen by 3 reviewers, and we include their comments at the end of this message. Please note that reviewer 4 replaces reviewer 3, who is no longer available. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. In particular for publication in Communications Earth & Environment we request that you (1) discuss limitation of sample size and agriculture land use compatibility and provide appropriate references for turbine performance, and (2) address the uncertainties in wind speed data and land use data as suggested by reviewer 4. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Martina Grecequet, PhD
Senior Editor,
Communications Earth & Environment
@CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

For Manuscripts that fall into the following fields:
• Behavioural and social science
• Ecological, evolutionary & environmental sciences
• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.pdf

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist: Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at <a href="http://www.nature.com/authors/policies/data/data-availability-statements-data-

citations.pdf">http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I have reviewed the comments provided by the authors. The authors have worked extensively to broaden the paper's analysis, with a deep and thoughtful analysis of sensitivity to test variability due to scale and time and physical factors. In my judgement, they have made significant additional analysis to test the variability in LUC effects according to location. The added sensitivity analysis examined site-specific locations with wind farms to generate a range of emissions.
A comment related to the response to Reviewer 2 on the limited data and scale of the analysis: the authors cannot expect to create a "precise" and good LCA, they should aim for accurate with some degree of uncertainty.
While the paper and analysis are very robust, I found the paper to need a thorough review to correct English language in numerous areas within the paper. For example, the abstract has many missing prepositions and incorrect choice of words. Take for example, the first sentence: the word "demands" should be "demand" and "climate goal" should be "climate goals". On line 29, it should say, "during the installation stage...". The paper has many examples of awkward sentences like this that must be addressed if accepted for publication.

Reviewer #2 (Remarks to the Author):

The manuscript has greatly improved after the revisions, and the authors have addressed most of my previous comments. However, two remain unaddressed.

First, the limitations arising from the small sample size can still be significant. Land use patterns within a typical wind farm tend to be quite uniform, as can be seen from Fig 7. Therefore, using only a single wind farm to represent an entire category may not be representative due to variations in turbine size, leading to potential bias in the results. This is particularly important as the authors tried to generalize the results beyond the specific case studied. The authors argued that "we identified and analyzed a total of 128 forest wind farms, 141 grassland wind farms, and 124 desert wind farms from the harmonized global datasets of wind and solar farms...". However, this dataset appears to focus on wind capacity rather than land-use patterns. The lack of land-use data for these farms weakens the representativeness of the sample size and could undermine the validity of the sensitivity analysis.

Second, addressing the decline in wind turbine performance by directly using data from Ref. 59 (Hamilton et al., Joule 2020) may be problematic. Ref. 59 explicitly attributes performance differences to **"loss of eligibility for the production tax credit"**. Therefore, the decreasing performance numbers may not be applicable to wind farms in China.

In addition, the authors did not discuss agricultural areas for wind farm deployment, despite including a section titled "Where to build wind farms". This omission could be significant because:
The Chinese government actively encourages integrating wind energy in agricultural areas (e.g., https://www.gov.cn/lianbo/bumen/202404/content_6942962.htm; http://paper.people.com.cn/rmrb/html/2024-04/05/nw.D110000renmrb_20240405_1-02.htm). Previous studies (e.g., Diffendorfer and Compton, 2014, PLOS One; Dai and Scown, 2025, Renewable and Sustainable Energy Reviews) demonstrate that land use changes in agricultural areas are minimal when wind farms coexist with agricultural activities. The authors should address this gap by discussing agricultural land use compatibility or by explaining why they are not included in the study scope.

Minor:
Line 87: Please consider using an alternative word for "proved".
Line 195: Remove the duplicate "that".
Line 332: Correct "life inventory" to "lifecycle inventory". Additionally, perform thorough proofreading to resolve similar errors.
Line 394: I recommend reproducing Figure 7 to include both an overview of the wind farm and detailed information on land use. It appears that this image has not been updated, as the authors mentioned they included the previously missing cable areas in response to my earlier comments.
Line 515: Reformulate scenario labels for consistency (e.g., "Slifetime:" instead of "Slifetime").
Line 565: Add a citation for the equation source, as noted in the rebuttal letter.

Reviewer #4 (Remarks to the Author):

The authors have delivered an interesting analysis on LUC emissions caused by wind parks for China. The analysis is relevant and timely, but there are significant methodological limitations which have to be addressed before publication.

*** Uncertainty in wind speed data ***

My largest concern is the use of MERRA-2 wind speed data without bias correction. As shown in [1], MERRA2 overestimates wind power generation for many world regions, and reanalysis data in general is too coarsely resolved to match wind conditions at wind park sites. The error of MERRA2 can be higher than 30% [1]. When using bias-correction with the global wind atlas, the error range can be reduced [1]. The headline results of the paper strongly depend on the capacity factors of the wind turbines. Please note that the capacity factor varies by a factor of 2 between the three wind parks and that the wind park with lowest generation has a capacity factor of only 13%. It seems unlikely that this is a sensible value for economic operation. I therefore strongly encourage to bias correct the used wind speed data with the global wind atlas (or another spatially highly resolved product) and assess generation data in detail.

As [1] shows that the current version 3 of the global wind atlas is overestimating wind resources, we recommend using version 2, which can be found online at [5]. A new version of the global wind atlas will come online soon, where the currently existing bias will be corrected, but it is unclear when this happens.

Furthermore, it would be great to see a boxplot that compares generation of turbines per land-use types for all sampled locations.

*** Uncertainty in land-use data ***
The uncertainty in land-use data is also high, as only three locations have been sampled. Instead of using generic 20% assumptions in your sensitivity analysis, you could use the data from two recent publications to have an empirical foundation for your sensitivity analysis. [2] reports land-use requirements of wind power in China for many installations, and [3] gives a global overview. This should better inform your sensitivity analysis and your estimates.

*** Language ***
The language needs to be improved, potentially with the help of a large language model. Parts of the text are hard to understand.

*** Minor issues ***
"For other energy forms that are less land intensive than wind energy, studies have found it takes non-negligible LUC induced emissions."

Wind power is one of the most least land intensive energy generation technology, this sentence gives a wrong impression [4].

"Over one-third of emissions were overlooked when excluding carbon loss-related indirect emissions. "

This is clear from the sentence before, the sentence can be removed.

"In order to compare the influence of different factors on life cycle GHG emissions and energy performance, we conducted ±20% changes and Monte Carlo sensitivity analysis in key factors and assumptions including capacity factor."

I thought you used actual wind park locations to vary the capacity factor? Can you explain better?

Table 1: Generation is given per turbine, not per installed capacity in MW. Please report also report Generation(GWh)/capacity(MW) to facilitate comparison between parks.

Table S1: add turbine power (likely given by the turbine name, but still relevant information)!

Table 1: Also report land conversion per installed capacity (i.e. MW) instead of generation only to be able to compare to other sources, which mostly report in capacity than in generation.

[1] https://www.sciencedirect.com/science/article/pii/S0360544221017680#fig5
[2] https://iopscience.iop.org/article/10.1088/1748-9326/add7ee
[3] https://www.cell.com/one-earth/fulltext/S2590-3322(24)00475-5
[4] https://unece.org/sites/default/files/2022-04/LCA_3_FINAL March 2022.pdf
[5] https://silo1.sciencedata.dk/shared/cf5a3255eb87ca25b79aedd8afcaf570?path=/GWA2.1

** Visit Nature Research's author and referees' website at www.nature.com/authors for information about policies, services and author benefits**

Communications Earth & Environment is committed to improving transparency in authorship. As part of our efforts in this direction, we are now requesting that all authors identified as ‘corresponding author’ create and link their Open Researcher and Contributor Identifier (ORCID) with their account on the Manuscript Tracking System prior to acceptance. ORCID helps the scientific community achieve unambiguous attribution of all scholarly contributions. You can create and link your ORCID from the home page of the Manuscript Tracking System by clicking on ‘Modify my Springer Nature account’ and following the instructions in the link below. Please also inform all co-authors that they can add their ORCIDs to their accounts and that they must do so prior to acceptance.
https://www.springernature.com/gp/researchers/orcid/orcid-for-nature-research

For more information please visit http://www.springernature.com/orcid

If you experience problems in linking your ORCID, please contact the Platform Support Helpdesk.

Version 2:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Chang,

Your manuscript titled "Accounting for Land-Use Change Is Critical to Avoid Overstating the Climate Benefits of Wind Energy" has now been seen by our reviewers, whose comments appear below. In light of their advice, we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment. Under the condition that you clarify bias correction when estimating wind power output for the geographical locations and discuss the limitations of your approach.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time, we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right-hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication. For further information about article processing charges, open access funding, and advice and support from Nature Portfolio, please visit https://www.nature.com/commsenv/open-access

At acceptance, you will be provided with instructions for completing the open access licence agreement on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Martina Grecequet, PhD
Senior Editor,
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

The authors have addressed all my comments, and the paper has greatly improved. While the study is still limited by its sample size, I think there is no need for another iteration of review. Regarding Reviewer #3's original comment, "Line 565...", the added reference #57 in the revised manuscript does not look correct. The equation (now located in Line 594) should be from the Eq. S10 in the Supporting Information in Dai et al. (2024) Environmental Science & Technology (https://doi.org/10.1021/acs.est.3c07908). Please also add an equation number for this equation. Please double-check other references, especially the equations used in the calculations, so readers can find the sources correctly.

Reviewer #4 (Remarks to the Author):

The authors have conducted a thorough revision of the manuscript and have addressed most of my concerns and the paper is almost ready for publication.

However, there remains one important open issue which clearly has to be addressed before publication:
You state that "The substantial variation of emission intensity caused by capacity factor reflected the diverse wind potential across 183 geographical locations, particularly for forest-located farms."
And indeed, the variation in capacity factors still seems to be high in the sensitivity analysis.

However, it is unclear if you have used the global wind atlas bias correction when estimating wind power output for the 183 geographical locations, which were used in the sensitivity analysis. Please clarify in methods. If you did not do so, bias-correction has to be included. If you did use bias-correction and capacity factor variation is still high, please discuss the limitations of your approach in the discussion section. Even with bias-correction, estimating wind power output from global climate data may introduce significant bias - this can be stressed in the discussion. This applies in particular to cases where capacity factors are below any economic viability.

** Visit Nature Portfolio's author and referees' website at www.nature.com/authors for information about policies, services and author benefits**

Open Access This Peer Review File is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.
In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.
The images or other third party material in this Peer Review File are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.
To view a copy of this license, visit https://creativecommons.org/licenses/by/4.0/

Dear Editor and Referees,

We would like to thank the three Referees for their valuable comments on the content of our manuscript and their suggestions for improving the document. Following the suggestions and comments, we carefully revised our manuscript (referred to as MS hereafter). We believe that the revised version satisfactorily addresses the referees' questions and concerns, and that the manuscript has improved as a result. In this reply, we seek to clarify the issues, raised by the referees, point by point. Please find the detailed response (in blue) to the referees' comments (in black). For your convenience, all the changes in the revised MS are in red, and the corresponding line numbers are noted in the point-by-point responses.

Thank you again for your time and efforts on our manuscript.

Yours sincerely,

Jinfeng Chang on behalf of all co-authors

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review Communications Earth & Environment

This article seeks to quantify and compare the land use change greenhouse gas emissions impact of expanding wind farms, considering land use type and soil-vegetation type. The work is focused and takes a systematic approach, employing life cycle assessment (LCA) to analyse alternative lands expected to be placed into service for wind energy. The analysis is well developed and the authors build a strong case for the analysis based on prior studies of wind deployment. Dividing contributions to C emissions from loss in biomass, loss of soil organic carbon (SOC) and loss of C sink capacity, the authors found the greatest GHG emissions for forest wind farms (FWF), followed by grass wind farms (GWF) and finally by desert wind farms (DWF).

Results from this study present important data that should not be ignored in GHG accounts of renewable energy. While the findings are quite small compared with GHGs from coal and other fossil fuel, they are important to consider when planning wind onshore farms.

The methods applied by the authors appear to be robust in applying the LCA framework and gathering data from three specific locations (Fig. 7) and LUC-land cover change from the Century model. But how can the results remain robust for wind capacity for electricity generation in other locations? What is the expected variability in wind capacity together with LUC-GHG effects for other extreme locations suitable for wind power? The authors should address this point in their sensitivity analysis.

[Response] We sincerely appreciate the reviewer's thoughtful and positive feedback on our manuscript and the insightful suggestion. To address the concern regarding potential uncertainty of life-cycle GHG intensity and energy performance due to variations in wind potential for electricity generation across different locations, we conducted a comprehensive sensitivity analysis in the revision. We expanded our study to consider the variation in wind capacity of China's onshore wind farms across different regions. Specifically, we first identified all China's wind farms located in forests, grasslands and deserts from the harmonized global datasets of wind and solar farm database (Dunnett et al., 2020). A total of 128 forest wind farms, 141 grassland wind farms, and 124 desert wind farms were identified, covering a wide range of area across China (Fig. S2). Based on MERRA-2 wind speed data and power curves, we further calculated the capacity factor for the entire 20-year lifecycle of all these wind farms. The capacity factors calculated from these geographically representative wind farms were used as inputs in the LCA model to quantify the uncertainty ranges for the three selected wind farms. To assess the uncertainty of other factors including material consumption, life time, land-use area, transport distance and curtailment rate, ±20% changes in key factors and assumptions combined with Monte Carlo simulation were applied to the LCA modelling. The description of the methods was added in the Methods section (Page 24, Line 494-508), and the results were illustrated in Fig. 4 and presented in the Results section (Page 11, Line 178-193). It can be seen from Fig. 4 that the results for our selected three wind farms (one from each of forest, grassland, and desert) fall within the interquartile range of the sensitivity analysis outcomes, indicating that our chosen sites are representative of the broader range observed across China's wind farms. Therefore, we concluded that while there may be variability in wind capacity and associated LUC-GHG effects among different locations, our case studies capture the essential characteristics and provide a reliable basis for understanding these impacts. The selected wind farms could be considered representative for understanding the wind capacity for electricity generation and associated LUC-GHG effects in other locations across China.

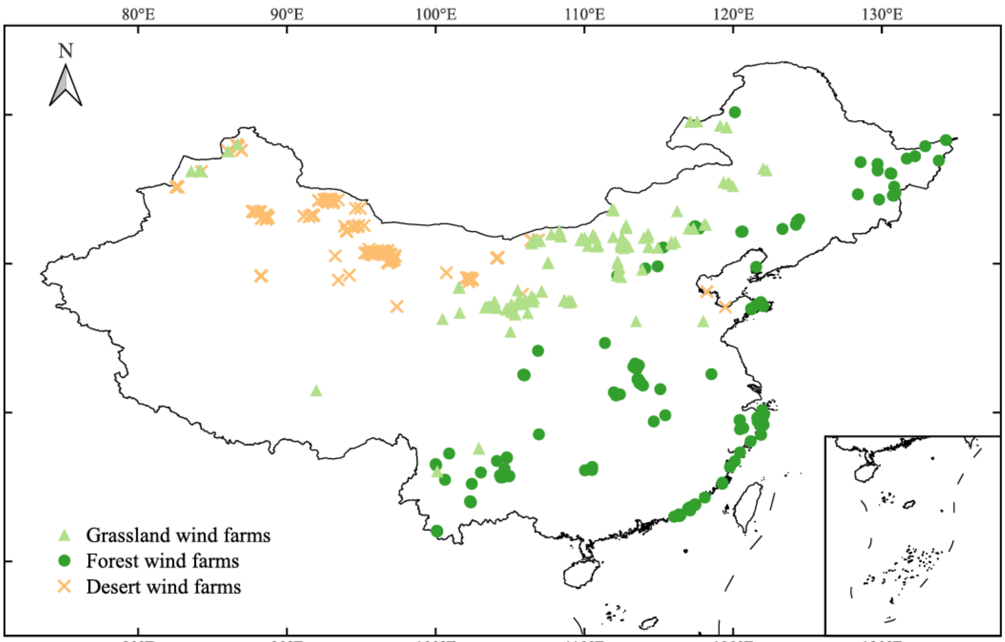

Fig S2 The spatial distribution of China's 393 wind farms and their land cover types.

Reference:

Dunnett, S., Sorichetta, A., Taylor, G. & Eigenbrod, F. Harmonised global datasets of wind and solar farm locations and power. *Scientific Data* 7, 130 (2020).

Other Comments:

1. Although the introduction offers a very focused case on LUC in energy via LCA approaches, it did not do a broad survey of how others have analyzed land and GHG

emissions for other forms of energy. Potentially, this work takes some inspiration from studies of biofuels, which have examined the LUC-GHG footprint from direct emissions (e.g., doi:10.1126/science.1152747) and indirect emissions (10.1186/s13068-017-0877-y). Furthermore, other studies have also examined these effects for unconventional oil and gas (see, 10.1021/es1013278). Some survey of this kind of literature and its relevance to wind would be beneficial.

[Response] Thanks for your suggestions. In the revised MS, we have cited the references regarding LUC induced GHG emissions of other energy forms to provide a broader background to emphasize the potentially important role of the LUC related emissions associated with other forms of energy. The revised text now reads as follows: "For other energy forms that are less land intensive than wind energy, studies have found it takes non-negligible LUC induced emissions. For example, for unconventional oil and gas, LUC induced emissions accounted for 4% of the life cycle emissions[22]. For renewables like solar photovoltaics, neglecting changes of carbon flux will result in an underestimation of emissions by 25%-51%[23]. GHG emissions of biofuels from LUC even produce much more CO2 than GHG reduction they provide by replacing traditional fossil fuels[24], especially for intensified production[25]. Therefore, it is imperative to integrate LUC induced GHG emissions from wind energy. The neglection of the carbon losses from LUC leads to incomplete and falsely estimation of life cycle GHG emissions and overestimation of wind's climate change mitigation potential compared to other energy sources."

We believe that these revisions address your concerns and provide a broader context for our study on LUC-GHG emissions in wind energy.

2. Table 1 data have too many significant digits; this needs correction.

[Response] We have revised Table 1 by setting all decimal places to one digit, ensuring both accuracy and readability.

3. Overall, the paper is clearly written; however, there are numerous awkward phrasings and use of incorrect prepositions and articles: lines 21 and 48, remove "the" before

“climate”; line 58, missing “are”;

[Response] We corrected these mistakes and checked the similar phrasing across the revised MS.

Reviewer #2 (Remarks to the Author):

This study conducted a life cycle carbon emission study on wind energy in China, focusing on the impact of land use change caused by wind energy. This study could potentially contribute to the regionalized life cycle assessment and the life cycle inventory availability of the directly impacted land of wind farms.

The main issue of the manuscript is that it was conducted on a small scale without enough depth of analysis or effort in data collection. The study was conducted at a relatively small scale, with only three wind farms; the life cycle assessment is not supported by a sufficient number of primary data, and the result analyses also do not include sufficient details/depth.

The only primary data is the manually annotated land use data. Key parameters, such as the amount of electricity generation, the value and the changes in capacity factor, and the land reclaiming process, are not impractical to collect for a small-scale analysis like this one, but in the study, the authors used simplified assumptions. As a result, the analysis is weak, especially since the key parameters of wind energy are sensitive to time.

[Response] Thank you for your valuable suggestion, which have helped us to improve the rigor and depth of our study. Below, we address your concerns in detail and explain the enhancements we have made to strengthen our analysis.

(1) Scale and depth of the study

You raised a valid point regarding the relatively small scale of our study, which initially focused on only three wind farms. While we acknowledge that expanding the sample size could enhance the generalizability of our findings, we would like to emphasize that our analysis of these three wind farms was highly detailed and comprehensive. We collected extensive primary data, including material quantities, wind turbine specifications, power curves from manufacturers, and detailed emission factors. These data allowed us to develop LCA models with a high degree of precision. However, we understand your concern about the limited number of wind farms analyzed.

To address this, we have now expanded the scope of our study by incorporating a sensitivity analysis using the Monte Carlo method, taking into account the wind potential variation of comparable wind farms located in various geographical locations across China (for details, also see our response to Reviewer #1 above). Specifically, we identified and analyzed a total of 128 forest wind farms, 141 grassland wind farms, and 124 desert wind farms from the harmonized global datasets of wind and solar farm database (Dunnett et al., 2020), covering a wide range of areas across the country (Fig. S2). This broader dataset and analysis covers a wide range of locations and ecological conditions, thereby enhancing the reliability and applicability of our findings. By considering variations in wind potential, ecological conditions, and turbine performance, we believe our conclusions are more representative and applicable to a wider context. It can be seen from Fig. 4 that the results for our selected three wind farms (one from each of forest, grassland, and desert) fall within the interquartile range of the sensitivity analysis outcomes, indicating that our chosen sites are representative of the broader range observed across China's wind farms.

(2) Data quality and depth of analysis

You noted that key parameters such as electricity generation, capacity factors, and land reclamation processes were based on simplified assumptions. While we agree that these parameters can significantly influence the results, we would like to clarify that our assumptions were carefully validated and justified.

i) We used wind speed data and power curves to accurately calculate capacity coefficients and electricity generation. This approach, combined with our comprehensive data collection, ensures that our estimates are reliable. In the revised manuscript, we have provided detailed information on our scenario assumptions and incorporated the performance decline of wind turbines over time into our model (following your suggestion below). This enhancement allows us to capture the dynamic changes in wind energy production more accurately.

ii) To improve our analysis of LUC impact, we integrated the CENTURY model to simulate vegetation restoration processes according to your suggestions. This model captures the dynamic recovery of vegetation in its natural state, providing a more realistic assessment of the carbon sequestration potential of reclaimed land. We have also accounted for land-use changes resulting from the replacement of turbines in a large-scale (6 MW) turbine deployment scenario according to your suggestion.

(3) Methodological improvement

To further strengthen our analysis, we conducted a comprehensive sensitivity analysis using the Monte Carlo method to evaluate the impact of all potential input factors. This analysis ensures that our results are robust and that the key drivers of environmental impacts are clearly identified. Our decomposition results indicate that LUC and wind resources are the primary factors influencing the life cycle GHG emissions of wind farms across different ecosystems (Fig. 3).

In conclusion, we believe that these revisions have substantially enhanced the quality, depth, and reliability of our study. Our work establishes a more systematic framework for wind power LCA, expanding traditional boundaries to integrate industrial lifecycle carbon emissions and biological processes for natural ecosystem carbon storage and sinks. This represents an important advancement compared to traditional LCA studies and provides valuable insights into the environmental impacts of wind energy development.

Thank you once again for your constructive feedback, which has greatly improved our manuscript.

Typically, the authors did not consider the changes in electricity generation during the lifetime of a turbine. The turbine performance (i.e., the capacity factor) is impacted by the maintenance of the turbines, and previous studies have shown that this can be dependent on energy policy (Hamilton et al. Joule. 2020).

[Response] We sincerely appreciate your suggestion regarding the consideration of changes in electricity generation during the lifetime of a turbine, particularly the impact of maintenance on turbine performance and its dependency on energy policy, as highlighted by Hamilton et al. (2020). According to your suggestions, we now considered the wind turbines' performance declines with increasing usage time and thoroughly revised our analysis to account for the performance decline of wind turbines over their operational lifetime (Page 22, Line 459-465). Specifically, the calculated capacity factors of wind farms were assumed to decline 0.17%/year for the first 10 years of operation, following the newer vintages wind plants in the United States (be operational after 2008). According to the performance difference of newer and older vintages of wind plants, the decline rate of capacity factor for the second 10 years was assumed to be 0.41%/year and the year-10 drop was assumed to be 1.15% in this study (Hamilton et al., 2020). While these assumptions are derived from United States data, we acknowledge that the actual performance decline rates in China may differ due to factors such as local climate conditions, operational practices, and the specific technologies deployed. For instance, the harsher climatic conditions in some regions of China may lead to faster degradation of turbine components, while advancements in technology and maintenance practices could mitigate some of these effects. However, given the lack of directly comparable long-term performance data for China’s wind turbines (most of which were established in the 2010s), we chose to reference the United States data as a reasonable approximation. This approach ensures that our model incorporates the accelerated performance decline typically observed as turbines age, thereby enhancing the robustness and reliability of our conclusions. Further research incorporating localized data on turbine performance and maintenance practices in China would provide valuable insights and refine these assumptions. We believe this revision strengthens our analysis and addresses your concerns regarding the dynamic nature of turbine performance over time.

Reference:

Hamilton, S.D., Millstein, D., Bolinger, M., Wiser, R. & Jeong, S. How Does Wind Project Performance Change with Age in the United States? *Joule* 4, 1004-1020 (2020).

The authors did not quantify the original land use during the construction of wind power projects, and the quantification procedure is not consistent among the three wind farms. It looks like the authors have recognized the partial reclaim process of the cable area between turbines (Figure 7c). However, the authors only included part of them (i.e., for typical turbines). The authors have not clarified why they addressed these differently. Additionally, the land use data is also not consistent. In Figure 7c, part of the cable areas is annotated, whereas no corresponding areas have been annotated for Figure 7 a and Figure 7b. Also, there are no images showing the whole picture of the wind farms. So it is hard to determine if a long access road is needed. Recent studies on wind in the US show that wind farms may require a long access road when they are located in a remote area. So, it is reasonable to guess that in China similar situation happens, especially in the forest case.

[Response] Thanks for pointing out a potential confusion made in the manuscript. We clarified it below and revised the relevant description in the MS:

(1) In this study, we indeed conducted detailed quantifications of all permanent land occupation areas including the roads, foundation clearing areas, cable areas. The quantification procedure was the same in the three wind farms. To avoid any potential ambiguity, we have revised the relevant descriptions in the MS (Page 18. Line 387-389), and included complete remote sensing images of the three wind farms in the SI files (Fig. S2) to provide more intuitive data support.

(2) Regarding the absence of cable area annotations in Fig. 7a and 7b, this is due to the partial remote sensing images provided in the manuscript not encompassing these areas. To address this, we have annotated the cable areas in Fig. S3 of the supplementary materials for reference. Additionally, we understand that comparing pre- and post-installation remote sensing images to determine the surface area impacted by wind farms may result in apparent inconsistencies due to different image acquisition times and angles. We have fully considered and addressed these factors in our analysis.

(3) We agree that the long access road will pose a significant impact on final result. For the three studied wind farms, there is truly a long road for forest wind farm (Fig. S2a).

This road was included in the quantifications and considerations of land use impacts in our study. We now provided the complete images of the wind farms in the SI files (Fig. S2).

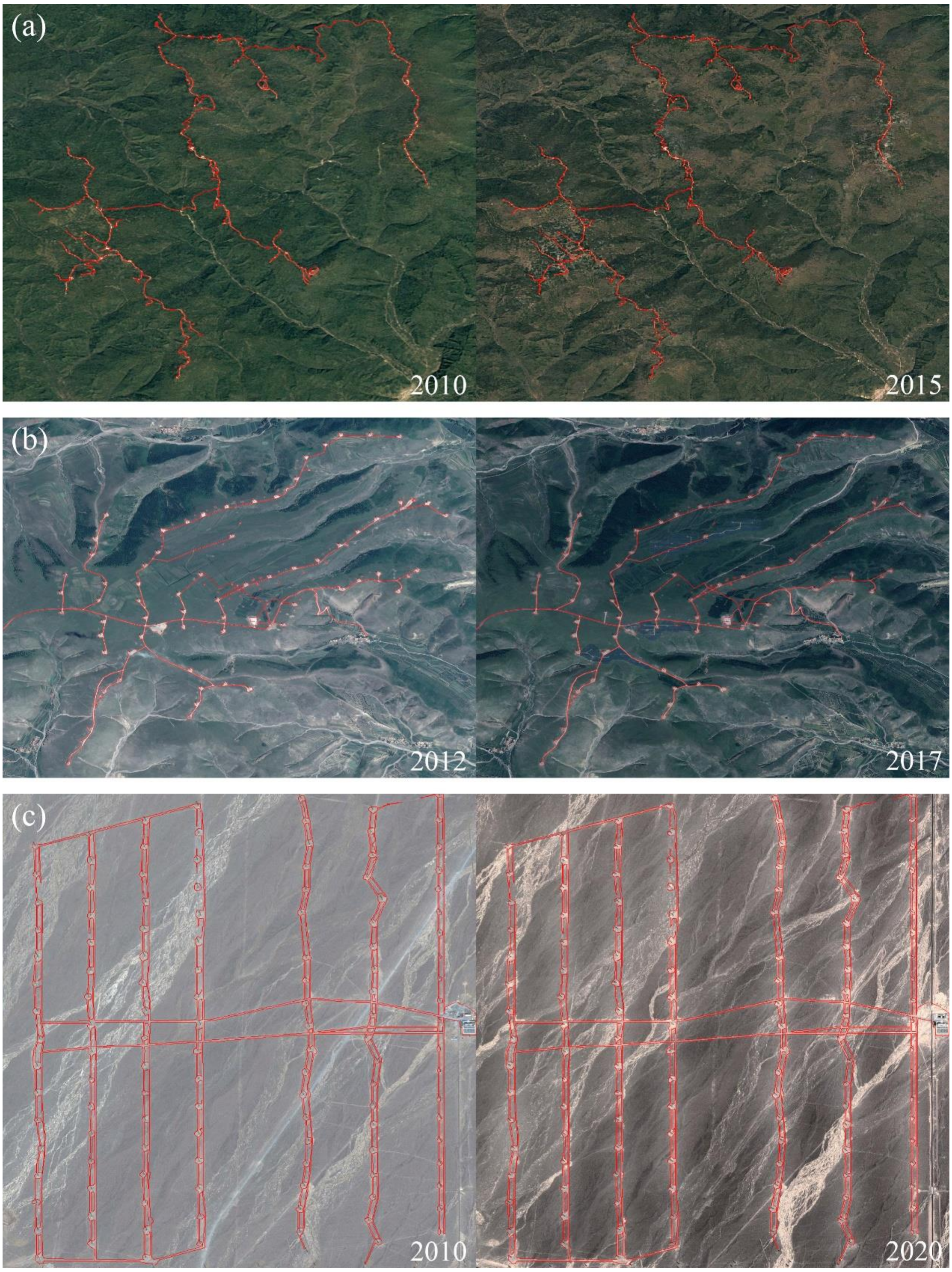

Fig. S2 The whole image of (a) forest wind farm, (b) grassland wind farm, and (c) desert wind farm from Google Earth Pro (version 7.3.6.10201).

The authors considered all the annotated land use as permanent land use in the baseline scenario and they did not consider the impact of turbine size, which combined shows that the authors lack of understanding of the land use of wind farms. After the installation, the circular clearings, the cable area, and other disturbances will undergo a vegetation recovery process, which indicates using remote sensing imagery only captures a typical time point. The authors have also not tried incorporating this process as part of the baseline scenario.

[Response] Thank you for the insightful comments. In our study, we determined the actual impact area of the wind turbines by analyzing the changes in land use before and after installation. We acknowledge that turbine size is indeed an important factor that can influence the land use area of wind farms. In the Large-scale (6MW) turbine deployment scenario, we have added the analysis of turbine size effect (see the response below).

Regarding the use of remote sensing imagery, we understand your concern that it may only capture a typical time point. It is important to note that we do not simply determine land occupation based on “a typical time point”. We have provided remote sensing images in the SI file (Fig. S3) that demonstrate the consistent land occupation over time. These images clearly shows that certain areas, such as roads, open spaces, and cable zones, remained unaltered even after the installation. This can be attributed to the ongoing maintenance requirements during the operational phase of the wind farms. We acknowledge your point regarding vegetation restoration, particularly in the grassland. In the revised MS, we incorporated the potential process of ecological succession into our analysis. Specifically, we simulated the regrowth of grassland plants in the second year of the wind farm’s operational life cycle. As a result, productivity recovered to 50% over a period spanning from the second to the sixth year, with both above-ground net primary productivity (ANPP) and below-ground net primary productivity (BNPP) gradually recovering from 0% to 50%. For the forest wind farms, we have taken into account the long-term presence of paved road surfaces for transportation purposes, as indicated by the remote sensing images. Consequently, we did not include vegetation restoration in the CENTURY model for these areas. However, for the wind field in the forest, due to maintenance reasons such as replacement and repair, we observed from satellite images that paved road surfaces and ground clearing areas still exist (Fig. S3a). Thus, we did not consider its restoration impact in our research. Similarly, for the desert wind farms (Fig. S3c), given the slow recovery of perennial vegetation and low biomass, we also did not consider vegetation restoration in the model. These clarifications and additional descriptions have been incorporated in detail in the Methods section (Page 21, Line 410-420) of our revised MS and that in the SI file (Page 6, Line 159-162).

In the "Large-scale turbine deployment scenario," the authors only considered the impact of material use but neglected the effect of land use change of a larger turbine. This scenario does not look valid. Larger turbines need larger space to site them.

[Response] Thank you for your comments. We agree that we should consider the differences in land use changes brought about by large-scale turbine deployment scenario. The use of larger turbines indeed requires more space for deployment, mainly due to the need to increase the spacing between turbines to ensure efficiency. Therefore, in the revised MS, we have now considered the impact of land use changes caused by larger turbine spacing distances as larger wind turbines. We adopted the formula from Dai et al., (2024):

$$\text{turbine spacing distance} = 0.39 * \text{rotor diameter}^{1.38},$$

and calculated the road length and corresponding land use impact for a large-scale turbine deployment scenario based on the turbine rotor diameter. The results showed that compared to the baseline scenario, the land use areas of FWF, GWF, and DWF increased by 82%, 7%, and 46% respectively. The results indicate that due to the increased land-use areas, the total effects on emission mitigation of the revised scenario have changed compared to the original scenario. Specifically, while the increase in turbine numbers contributes to enhanced overall power generation capacity, the increased land use areas may also bring additional LUC emissions. Therefore, when assessing the emission reduction effects of large-scale turbine deployment, it is essential to consider these factors comprehensively. In the revised MS, we have elaborated on these changes and their impacts on emission reduction, providing corresponding data and chart support (as shown in Figure 5). We believe these improvements will make the study more comprehensive and accurate, facilitating a better understanding of the environmental impacts of large-scale turbine deployment.

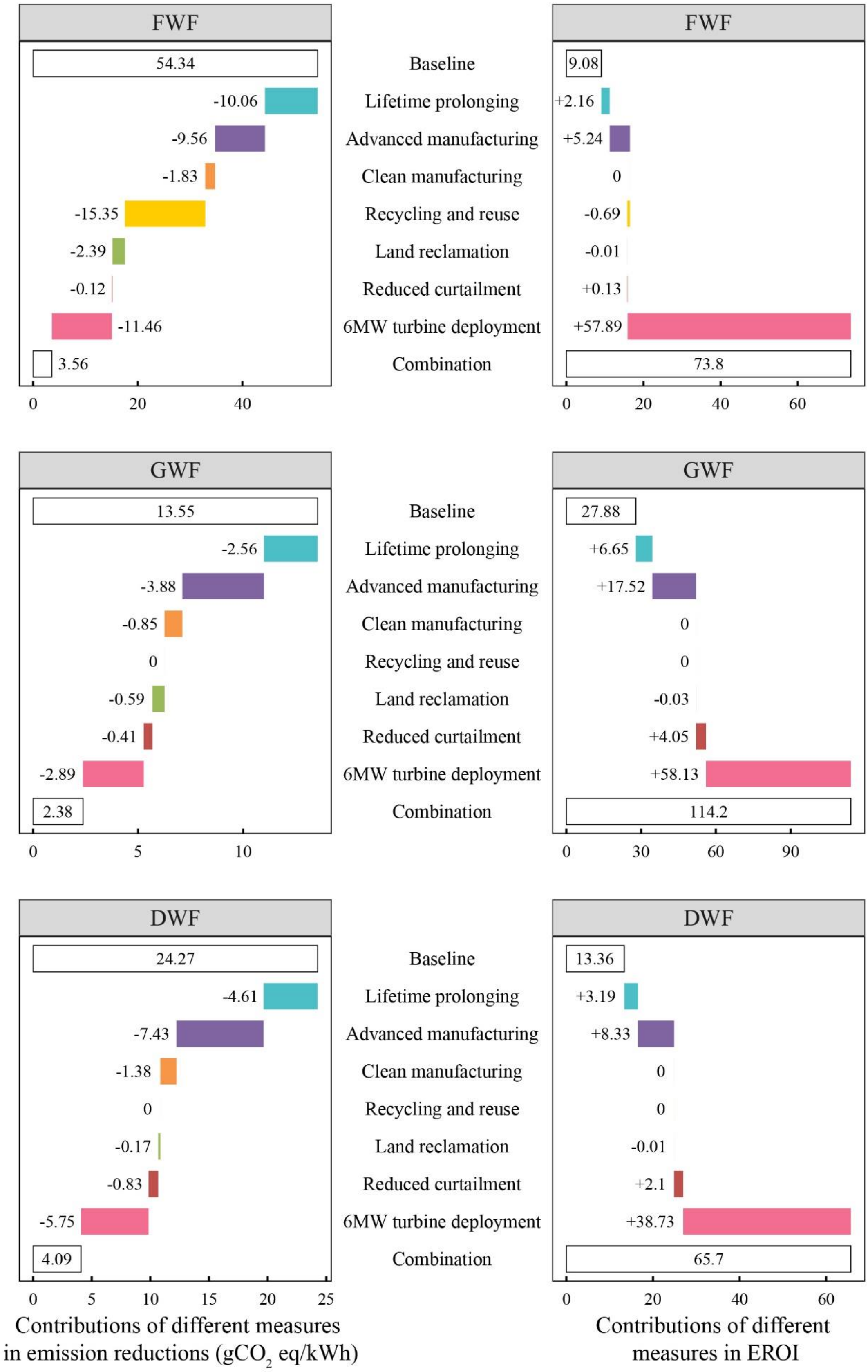

Fig. 5 The contributions of different measures in GHG emission mitigation of a) FWF; b) GWF; c) DWF and EROI increases of d) FWF; e) GWF; f) DWF.

Some minor comments.

Line 39. Please consider changing * to \cdot

[Response] We changed " * " to " · ".

Line 74. Please revise the citation (too many names)

[Response] We have revised the sentence.

Fig. 6. 1) Is wind considered a resource input or resource depletion? (Wind is currently listed as an input); 2) could you please try to separate the assemble stage and the onsite-installation stage? The current workflow sounds misleading and is not consistent with the description in the supporting material.

[Response] (1) Wind is considered as a resource input for the calculation. Wind speed directly affects the capacity factor, leading to changes in the life cycle electricity production. Therefore, in this study, wind was considered as an input factor. (2) In the revised MS, we have revised the presentation in the Methods section and description of relevant supplementary materials (Page 18, Line 363-366) to ensure that all information is consistent.

Line 447. Please consider revising "Life cycle interpretation" to something similar to "result interpretation."

[Response] We revised "life cycle interpretation" to "result interpretation"

Uncertainty analysis. Please provide a list of uncertainty sources in the entire analysis.

[Response] We provided the detailed information of uncertainty sources and the analysis process in the Methods section (Page 23, Line 490-508) and in SI files (Page 9, Line 234-254). We conducted Monte Carlo sensitivity analysis in key factors and assumptions including the consumption of different materials, capacity factor, life time, land-use area and transport distance and curtailment rate based on previous research and datasets. We included the new results from the Monte Carlo sensitivity analysis in the revised Fig. 4. This figure not only illustrates the impact of uncertainty on the key outputs but also prove that the selected wind farms are representative of the broader trends observed across China’s wind farms.

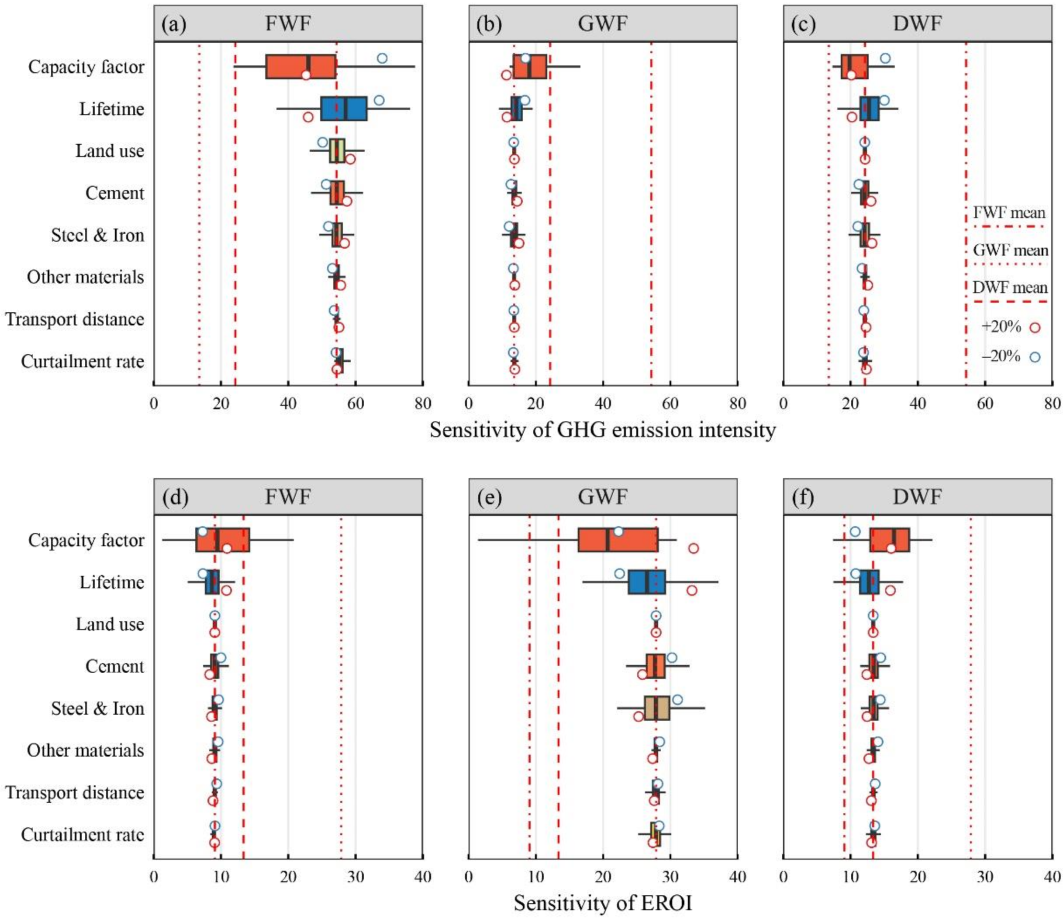

Fig. 4 Sensitivity analysis for the LCA results derived from Monte Carlo simulations for each of the input parameters. The bars represent the changes GHG emission intensity of (**a**) FWF; (**b**) GWF; (**c**) DWF and EROI of (**d**) FWF; (**e**) GWF; (**f**) DWF in relating to the variations in capacity factor, lifetime, occupied area, cement use, steel & iron use, other material use and transport distance. The mean values for FWF, GWF, and DWF are represented by dotted-dashed lines, dotted lines, and dashed lines, respectively. Red plots and blue plots indicate the increase (+20%) and decrease (-20%) of input parameters, respectively.

Supporting Materials.

1. Please consider adding the time construction of the projects and provide more

information regarding the turbine models (if they are not confidential).

[Response] We have provided further detailed information of all the wind turbines, including construction year, rotor diameter, hub height, cut-in and cut-out wind speed in the SI files (see Table S1).

Table S1 Detailed information of wind farms and wind turbines.

Wind farm	Wind turbine	Construction year	Rotor Diameter (m)	Hub height (m)	Cut-in wind speed (m/s)	Cut-out wind speed (m/s)
FWF	GW77-1500	2009	76.9	65	3.0	22.0
GWF	V80-2000	2010	80.0	78	4.0	25.0
DWF	GW82-1500	2009	82.3	70	3.0	22.0
	FD77B-1500	2008	77.0	65	3.0	20.0

2. The lifetime of a wind farm with 20- 25-year-old turbines looks small for modern turbines. The use of Denmark may lack representativeness as turbines there are older.

[Response] We acknowledge that Denmark's wind farms, with turbines that have been operational for 20-25 years, may not fully reflect the modern turbine's lifespan. Nonetheless, we believe that Denmark's decommissioning data remains highly reliable and informative for several reasons. Firstly, many leading wind energy nations, such as China, initiated large-scale wind power development after the 21st century. As a result, there is a dearth of decommissioning data available from these countries, where the majority of wind turbines are designed for a 20-year lifespan. In contrast, Denmark's extensive experience with older turbines provides a comprehensive and invaluable dataset. Secondly, Denmark's wind energy sector has consistently been a pioneer in technological innovation, lending it significant representativeness. Lastly, even if the estimated lifetime of wind turbine is somewhat underestimated, it provides a conservative estimate in the scenario assumption. Underestimate the lifetime will reduce carbon emissions throughout the entire lifecycle, but the impact on emissions caused by LUC is relatively small (because the sensitivity of land-use was smaller than lifetime, Fig. 4). Therefore, we believe that using Denmark's wind power lifetime is a conservative estimate of future emission reduction benefits. Moreover, even if the actual lifespans of modern turbines are longer, the impact on LUC emissions is relatively small compared to the overall emission reductions achieved through wind energy. And we added the discussion in the MS (Page 14, Line 269-272, "It is noted that the lifetime of Denmark's wind turbines is relatively small for modern turbine. Therefore, our results is a conservative estimate of future emission reduction benefits for extending lifetime, and may underestimate the LUC induced GHG emissions in the $S_{lifetime}$.") We sincerely appreciate your feedback and trust that this clarifies the reasons for incorporating Denmark into our study.

3. It looks to me that a land recovery scenario should be included in a baseline scenario.
[Response] Thanks for your valuable suggestions. We have incorporated the potential process of ecological succession of grassland into our analysis. Vegetation productivity recovered to 50% over a period from the second to the sixth year, with both ANPP and BNPP gradually recovering from 0% to 50%. For the land recovery scenario, we have now changed it to the Land reclamation scenario to distinguish it from the land recovery simulation in the baseline scenario. Land recovery here refers to natural restoration, while land reclamation refers to human made land restoration.

Reviewer #3 (Remarks to the Author):

This is a well written and organized manuscript that used LCA to simulate carbon dynamics at wind farms. The concept is quite good and I agree with the authors that the work is relevant and needed. I do not know if the paper was limited by page constraints, but there is simply not enough detail in the methods to fully assess the work and I'm concerned some of the assumptions made, and the structure of the scenarios call the results into question. I have a few general statements then provide some line by line comments.

[Response] Thanks for your positive feedback and insightful suggestions on our manuscript. (1) We have now included the detailed information regarding the assumptions and scenario designs in the main text (Page 24-26, Line 515-565), which was previously included in the SI file. (2) We revised the Introduction and Discussion section and remove the parts that not strongly related to our topic, allowing us to provide a more focused and coherent narrative. (3) We revised the Methods section to clarify all the assumptions and methods used and provided all relevant processing codes, including those for LCA calculation, scenario assumptions, and sensitivity analysis (deposited in the Figshare repository with a permanent DOI: 10.6084/m9.figshare.28598276). The codes are publicly available under a CC-BY 4.0 license.. This will enable other researchers to replicate our study and build upon our findings. (4) Following your suggestions, we have updated our citations to reflect the most recent and relevant research. Additionally, we have revised the language to avoid vague terms such as "large amount" and have corrected any earlier criticized studies, such as Keith et al., 2004, to ensure the accuracy and reliability of our references.

In the introduction, the authors sometimes use citations that are not the best fit for their statements and make overly broad, vague statements about wind energy impacts that simply are not yet supported though may be in the future.

[Response] We have revised the introduction and discussion section, removing some overly broad statements and conclusions that are not supported by sufficient research results accordingly. For example, we have condensed the context regarding China's wind energy, which is growing rapidly and making a substantial contribution to climate goals, yet its large-scale deployment demands substantial land and entails land-use impacts, as revised below:

"Wind energy provides substantial benefits for climatic goals. Currently, the GHG emission intensity of China's wind energy was 19.88 g CO_2-eq kWh^{-1}, providing a 98% mitigation effect compared to fossil fuels [4]. With the world's fastest wind power growth, China accounted for 56% of the global new installation in 2020 [5]. It is foreseeable that wind energy is and will be growing rapidly to meet the increasing electricity demands and displace existing fossil-based generation. It is estimated that the wind power generation of China reaches 4860 TWh and 5760 TWh in 2050 under 2 ℃ or 1.5 ℃ scenario, accounting for 37% and 40% of the total electricity demands, respectively [6]. However, wind farms require more land than other energy sources [7-9], with turbines typically spaced 7-15 rotor diameters apart [10]. The rapid and large-scale deployment of wind energy requires a large amount of land and has a substantial land-use footprint through vegetation removal, on-site construction of wind facilities [11]."

We also cited the references regarding LUC-GHG emissions of other energy forms as a broader background to emphasize the potentially important role of the LUC related emissions in wind energy (Page 4, Line 74-81, according to the suggestions of Reviewer 1#) and removed the discussion on the conflicts between cropland and wind energy, along with the related socio-economic issues (Page 19, Line 336-349).

The methods are not well-explained and this leads me to a number of concerns.

First, I'm concerned the 'baseline' scenario, that is the focus of the main results and conclusions of the paper is unrealistic and over-estimates carbon losses. The main analysis seems to assume the land change at wind farm is permanent for all 20 years and there is no recovery of the vegetation/carbon dynamics. The authors don't explain this clearly, but scenario 5 is land recovery. Land recovery will happen naturally, and in some systems (like grasslands) it can be very fast if there is enough rainfall. Furthermore, in forest systems, the disturbed land will often convert to either grasslands or shrublands depending on the environment and how the vegetation is managed. It is entirely unrealistic to assume vegetation recovery and carbon dynamics are static after construction. The "baseline" scenarios should all include some amount of ecological succession (a fundamental concept) and temporal patterns in carbon dynamics. This should be the basis of analyses.

[Response] Thanks for pointing this out and the valuable suggestions.

(1) Regarding the baseline scenario, we understand your concerns about the permanence of land changes and the lack of vegetation/carbon dynamics recovery. In our work, we determined the actual impact area of the wind turbines according to the changes in land-use before and after installation. Upon reviewing the remote sensing images, it showed that certain areas, such as roads, open spaces, and cable zones, remained unaltered even for over ten years post-installation. We have provided the remote sensing images in the SI file (Fig. S3).

(2) We agree with your point that land recovery will happen naturally, particularly in the forest and grassland. For the grassland wind farm, we incorporated the potential process of ecological succession in the CENTURY model (also in response to Reviewer #2). Specifically, we simulated the regrowth of grassland plants in the second year of the wind farm's operational life cycle. As a result, productivity recovered to 50% over a period spanning from the second to the sixth year, with ANPP and BNPP gradually recovering from 0% to 50%. For the forest wind farms, we observed no natural recovery due to the long-term presence of paved road surfaces for transportation purposes, as indicated by the remote sensing images. Further forest degradation was not observed either. Consequently, we did not include vegetation recovery or degradation in the CENTURY model for forest areas. Similarly, for the desert wind farms, given the slow recovery of perennial vegetation and the low biomass, we also did not consider vegetation recovery. The baseline scenario now accounts for natural vegetation succession and temporal patterns in carbon dynamics, reflecting a more realistic representation of land use changes and their impacts over time. Furthermore, we have revised the scenario naming to avoid confusion. The original "Land recovery scenario" has been changed to "Land reclamation scenario" to distinguish it from the land recovery simulation included in the baseline scenario. Land recovery now refers to natural restoration, while land reclamation refers to human-made restoration process.

Second, The scenarios are not explained at all and need to be. 468-474 is simply not enough detail.

[Response] We have now included the detailed information regarding the assumptions and scenario designs in the main text (Page 24-26, Line 515-565), which was previously included in the SI file. We illustrated the assumption, estimation methods and cited references for all scenarios

Third, the energy production analysis using wind Ninja and Merra is not explained. This work is detailed and should include uncertainty that does not seem to be input into the LCA. Its very confusing.

[Response] We thank the reviewer for pointing this out and recognize the potential confusion. In this study, we used power curve data from manufacturer and Renewable Ninja database, while hourly wind speed data product of MERRA-2 is used to calculate the capacity factor for different turbines throughout their entire lifecycle. MERRA-2 integrates multiple observational datasets through data assimilation techniques to provide relatively accurate historical wind speed data. We calculated the aggregate power curve (PC_A) based on turbine power curve from the manufacturers or database using wind speed v from the integral of the turbine power curve multiplied by the Gaussian filter Γ:

$$PC_A(v,\sigma) = \sum_{n=-4\sigma}^{4\sigma} PC_T(v-n) \ \ \Gamma(n,\sigma).$$

The MERRA-2 wind speed and PC_A was used to calculate all the life cycle cf_i values. Accounting for the potential decline in wind turbine performance (suggested by Reviewer 2#), the calculated cf values of wind farms were estimated to decrease by 0.17% per year over the first 10 years of operation. For the following 10 years, the decline was projected to be 0.41% annually, with an additional drop of 1.15% in the 10th year, consistent with the performance trends observed in newer-generation wind turbines in the United States. We used the calculated corrected cf values and the nominal power to calculate the life cycle power generation (PG):

$$\mathrm{PG}=P\times \sum_{\mathrm{i}=1}^{8760\times 20} cf_i.$$

Now we clarified the text in the MS (Page 21, Line 406-408; Page 22, Line 459-464) and SI file (Page 4, Line 129-138), and provided all the processing R codes (DOI: 10.6084/m9.figshare.28598276).

In the revised MS, to illustrate the impact of wind potential variation on life-cycle GHG emissions and energy performance, we further account for the uncertainty caused by wind speed in the sensitivity analysis. We now examined all China's wind farms with same land type to the three wind farms we selected, aiming to calculate the variation in wind capacity across different regions (also see above response to Reviewer #1). Specifically, we have selected wind farms located in forests, grasslands, and deserts based on the locations of all wind farms in China. Wind turbines and wind farms within a distance of 1km are considered as one wind farm, and we have identified a total of 128 forest wind farms, 141 grassland wind farms, and 124 desert wind farms (Fig. S2). We calculated the capacity factors of China's wind farms to conduct the uncertainty analysis. The results of uncertainty analysis are showed in Fig. 4. The detailed information is added in Methods section (Page 24, Line 494-508).

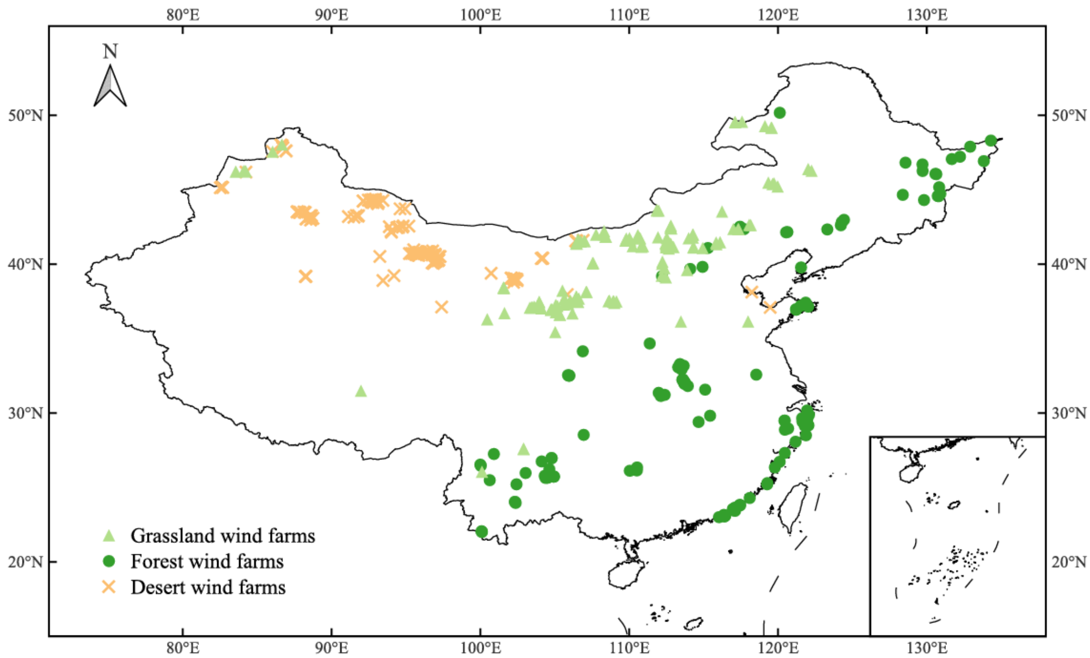

Fig S2 The spatial distribution of China's 393 wind farms and their land cover types.

Detailed comments

57. This is a better citation. It uses better methods than older papers and shows "of 148

specimens that onshore wind farms are the second most dilute source for power generation based". Nøland, J. K., Auxepaules, J., Rousset, A., Perney, B. & Falletti, G. Spatial energy density of large-scale electricity generation from power sources worldwide. Sci Rep 12, 21280 (2022).

[Response] Thanks for the suggestion. We cited this reference.

60. "large amount" is quite vague. Diffendorfer et al, suggested ~2% loss of undeveloped land around wind facilities but not (I did not see it) calculate a capacity density. Some might consider their 2% small. It might be better here, to find papers that project the amount of land that may be required for new wind energy. I believe papers by Rebecca Hernandez's lab may have some of these. I'm less aware of such projections outside of North America but feel I've seen one from agroup in the UK. I cannot find it right now!

[Response] Thank you for the suggestions. Now we have revised this part to avoid using vague words like "large amount". Furthermore, we have further improved the references cited and listed capacity-based land-use efficiency (unit: W/m^2) or generation-based land-use efficiency (unit: kWh/m^2) to summarize the relationship between wind energy and land use, clarifying that the efficiency of wind energy in land use is relatively low. The added references included Ferrell et al., (2015) Miller and Keith (2019), Hernandez et al., (2022), Harrison et al., (2022), and Dai et al., (2024).

63. "large" again. See. https://doi.org/10.1016/B978-0-12-819727-1.00018-2. This is done by leading wind meteorologists (much more knowledgeable then Keith..whose paper has been criticized). They state: "Despite increasing number of research efforts, our assessment of potential WF impacts is still very limited. Although the WF impacts are mostly local and limited to the near-surface ABL, this is the layer where we live and plants grow. Hence, more studies are needed to improve our understanding of WT-atmosphere-surface interactions and our capability to model and project the weather, climatic and ecological impacts of large WFs."

[Response] Yes, assessments of climate impacts are still limited, and more studies are needed to improve our understanding of wind turbine-atmosphere-surface interactions. The impact of wind farms on local climate and vegetation may be influenced by various factors such as ecosystem types. This impact can be positive or negative, and in some places it may be much smaller than the interannual dynamics of climate or vegetation. So using 'large' is not appropriate. We agree with your comments and revised the term “large” to “non-negligible”. In addition, we deleted the early and criticized Keith et al.’s work and cited Zhou et al. (2022).

Figure 6. typo. Ramoval change to removal.

[Response] We corrected the mistake in Fig. 6.

397. How did you do this? Custom code, does renewable.ninja do it for you? Did you use the WRF? There are lots of assumptions and methods here that are not explained. There should be lots of uncertainty in these models and these could be fed into the LCA to better characterize the overall uncertainty in total carbon budget.

[Response] Thank you for pointing out the unclear description in the original MS. We revised the Methods section to clarity all the assumptions and methods used. (1) In this study, we did not use the WRF of Renewable Ninja directly, but instead used the power curve from that database. Now we rewritten the sentence clarified the text in the MS (Page 21, Line 405-409, “Site-specific capacity factors and electricity generation were calculated using turbine power curves and hourly wind speed. The power curves were derived from manufacturers and the power curve database of Renewables.ninja [53] and hourly wind speed data were from MERRA-2 (M2I1NXLFO) [54].”) and). We provided all the processing R codes to ensure the code availability (deposited in the Figshare repository with a permanent DOI: 10.6084/m9.figshare.28598276). (2) For uncertainty, we now consider the differences in wind capacity and carbon loss of all forest, grassland, and desert wind farms in China into our model to calculate the impact of different factors on the overall uncertainty of GHG emissions and energy performance (also see above response to Reviewer #1).

Dear Editor and Referees,

We sincerely thank you and the reviewers for your insightful feedback on our manuscript, "Land-Use Change Emissions from Wind Farms in China: A Life-Cycle Assessment." Following the suggestions and comments, we reanalyzed the results and carefully revised our manuscript (referred to as MS hereafter). We believe that the revised version satisfactorily addresses the referees' questions and concerns. In this reply, we seek to clarify the issues, raised by the referees, point by point. Please find the detailed response (in blue) to the referees' comments (in black). For your convenience, all the changes in the revised MS are in red, and the corresponding line numbers are noted in the point-by-point responses.
Thank you again for your time and efforts on our MS.

Yours sincerely,
Jinfeng Chang on behalf of all co-authors

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I have reviewed the comments provided by the authors. The authors have worked extensively to broaden the paper's analysis, with a deep and thoughtful analysis of sensitivity to test variability due to scale and time and physical factors. In my judgement, they have made significant additional analysis to test the variability in LUC effects according to location. The added sensitivity analysis examined site-specific locations with wind farms to generate a range of emissions.
A comment related to the response to Reviewer 2 on the limited data and scale of the analysis: the authors cannot expect to create a "precise" and good LCA, they should aim for accurate with some degree of uncertainty.

While the paper and analysis are very robust, I found the paper to need a thorough review to correct English language in numerous areas within the paper. For example, the abstract has many missing prepositions and incorrect choice of words. Take for example, the first sentence: the word "demands" should be "demand" and "climate goal" should be "climate goals". On line 29, it should say, "during the installation stage...". The paper has many examples of awkward sentences like this that must be addressed if accepted for publication.

[Response] Thank you very much for your positive feedback and valuable suggestions on our revised MS. We greatly appreciate your recognition of our efforts in broadening the analysis - particularly the in-depth sensitivity analysis on location-specific variability of land-use change (LUC) effects and the examination of emissions from wind farm sites. We take your feedback on the English language issues very seriously. We have conducted a thorough, line-by-line review of the entire MS. We hope these revisions have elevated the language quality to meet publication standards. The revised abstract, incorporating these improvements and reflecting the key findings more accurately, is provided below.

"Rapid development and deployment of wind energy play a vital role in meeting rising electricity demand and achieving climate goals. However, wind farms have substantial land-use footprints due to vegetation removal, on-site construction of wind facilities on cement foundations, and road sprawl. Ignoring the impacts of land-use may overestimate the greenhouse gas (GHG) mitigation potential of wind energy. We employed the life cycle assessment (LCA) methodology to explore the land-use impacts on GHG emissions and energy performance for three typical wind farms located in forest, grassland and desert ecosystems. We included the effects of vegetation and soil removal during the installation stage, and the loss additional carbon sink capacity during the operation and maintenance stage. Land-use change (LUC) induced emissions accounted for 37.9% of the life cycle emissions for the forest farm, while contributions were much lower for the grassland and desert farm (4.3% and 1.2%, respectively). Grassland deployment offered a triple win with highest energy return, lowest land-use intensity, and lowest GHG emissions. By applying a combination of multiple mitigation measures, farms in all ecosystems can achieve very low emission intensity (below 5 g CO_2-eq kWh^{-1}), greatly reducing land-use and ecosystem-based emission intensities."

Reviewer #2 (Remarks to the Author):

The manuscript has greatly improved after the revisions, and the authors have addressed most of my previous comments. However, two remain unaddressed.

First, the limitations arising from the small sample size can still be significant. Land use patterns within a typical wind farm tend to be quite uniform, as can be seen from Fig 7. Therefore, using only a single wind farm to represent an entire category may not be representative due to variations in turbine size, leading to potential bias in the results. This is particularly important as the authors tried to generalize the results beyond the specific case studied. The authors argued that "we identified and analyzed a total of 128 forest wind farms, 141 grassland wind farms, and 124 desert wind farms from the harmonized global datasets of wind and solar farms...". However, this dataset appears to focus on wind capacity rather than land-use patterns. The lack of land-use data for these farms weakens the representativeness of the sample size and could undermine the validity of the sensitivity analysis.

[Response] Thanks for your suggestions. we have expanded our analysis in the revised MS. We identified 493 wind farms across China (128 forest, 141 grassland, 124 desert) and quantified their specific land-use impacts using the CENTURY model and biomass data. Specifically, we simulated the SOC pools to a stable baseline condition reflective of local climate and then simulated the 20-year SOC loss attributable to the installation and operation stage of the wind farms (using the same assumption for FWF, GWF and DWF). The resulting uncertainties in SOC and biomass changes were systematically incorporated into the "Ecosystem" uncertainty category. Additionally, according to Reviewer #4's suggestions, we integrated comprehensive land-use area data from China's wind farms across different land types to conduct a Monte Carlo simulation.

Our comprehensive analysis of these 493 farms confirms that ecosystem variability is an important factor affecting the land-use footprint, particularly for forest wind farms (Fig. 4). While the emission intensity of our specific case-study FWF (33.59 g CO_2-eq kWh^{-1}) was higher than the mean value calculated for all forest-located wind farms in China (28.27 ± 3.55 g CO_2-eq kWh^{-1}), it should be noted that the mean GHG emission intensity for wind farms located in forests was demonstrably higher than the mean emission intensities for wind farms in deserts (19.43 ± 0.20 g CO_2-eq kWh^{-1}, $p < 0.05$) and grasslands (14.65 ± 0.38 g CO_2-eq kWh^{-1}, $p < 0.05$).

We believe this analysis, incorporating SOC and biomass dynamics, substantially strengthens the representativeness of our findings and the validity of our sensitivity analysis regarding ecosystem impacts. We think it could address the potential bias concern by demonstrating the variability within and between land-use categories using empirically derived land-use impact data.

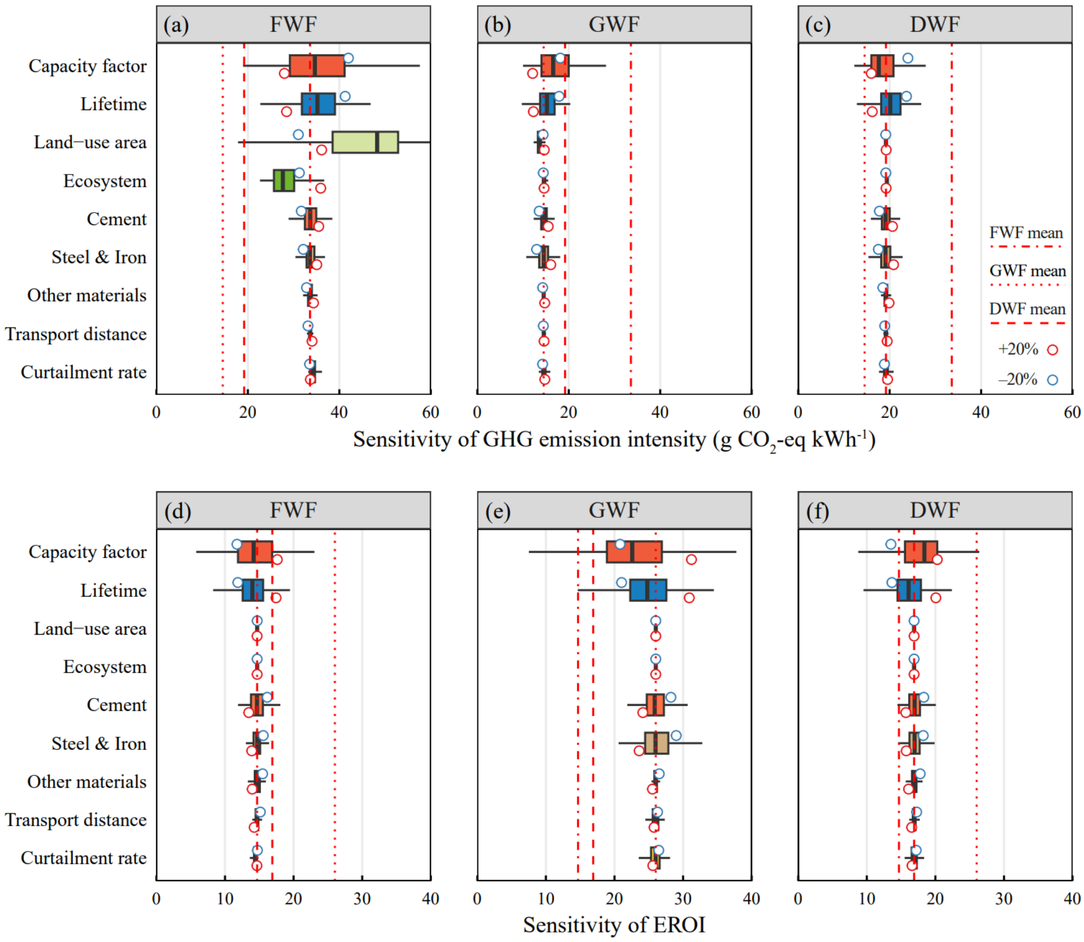

Fig. 4 Sensitivity analysis of the LCA results given ±20% variations and the Monte Carlo simulation of different input parameters. The boxplots represent the variations

in the GHG emission intensity of (**a**) FWF; (**b**) GWF; (**c**) DWF and the EROI of (**d**) FWF; (**e**) GWF; (**f**) DWF in relating to the variations in capacity factor, lifetime, occupied area, cement use, steel & iron use, other material use and transport distance across the 128 forest, 141 grassland, 124 desert wind farms within China. The mean values for FWF, GWF, and DWF are represented by dotted-dashed lines, dotted lines, and dashed lines, respectively. Red and blue circles indicate the increase (+20%) and decrease (-20%) of input parameters, respectively.

Second, addressing the decline in wind turbine performance by directly using data from Ref. 59 (Hamilton et al., Joule 2020) may be problematic. Ref. 59 explicitly attributes performance differences to **"loss of eligibility for the production tax credit"**. Therefore, the decreasing performance numbers may not be applicable to wind farms in China.

[Response] Thank you for highlighting this critical concern. We agree that directly applying the performance decline data from Hamilton et al. (2020, Ref. 59) may not be appropriate for our study, as their analysis specifically links performance differences to the “loss of eligibility for the production tax credit” - a policy context unique to the U.S., which does not align with the operational environment of wind farms in China. To address this, we systematically reviewed global literature on wind turbine performance decline, focusing on studies that analyze aging effects, technical degradation, and operational factors (rather than policy-driven incentives). The table below summarizes the key findings from these studies:

Reference	**Year**	**Turbine type/location**	**Performance decline rate**
How Does Wind Project Performance Change with Age in the United States	2020	U.S. turbines	0.53% per yr for the first 10 years, 1.27% per yr for the second 10 years, and a 3.6% year-10 drop

Analysis of Wind Turbine Aging through Operation Curves	2020	Vestas V52	8% in 10yr (ws 5-9 m/s) 1.3% in 10yr (ws 9-13 m/s)
A Study of Wind Turbine Performance Decline with Age through Operation Data Analysis	2020	Vestas V52	5% in 10yr
How does wind farm performance decline with age?	2014	UK's 282 wind farms	1.6 ± 0.2% per yr
Analysis of Wind Turbine Aging through Operation Data Calibrated by LiDAR Measurement	2021	IEC Class IIA 1 MW wind turbine	0.52% per yr
Wind turbine performance decline in Sweden	2017	Sweden wind turbines constructed before 2007	6% in 20yr
Have wind turbines in Germany generated electricity as would be expected from the prevailing wind conditions in 2000-2014?	2017	Germany wind turbines	0.63 ± 0.01% per yr
Data-driven wind turbine aging models	2021	Fifteen 2 MW wind turbines	0.2% per yr
Quantification of performance degradation due to wind turbine aging:	2025	2.3 MW turbine	0.72% per yr

Estimating the reduction in annual energy production using the annual degradation rate			
What drives the change of capacity factor of wind turbine in the United States?	2023	U.S. 943 wind farms	1.52% per yr

We have added the Table in Supplementary Information (Table S3). After careful evaluation, we excluded the 2014 UK study ("How does wind farm performance decline with age?") because its long-term dataset (spanning earlier turbine models) may overestimate degradation rates for modern turbines, which benefit from improved design and maintenance standards. For the remaining studies, we calculated the median decline rate, i.e. 0.53% per year, to correct the capacity factor in our analysis. We believe this improvement addresses your concern and strengthens the reliability of our analysis.

In addition, the authors did not discuss agricultural areas for wind farm deployment, despite including a section titled "Where to build wind farms". This omission could be significant because:

The Chinese government actively encourages integrating wind energy in agricultural areas (e.g., https://www.gov.cn/lianbo/bumen/202404/content_6942962.htm; http://paper.people.com.cn/rmrb/html/2024-04/05/nw.D110000renmrb_20240405_1-02.htm). Previous studies (e.g., Diffendorfer and Compton, 2014, PLOS One; Dai and Scown, 2025, Renewable and Sustainable Energy Reviews) demonstrate that land use changes in agricultural areas are minimal when wind farms coexist with agricultural activities. The authors should address this gap by discussing agricultural land use compatibility or by explaining why they are not included in the study scope.

[Response] Thanks for your suggestions. We agree that agricultural land compatibility deserves attention given China's policy priorities and global research findings. We have now incorporated a dedicated discussion on agricultural wind integration in Section "Where to build wind farms" of the revised MS.

"Siting wind facilities on agricultural or marginal land, contaminated sites or in the built environment rather than in undisturbed natural systems might decrease unintended consequences of wind energy development. Specifically on agricultural land, wind energy deployment is often compatible with agriculture and allows power generation and crop production to coexist on the same landscape. Empirical studies consistently show that co-locating wind infrastructure with farming operations induces minimal land-use change (Dai and Scown 2025; Diffendorfer and Compton 2014), Emerging evidence even suggests certain configurations may enhance neighboring crop yields through microclimate modification (Kaffine 2019). The Chinese government actively promotes wind energy integration in agricultural areas, such as "Thousands of townships and tens of thousands of villages harnessing the wind program", to advance rural energy's green, low-carbon transformation and boost farmers' incomes (Agency 2024; Ding 2024). However, siting wind turbines in rural areas that include a mix of homes and smallholder farms can also be challenge given the fact that building turbines would require permission and lease agreements with multiple landowners. In addition, attention needs to be paid to turbines located in built environment due to the noise and shadow-clicker which promote annoyance and stress effects on people living nearby (Hubner et al. 2019; Radun et al. 2019). When these socio-technical challenges are adequately addressed, agricultural areas represent a high-priority avenue for sustainable wind development that balances energy goals with land stewardship."

Minor:

Line 87: Please consider using an alternative word for "proved".

[Response] We have replaced "proved" with "comprehensive " for more precise academic phrasing.

Line 195: Remove the duplicate "that".

[Response] We apologize for this mistake. The duplicate "that" has been removed.

Line 332: Correct "life inventory" to "lifecycle inventory". Additionally, perform thorough proofreading to resolve similar errors.

[Response] "Life inventory" was corrected to "lifecycle inventory" and completed proofreading pass resolving similar errors throughout.

Line 394: I recommend reproducing Figure 7 to include both an overview of the wind farm and detailed information on land use. It appears that this image has not been updated, as the authors mentioned they included the previously missing cable areas in response to my earlier comments.

[Response] Figure 7 has been regenerated to include wind farm overview map and cable corridors added in previous revision.

Line 515: Reformulate scenario labels for consistency (e.g., "Slifetime:" instead of "Slifetime").

[Response] Scenario labels standardized to "Slifetime:" format consistently across all figures and text.

Line 565: Add a citation for the equation source, as noted in the rebuttal letter.

[Response] Citation added to Equation 5: "(Source: Staffell, I. & Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **114**, 1224-1239 (2016).)" matching our rebuttal letter reference and Supplementary Information Ref. 20.

Reviewer #4 (Remarks to the Author):

The authors have delivered an interesting analysis on LUC emissions caused by wind parks for China. The analysis is relevant and timely, but there are significant methodological limitations which have to be addressed before publication.

[Response] Thanks for your suggestions. To address these concerns, we have recalculated the CFs using corrected MERRA-2 and ERA5-Land wind speed data with GWA v2 as recommended. This methodology transformation yielded critical improvements: The forest wind farm's capacity factor increased dramatically from 20.8% to 34.5%. All subsequent emission intensity calculations have been updated using these validated metrics. These revisions fundamentally strengthen our generation data reliability by mitigating overestimation bias of the MERRA-2 dataset and enhancing spatial representativeness through GWA v2's resolution.

*** Uncertainty in wind speed data ***

My largest concern is the use of MERRA-2 wind speed data without bias correction. As shown in [1], MERRA2 overestimates wind power generation for many world regions, and reanalysis data in general is too coarsely resolved to match wind conditions at wind park sites. The error of MERRA2 can be higher than 30% [1]. When using bias-correction with the global wind atlas, the error range can be reduced [1]. The headline results of the paper strongly depend on the capacity factors of the wind turbines. Please note that the capacity factor varies by a factor of 2 between the three wind parks and that the wind park with lowest generation has a capacity factor of only 13%. It seems unlikely that this is a sensible value for economic operation. I therefore strongly encourage to bias correct the used wind speed data with the global wind atlas (or another spatially highly resolved product) and assess generation data in detail.
As [1] shows that the current version 3 of the global wind atlas is overestimating wind resources, we recommend using version 2, which can be found online at [5]. A new version of the global wind atlas will come online soon, where the currently existing bias will be corrected, but it is unclear when this happens.
[Response] Thanks for your suggestions. Following your suggestions, we replaced the single-source MERRA-2 data with complementary reanalysis products (MERRA-2 and ERA5-Land) to enhance robustness. We further conducted bias-correction for these two reanalysis data using the version 2 of the global wind atlas (GWA v2). We first calculated the ratio between GWA v2's long-term wind speed values (V_{GWA2}) and 20-

year mean wind speeds from each reanalysis dataset ($Mean_{MERRA\text{-}2}$ and $Mean_{ERA5\text{-}Land}$). Hourly wind speeds were then corrected using the following equation:

$$V_{MERRA\text{-}2\ corrected} = V_{MERRA\text{-}2} * V_{GWA2}/Mean_{MERRA\text{-}2}$$

$$V_{ERA5\text{-}Land\ corrected} = V_{ERA5\text{-}Land} * V_{GWA2}/Mean_{ERA5\text{-}Land}$$

The corrected hourly wind speed ($V_{MERRA\text{-}2\ corrected}$ and $V_{ERA5\text{-}Land\ corrected}$) was used to calculated the corrected CF value of each turbine. Now the corrected CF for FWF, GWF and DWF was 0.3453, 0.4015 and 0.3451, respectively. The correction significantly improved CF realism, particularly for the FWF:

Site	Original CF	Corrected CF	Change
FWF	0.2079	0.3453	+66%
GWF	0.4190	0.4015	-4%
DWF	0.2658	0.3451	+30%

The revised CF of FWF now aligns with typical operational thresholds, resolving your concern about the plausibility in the original value. All the subsequent calculations in emission intensity were updated using these validated generation metrics. Further sensitivity analyses of capacity factor were conducted utilizing the corrected CFs, with full distributions now visualized in Fig. 4. This comprehensive approach not only mitigates MERRA-2's inherent biases but also substantially strengthens the spatial representativeness of our generation estimates through GWA v2's enhanced resolution.

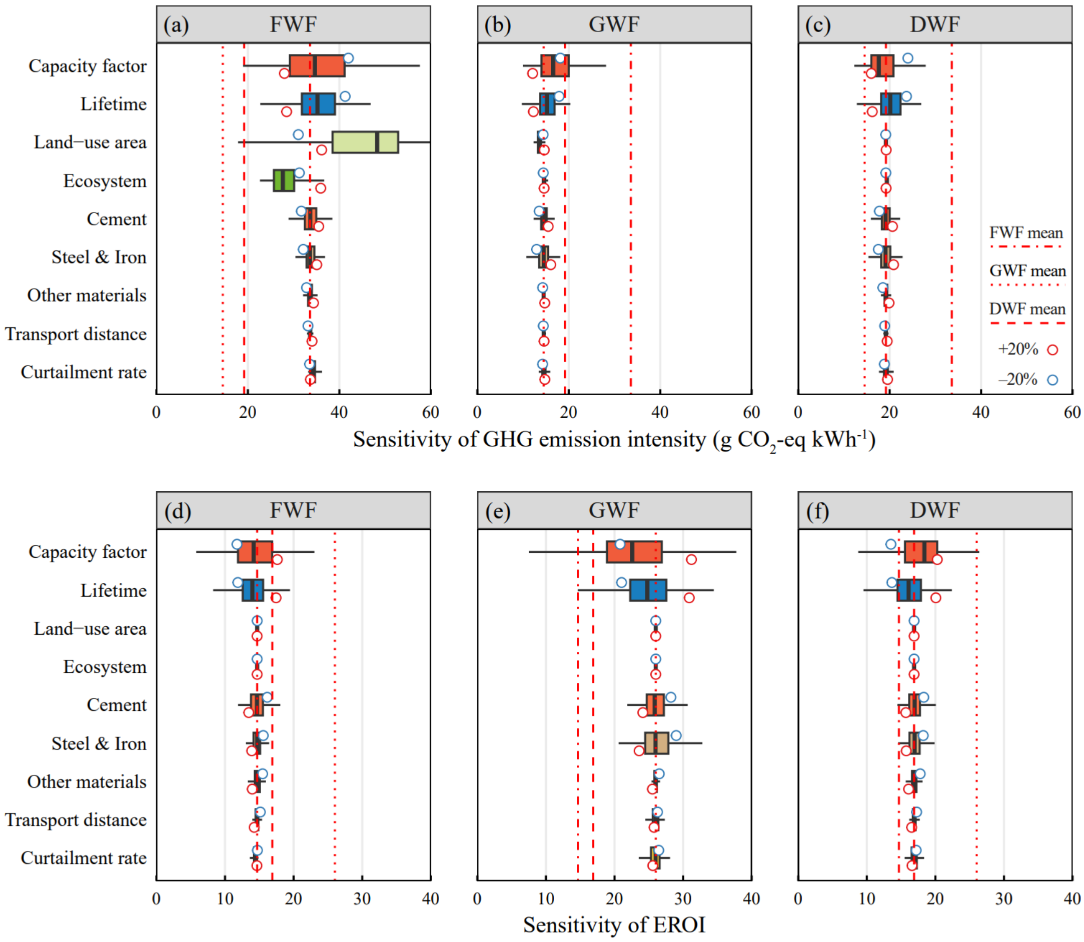

Fig. 4 Sensitivity analysis of the LCA results given ±20% variations and the Monte Carlo simulation of different input parameters. The boxplots represent the variations in the GHG emission intensity of (**a**) FWF; (**b**) GWF; (**c**) DWF and the EROI of (**d**) FWF; (**e**) GWF; (**f**) DWF in relating to the variations in capacity factor, lifetime, occupied area, cement use, steel & iron use, other material use and transport distance across the 128 forest, 141 grassland, 124 desert wind farms within China. The mean values for FWF, GWF, and DWF are represented by dotted-dashed lines, dotted lines, and dashed lines, respectively. Red and blue circles indicate the increase (+20%) and decrease (-20%) of input parameters, respectively.

Furthermore, it would be great to see a boxplot that compares generation of turbines per land-use types for all sampled locations.

[Response] Following your valuable suggestions, we have added a boxplot figure (Fig. S5) in Supplementary Information. comparing power generation across land-use types for all 493 wind farms (standardized to 1.5MW turbine). This result reveals insignificant differences in generation capacity between forest, grassland, and desert sites ($p > 0.05$), reinforcing that emission variations across different sites stem primarily from land-use impacts rather than wind resource.

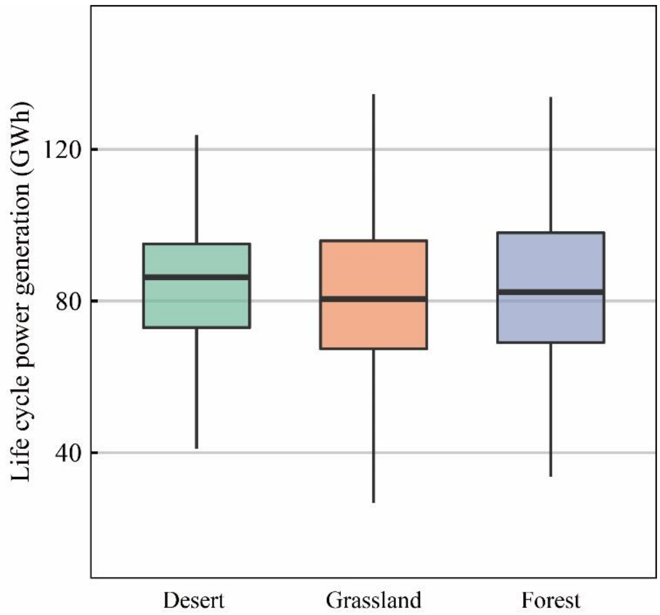

Fig. S5 Power generation across three land-use types for 493 wind farms in China.

*** Uncertainty in land-use data ***

The uncertainty in land-use data is also high, as only three locations have been sampled. Instead of using generic 20% assumptions in your sensitivity analysis, you could use the data from two recent publications to have an empirical foundation for your sensitivity analysis. [2] reports land-use requirements of wind power in China for many installations, and [3] gives a global overview. This should better inform your sensitivity analysis and your estimates

[Response] Thanks for your suggestions. We improved our sensitivity analysis using the recommended empirical foundations. We integrated comprehensive land-use area data from Ref. [2] covering wind farms across different land types to conduct a Mont Carlo simulation. For this simulation, we adopted the mean and standard deviation values derived from the aforementioned reference as the respective parameters for our model. For the impacts on ecosystem carbon dynamics, we implemented a process-based modeling with the CENTURY model. Specifically, we simulated the SOC pools to a stable baseline condition reflective of local climate and then simulated the 20-year SOC loss attributable to the installation and operation stage of the wind farms (using the same assumption for FWF, GWF and DWF). The resulting uncertainties in SOC and biomass changes were systematically incorporated into the “Ecosystem” uncertainty category.

*** Language ***

The language needs to be improved, potentially with the help of a large language model. Parts of the text are hard to understand.

[Response] Thanks for your suggestions. We’ve conducted comprehensive language editing using advanced LLMs (GPT-4 and Deepseek R1) to enhance clarity, fluency, and academic tone throughout the MS. And we wish to emphasize that these tools were used solely for language refinement and were not involved in any data analysis processes.

*** Minor issues ***

"For other energy forms that are less land intensive than wind energy, studies have found it takes non-negligible LUC induced emissions." Wind power is one of the most least land intensive energy generation technology, this sentence gives a wrong impression [4].

[Response] The sentence was revised to: “For energy forms with higher land-use intensity than wind, studies still report non-negligible LUC emissions” to accurately reflect wind’s low land requirements.

"Over one-third of emissions were overlooked when excluding carbon loss-related indirect emissions. "

This is clear from the sentence before, the sentence can be removed.

[Response] The sentence “Over one-third of emissions were overlooked when excluding carbon loss-related indirect emissions.” has been removed.

"In order to compare the influence of different factors on life cycle GHG emissions and energy performance, we conducted ±20% changes and Monte Carlo sensitivity analysis in key factors and assumptions including capacity factor."

I thought you used actual wind park locations to vary the capacity factor? Can you explain better?

[Response] The sentence was revised to "We conducted sensitivity analysis using both: 1) location-specific capacity factors from existing wind farms, and 2) systematic ±20% parameter variations with a Monte Carlo simulation in key factors including capacity factor, consumption of different materials (divided into three parts: steel & iron, cement and other materials), life time, land-use area and transport distance curtailment rate and ecosystem.."

Table 1: Generation is given per turbine, not per installed capacity in MW. Please report also report Generation(GWh)/capacity(MW) to facilitate comparison between parks.

Table S1: add turbine power (likely given by the turbine name, but still relevant information)!

[Response] We added new row: "Generation Intensity (GWh/MW)" in Table 1 to show annual output per MW capacity. We also added "Rated Power (MW)" column specifying turbine capacities in Table S1.

Table 1: Also report land conversion per installed capacity (i.e. MW) instead of generation only to be able to compare to other sources, which mostly report in capacity than in generation.

[Response] We added new row "Land Conversion per MW (ha/MW)" for cross-study comparison.

[1] https://www.sciencedirect.com/science/article/pii/S0360544221017680#fig5

[2] https://iopscience.iop.org/article/10.1088/1748-9326/add7ee

[3] https://www.cell.com/one-earth/fulltext/S2590-3322(24)00475-5

[4] https://unece.org/sites/default/files/2022-04/LCA_3_FINAL March 2022.pdf

[5] https://silo1.sciencedata.dk/shared/cf5a3255eb87ca25b79aedd8afcaf570?path=/GWA2.1

Reference

1. Xin Hua Agency (2024). A Batch of Local Wind Power Projects to Be Built in Rural Areas of Counties in China. 我国将在县域农村建成一批就地就近的风电项目. In. https://www.gov.cn/lianbo/bumen/202404/content_6942962.htm
2. Dai, T., & Scown, C.D. (2025). A novel approach for large-scale wind energy potential assessment. *Renewable and Sustainable Energy Reviews, 211*
3. Diffendorfer, J.E., & Compton, R.W. (2014). Land cover and topography affect the land transformation caused by wind facilities. *PLoS One, 9*, e88914
4. Ding, Y. (2024). Launching the "Thousands of townships and tens of thousands of villages harnessing the wind program" to Explore a New Model of Village-Enterprise Cooperative Investment and Construction – Promoting the Development of Wind Power in Rural Areas in Light of Local Conditions (Policy Interpretation). 开展“千乡万村驭风行动”，探索村企合作投资建设新模式——推动农村因地制宜发展风电（政策解读）. In, *People's Daily*
5. Hubner, G., Pohl, J., Hoen, B., Firestone, J., Rand, J., Elliott, D., & Haac, R. (2019). Monitoring annoyance and stress effects of wind turbines on nearby residents: A comparison of U.S. and European samples. *Environment International, 132*, 105090
6. Kaffine, D.T. (2019). Microclimate effects of wind farms on local crop yields. *Journal of Environmental Economics and Management, 96*, 159-173
7. Radun, J., Hongisto, V., & Suokas, M. (2019). Variables associated with wind turbine noise annoyance and sleep disturbance. *Building and Environment, 150*, 339-348