

Renewable energy quality trilemma and coincident wind and solar droughts

Corresponding Author: Professor Mingquan Li

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

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Professor Li,

Your manuscript titled "Renewable energy quality trilemma and coincident wind and solar droughts" 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. Specifically, we ask you to:

1. Provide clarification on the concept of energy droughts used in previous literature, and compellingly demonstrate the novelty of the definitions or applications presented in your study and provide a discussion on integrating findings into policy implications.
2. Provide a better explanation of your metrics and better explain general trends and the impact of climate changes on capacity factors.
3. Compellingly demonstrate the underlying meteorological and geographical conditions and make a robust argument regarding how a future energy system could bridge potential periods of resource scarcity.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. 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.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your 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.

Important: The response to reviewers must not include any figures, tables or graphs. If you wish to respond to the reviewer reports with additional data in one of these formats, please add them to the main article or Supplementary Information, and refer to them in the rebuttal. Due to current technical limitations, any figures, tables, or graphs embedded in your rebuttal will not be included in the peer review file, if published.

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:

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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,

Dr Alireza Bahadori
Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This paper uses resource availability, variability, and extremeness to categorize the temporal and spatial characteristics of renewable energy droughts. It further maps out these energy droughts using China as an example. The framework provides a more comprehensive matrix of resource quality for renewable investors, planners, and policymakers. The presentation is clear, but I have a few small questions for the authors to consider.

The paper introduces the concept of energy droughts and its associated matrix as new. However, it would be helpful if the authors clarified whether these concepts are used in existing literature and, if so, how their definitions or applications differ in this paper.

The authors selected the period from 2000 to 2018 for their study. Is this selection based on data availability, or are there other reasons? I am also curious about the general trend in capacity factors (CFs) during this period. Would it be more effective to use annual averages rather than a single average for the entire period? Additionally, how do evolving climate changes impact CFs? This part needs better justification or elaboration.

Including a map of "eligible sites" for wind and solar energy would aid in understanding the energy drought maps by clearly indicating whether the uncolored areas are ineligible sites or high-quality sites.

Lastly, it is unclear how the matrix can be used to guide investment or policy strategies. Perhaps the authors could discuss more about integrating their research findings into policy implications.

Reviewer #2 (Remarks to the Author):

Overview

The manuscript presents the findings of a statistical analysis of renewable energy production. The geographic focus is on the People's Republic of China. The analysis aims at changing the understanding of the reliability of energy production based on wind and solar energy. The focal point is renewable energy droughts, that is longer periods without or very little wind and/or solar energy production. On that basis, the authors suggest a way to assess the reliability of regions in that regard, and hence the needs in terms of power system design.

Major claims of the paper

The central argument of the manuscript is that literature on the security of renewable energy-based electricity systems suffers from a focus on the availability and short-term variability of energy resources (wind, solar). The authors suggest including the concept of energy droughts, that is extreme and prolonged reductions in renewable power generation to determine the outlines of a secure energy system based on renewables. The manuscript argues that the inclusion of energy droughts in the analysis allows to go beyond too narrow a view on energy security in a decarbonised electricity system. According to the authors, including energy droughts is suited to highlight a significant lack of sites with favorable renewable energy conditions, which in turn leaves system builders with important challenges.

Novelty and interest to others in the community and the wider field

The authors argue convincingly that the current premises of renewable energy system building are too narrow to understand potential supply gaps under the condition of a decarbonized electricity system based on wind and solar energy. I believe this paper will greatly stimulate research on energy security, as it puts into question certain assumptions in that field. For example, a standard argument in this field of study is the broad availability of renewable energy resources (in contrast to fossil fuel which is more geographically focused); on the basis of this premise, and with a positive outlook on technology development (for example in the area of storage), it is generally assumed that renewables will lead to higher energy security. The authors of this manuscript show convincingly that securing electricity supply can be more demanding than what is generally assumed. The lack of geographic regions that meet the three conditions of 'availability', 'low variability', and 'low extremeness' is one of the central points in that regard. If only a small minority of regions meet those conditions, energy security in a renewables-based system will have to be discussed in much more detail. Getting this issue wrong at the current point in time may come with great costs in the future (retroactively changing the energy system that has been built on wrong assumptions about energy security). Moreover, the significance of individual regions for energy security may shift greatly, with potentially strong social, economic, and political implications.

Conclusions

The conclusions are directly connected to the presented material. All in all, I find the manuscript convincing and believe it will be an important contribution to various fields. Despite it being located in a field of study that I am not directly part of (more statistical-oriented energy studies), the readability is high and it is generally possible to follow the argument. However, at times it is somewhat difficult to grasp how the different metrics used by the authors work. In particular, I was struggling to understand the definition of 'extremeness' and how it differs from droughts. After having read the manuscript several times I am still not quite sure whether this is the same concept or whether there are differences between the two. Possibly, these difficulties are connected to the structure of the text which first deals with droughts and subsequently deals with three energy metrics. Is it possible to explain both the definitions and the article structure a bit clearer from the start?

On a more subjective note, do you feel that the paper will influence thinking in the field?

As mentioned before, I tend to think that the text will greatly stimulate the debate, as it questions the accurateness of both system-building and the way we are currently conceiving its social, economic, and political implications. Having seen the study results in China, I immediately would like to know what the results of a similar study on my region would look like, and what the implications could be. In particular, I am wondering about how the paradoxes of high availability and high extremeness (which I understand as droughts) would translate into. Also, given the strong interactions between regions in the electricity grid, I am wondering how the study results would look for an area with a generally smaller geography and current initiatives for increasing grid integration levels. Finally, I believe that the small number of regions with overall favorable conditions could stimulate discussions about the differences and similarities between fossil fuel-based energy systems and renewables-based systems.

Open questions

There are also several open questions:

- Is 'extremeness' the same as 'droughts'? Can this be clarified?
- How do 'resource availability', 'variability' and 'extremeness' compare in terms of their strength? Are these equally strong factors when it comes to determining the quality of a specific site? Could this be mentioned in the earlier parts of the text to help the reader seeing how these factors compare?
- Why do the authors mention only blue droughts in Fig. 4 and 5, while red droughts are seemingly more significant?
- Is it possible to make clearer what the 'Spatial correlation matrices' in Fig. 4 and 5 are showing? I believe you are explaining mainly/only the nodes and links in Fig. 4 (C, D), but not the matrices on the left (A, B);
- Could mentioning how energy droughts come about make the text more accessible? It is probably well explained in the methods, yet explaining the causes in simple terms might help increase readability;
- In the 'One-Sentence Summary' it says 'No place has rich, less variable, and less extreme renewables'. Yet there are a

number of purple circles in the lower left corners of Fig. 6; doesn't that suggest that there is a number of quality sites? Also, I find the word 'less' a bit problematic as it is not really intuitive

- What exactly is the 'trilemma'? I think it is important to get a bit more specific

- Could 'resource availability' be included in Fig. 3 (D, Spatial distribution)? I think this could make the graph more telling as you are saying that (paradoxically) resource endowments coincide largely with droughts occurring. I assume that would be difficult since then two graphs would be needed, one for solar and one for wind, but as it is now the text indicates that the benefits of certain regions are offset by droughts, but it doesn't really come across visually in this section (at least I don't see it). It would also connect sections 2.2 and 2.3 better

Reviewer #3 (Remarks to the Author):

This paper presents a statistical analysis on the occurrence of wind and solar droughts for the geographical area of China. My overall judgement is that, while there are some interesting insights, I am skeptical that there are sufficient new insights beyond what previous work has presented to justify publication.

My main criticism of the work is that it merely presents a statistical analysis of the resource droughts. Explanations of the underlying meteorological and geographical conditions are not given, neither are measures for how a future energy system could bridge potential periods of resource scarcity compared (short-term and long-term storage, continental transmission grids, demand-side management).

Furthermore, I do not believe the authors' novelty claim is valid. There is just a lot of existing literature on this topic (also looking beyond resource quantification and into meteorological drivers and power system integration). It did not convince me that the authors' metrics go beyond the state of the art. Here are just a few examples from the literature:

<https://iopscience.iop.org/article/10.1088/1748-9326/ad374a/meta>

<https://iopscience.iop.org/article/10.1088/1748-9326/ab38d3/meta>

<https://arxiv.org/abs/2402.06758>

<https://doi.org/10.1016/j.rser.2019.04.065>

<https://doi.org/10.1002/met.2141>

<https://iopscience.iop.org/article/10.1088/1748-9326/11/12/124025/meta>

<https://arxiv.org/abs/2404.12178>

<https://www.nature.com/articles/nclimate3338>

Given the large and consequentially limited contribution, I do not recommend publication of this manuscript.

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Version 1:

Decision Letter:

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Dear Professor Li,

Your manuscript titled "Renewable energy quality trilemma and coincident wind and solar droughts" 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.

We therefore invite you to revise your paper one last time to address the remaining concerns of reviewers 2 and 3. 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.

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

Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have carefully addressed my comments, and I do not have further comments.

Reviewer #2 (Remarks to the Author):

The revised version of the text seems much clearer and readable to me. Compared to the original manuscript, the current version should also be suitable for a wider audience as it combines more technical insights with societal implications.

I only have two suggestions concerning the following points:

The 'trilemma' and its representation in the text:

Coming from Social science, the nature of the trilemma is much clearer to me now, as is its depth (explained in a new paragraph on pages 22 and 23). However, I do not fully see the implications of this trilemma yet. It reminds me of an article that is trying to capture another trilemma that system builders are confronted with (the 'impossible energy trinity' by Thaler and Hofman: <https://doi.org/10.1016/j.polgeo.2021.102579>). The authors of this article visualize the trilemma that they have researched. I think that could be an option here as well. What is more, they also include different courses of action that system builders, policy makers etc. can pursue (see section 2.3 of that article). To me, this is very intuitive and also very helpful for discussing the trade-offs of the energy transition. I am therefore wondering whether it may be possible to a) visualize the energy trilemma that you are about to establish, and b) whether you could also indicate certain options for decision-makers when facing the trilemma.

If it is not possible to add such a graph, then I am wondering whether the phenomenon that you are studying can be called a 'trilemma' (as this term suggests 'a state of things in which it is difficult to determine which one of three courses to pursue' - see <https://www.merriam-webster.com/dictionary/trilemma>). The question is whether the solution that you are presenting for the 'droughtiness' of certain regions - sharing storage capacity across regions through (new?) grids - conflicts with one or both of the other two 'corners' of the 'trilemma': variability and availability. This probably can only be answered if you go a little bit more into the questions that the trilemma poses for system builders and what the answers may be and whether there are conflicts between the answers (these could be technological, political, societal etc.). If there are no such conflicts, then the droughtiness merely adds another layer of difficulty on top of existing ones.

- Figure 2:

The location of favourable sites for solar power generation is barely readable. Can this possibly be improved?

Reviewer #3 (Remarks to the Author):

With the current revision, I understand the contribution of the paper better. While I still feel that the paper somewhat exaggerates the research gap in the literature, based on the revisions and other reviewers' comments, I now believe that it would give sufficient new material for discussion and I would have no fundamental objection to this study being published, barring a few improvements:

The study by Antonini et al. (2024) in 'Communications Earth & Environment' (<https://www.nature.com/articles/s43247-024-01260-7>) goes in a very similar direction, using three reliability indicators (mean power density, seasonal variability, weather variability). It might be that that paper came out after this manuscript was submitted, but I think it is worthwhile comparing and discussing the approach taken there to the one taken here.

One of the other reviewers also asked about whether 19 years would be enough to comprehensively capture variability. I found the line of argumentation in the response not very convincing. First, it's hard to argue for consistency with previous literature as a broader range of years has been evaluated in the literature, also pre-2000. Second, lack of data availability should be no issue, in principle, as ERA5 reanalysis data is provided from 1940 to 2024 at a 0.25 x 0.25 grid resolution. This would also allow further analysis of multi-decadal trends. Third, based on my impressions of the calculations required for the study, I find it hard to believe that the computational resource is a limiting factor. It will likely be possible to optimise the resource consumption with optimised code (e.g. using lazy memory allocation). Perhaps the authors can reconsider to expand the temporal scope of their analysis.

The authors should upload the code and data used for their analysis under an open license. "Data availability on reasonable request" hinders reproducibility and transparency in research by creating barriers to data access, potentially leading to selective sharing, delays, or outright refusal, which prevents other researchers from independently verifying results or building upon the study's findings. Services like Github and Zenodo could be used for sharing.

Finally, I would note that through the detailed revisions, the manuscript got a bit wordy with low content density in parts (example: "Addressing the challenge of unraveling the mechanisms behind this trilemma requires a concerted effort to conduct in-depth investigations and to develop sophisticated models."). I would suggest to edit for conciseness.

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<Title: Renewable energy quality trilemma and coincident wind and solar droughts>

August 25, 2024

Dear reviewers,

We want to thank you for the opportunity to resubmit a revised version of our manuscript entitled “*Renewable energy quality trilemma and coincident wind and solar droughts*”, to be considered for publication in *Communications Earth & Environment*. We appreciate the time and effort you invested in providing feedback on our manuscript.

We have substantially rewritten the manuscript to address the comments and suggestions we received. We have responded to each of those comments and suggestions in our point-by-point response below. For clarity, we present our responses in blue font and the changes to the manuscript in red font. We have also included a revised manuscript in which we have tracked all the changes made in response to the feedback we received.

We thank you once again for providing us with valuable reviews and look forward to your response.

Sincerely Yours,

All authors

Response to reviewer #1:

This paper uses resource availability, variability, and extremeness to categorize the temporal and spatial characteristics of renewable energy droughts. It further maps out these energy droughts using China as an example. The framework provides a more comprehensive matrix of resource quality for renewable investors, planners, and policymakers. The presentation is clear, but I have a few small questions for the authors to consider.

Comment 1: *The paper introduces the concept of energy droughts and its associated matrix as new. However, it would be helpful if the authors clarified whether these concepts are used in existing literature and, if so, how their definitions or applications differ in this paper.*

Response: We thank the reviewer for this excellent suggestion. In response, we have added text to the introduction to a) present a review of the drought definitions used in the literature and b) to clarify that although defining drought is not new, seeing drought propensity as an intrinsic property of a renewable energy site and measuring it with the Relative Drought Frequency index is novel and a contribution.

In the introduction section, we reviewed how the previous literature characterizes the energy drought and how we learned but differ from previous literature. We have added the following text to the Introduction section (Pages 2-3 of the manuscript):

“While there is an abundance of research analyzing how renewable energy droughts affect the power system ^{17–19}, there is no consensus on the definition and characterization of renewable energy droughts. Raynaud et al. defined an energy drought as uninterrupted sequences of days with low power production or as sequences of days with a significant mismatch between production and demand ²⁰. Rinaldi et al. applied the energy drought concept on the production side, defining it as a solar or wind capacity factor less than 50% of the daily mean for that day of the year ²¹. Kapica et al. built upon the definition of a drought as a capacity lower than a threshold and proposed measuring the duration of the drought as the number of time periods it occurs, represented by a sum of binary variables ²². Allen and Otero proposed standardized indices to describe energy droughts, adopting a quantile-based definition rather than a percentage of the mean. They defined moderate, severe, and extreme droughts using the distribution’s 90th, 95th, and 97.5th percentiles. Furthermore, they defined the magnitude of the drought as the sum of their drought index over a certain period, considering both the duration and severity of the drought ²³. In this study, we build upon the metrics used in previous studies to characterize energy droughts. We take the

expected value as a key reference, similar to Rinaldi et al.²¹, and calculate the differences from the expected value. The expected value is critical for grid operators to plan dispatch decisions and thus should be considered. Then we, following Allen and Otero's approach, we set thresholds based on different quantiles of the distribution. We also adopt the system of binary variables used by Kapica et al. to mark whether a drought is occurring or not in a specific region and during a particular time period to analyze the spatial and temporal coincidence of energy droughts and the co-occurrence of droughts among different renewable resources."

Moreover, we do not only focus on energy drought itself, but treat the frequency of energy drought as a part of the resource quality in a certain site. In other words, the research subject is not merely to characterize the energy drought but to characterize the resource quality in different sites. To clarify the need for new metrics of drought and the novelty of our contribution we have added a few sentences in the introduction as follows (Page 4 of the manuscript):

"...Still, there is a fundamental literature gap in understanding the resource drought at different sites. There is a notable difference between the impacts of resource variability, which can be managed with the installation of short-duration battery energy storage, and the impacts of resource droughts, which require backup generation and long-duration energy storage resources to prevent blackouts. Given this difference, there is a lack of a metric to describe the resource quality in terms of its propensity to energy droughts. We term this attribute of proneness to droughts as "extremeness"."

We have also added the first two paragraphs of the results section (Pages 6-7 of the manuscript):

"We propose using a triad of indicators to assess renewable energy quality: availability, measured with the annual Capacity Factor; variability, measured with standard deviation; and extremeness, measured with the RDF index, an index we propose that measures the "droughtiness" of the resource. This droughtiness, which we term "extremeness", measures the severity and frequency of episodes when wind power, solar power, or both are low relative to their expected value. Using these metrics, we find that no sites have the three desirable qualities of high availability, low variability, and low extremeness of wind or solar energy resources; only 2.8% of the suitable wind sites and 1% of the solar sites in China rank slightly above average in the three renewable energy quality dimensions, that is, have high energy quality.

While availability and variability are measured with commonly used metrics, assessing extremeness requires us to define a drought. We define a drought as an episode when the resource's performance significantly deviates from its statistical expectation (more

on the Methods section). Because renewable energy droughts differ in their severity, we define three (blue, orange, and red), each one denoting a higher level of severity. We analyze over 19 years (2000-2018) of hourly data on wind and solar resources in each grid cell of 0.5-latitude-degree and 0.625-longitude-degree to identify past periods of droughts and determine their coincidence across resource (i.e., wind or solar), time, and space.”

Comment 2: *The authors selected the period from 2000 to 2018 for their study. Is this selection based on data availability, or are there other reasons? I am also curious about the general trend in capacity factors (CFs) during this period. Would it be more effective to use annual averages rather than a single average for the entire period? Additionally, how do evolving climate changes impact CFs? This part needs better justification or elaboration.*

Response: We thank the reviewer for these pertinent questions and the opportunity they provide us to clarify our research in the paper. In what follows, we respond to each of the four questions and describe the changes made to the manuscript.

1. The selection of the 2000–2018 time period was based on several considerations. Firstly, we aimed to maintain consistency with previous literature (reference 54 cited in our manuscript), which focused on identifying eligible sites for wind turbine and solar panel installations. This study adopts the same method to select eligible sites. By using the same data set to select eligible sites and evaluate the quality of renewable energy at these locations, we facilitate a comprehensive understanding of the results for our readers. Secondly, computational resource limitations played a role in our decision. This study utilizes high-resolution time-series data with spatial granularity (0.5-latitude-degree and 0.625-longitude-degree) and temporal detail (hourly) to characterize renewable energy droughts, a method that significantly differs from the daily or monthly averages typically used in existing studies, offering a more nuanced depiction of these events. However, this approach is computationally demanding; the analysis for the 2000-2018 period required over 200GB of memory. Extending the time frame would necessitate even greater RAM capacity. Additionally, during manuscript preparation, we conducted robustness checks comparing results from shorter time periods and confirmed the reliability of our findings.

2. We appreciate the reviewer’s insight regarding the potential trends in capacity factors (CFs) over the research period. Initially, during the preparation of the manuscript, we conducted an analysis of CFs and their standard deviations for wind energy but did not identify any clear trends. We chose to prioritize the characterization of renewable

energy droughts and the introduction of a triad of indicators for assessing renewable energy quality, rather than including the annual CFs and standard deviations. However, in response to the reviewer’s suggestion, we have revisited the data and expanded our investigation to include both wind and solar energy over the 2000-2018 period. Our revised analysis reveals no significant trend for wind energy, but we have observed a modest declining trend in the CFs and standard deviations for solar energy. To address the reviewer’s query, we have now included the annual CFs and standard deviations for both energy sources as follows (see Figures S17 and S19 in the Supplementary Information):

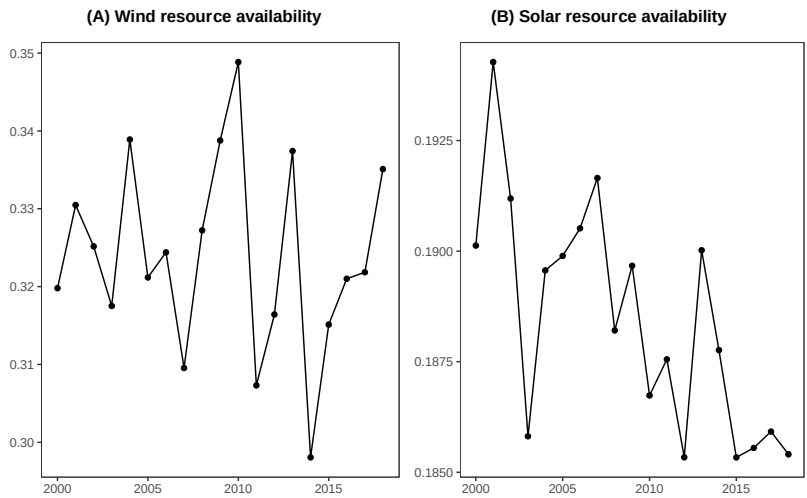


Figure S17. Trends in annual capacity factors for wind and solar energy over the period 2000-2018.

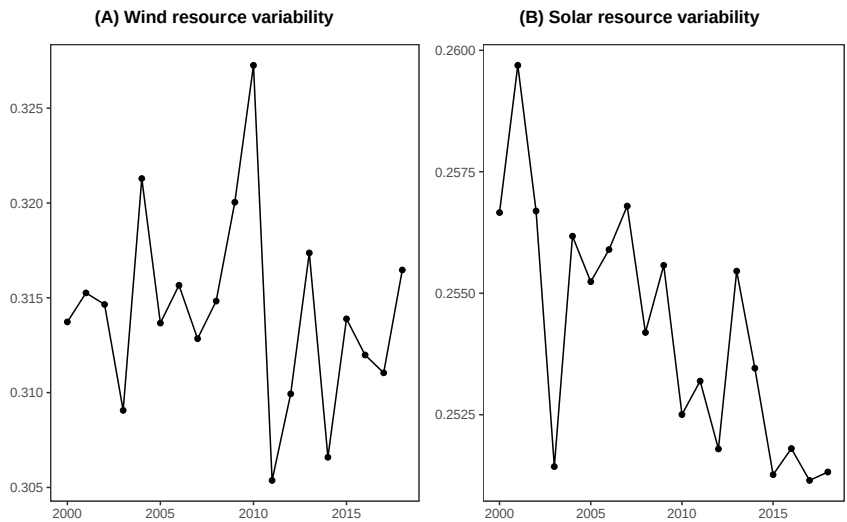


Figure S19. Trends in annual standard deviations for wind and solar energy over the period 2000-2018.

3. Instead of using annual averages as benchmarks for the resource’s attributes, we prefer a single average calculated for the entire period. The reason hinges on the fact

that electric power infrastructure is long-lived, and the assets developed at the beginning of the economic life of the renewable energy project are likely to last two or more decades unchanged. This means that the size and type of the wind turbines, solar panels, interconnection lines, and storage systems will all need to be sized based on the wind or solar resource attributes for the entire life-time. Additionally, given that there are no significant changes in most sites, we opt to use the average value of the entire period.

4. Indeed, climate change influences wind and solar availability (as measured by its CF) and possibly affects other attributes. In response to these comments, we have added the following text to the discussion section (Page 25 of the manuscript):

“The energy system is profoundly affected by climate change⁵³. While most research focuses on the effects on generation or resource potential^{53–56}, the impact on the variability and extremeness of local resources is less understood. Recent studies have analyzed how historical climate change has affected long-duration energy supply shortages⁵⁷, but they do not provide guidance for system planners on where to install renewable energy infrastructure to mitigate these impacts. Although our research does not project how future climate change may affect resource quality in three dimensions, it lays a strong foundation for future studies. It can help answer critical questions such as where to install renewable infrastructures to adapt to future climate conditions.”

Comment 3: *Including a map of "eligible sites" for wind and solar energy would aid in understanding the energy drought maps by clearly indicating whether the uncolored areas are ineligible sites or high-quality sites.*

Response: We thank the reviewer very much for this comment. In response, we have added to the results section in the manuscript the map of eligible sites and the capacity factors of these sites shown below (Figure 2 in Page 11 of the manuscript):

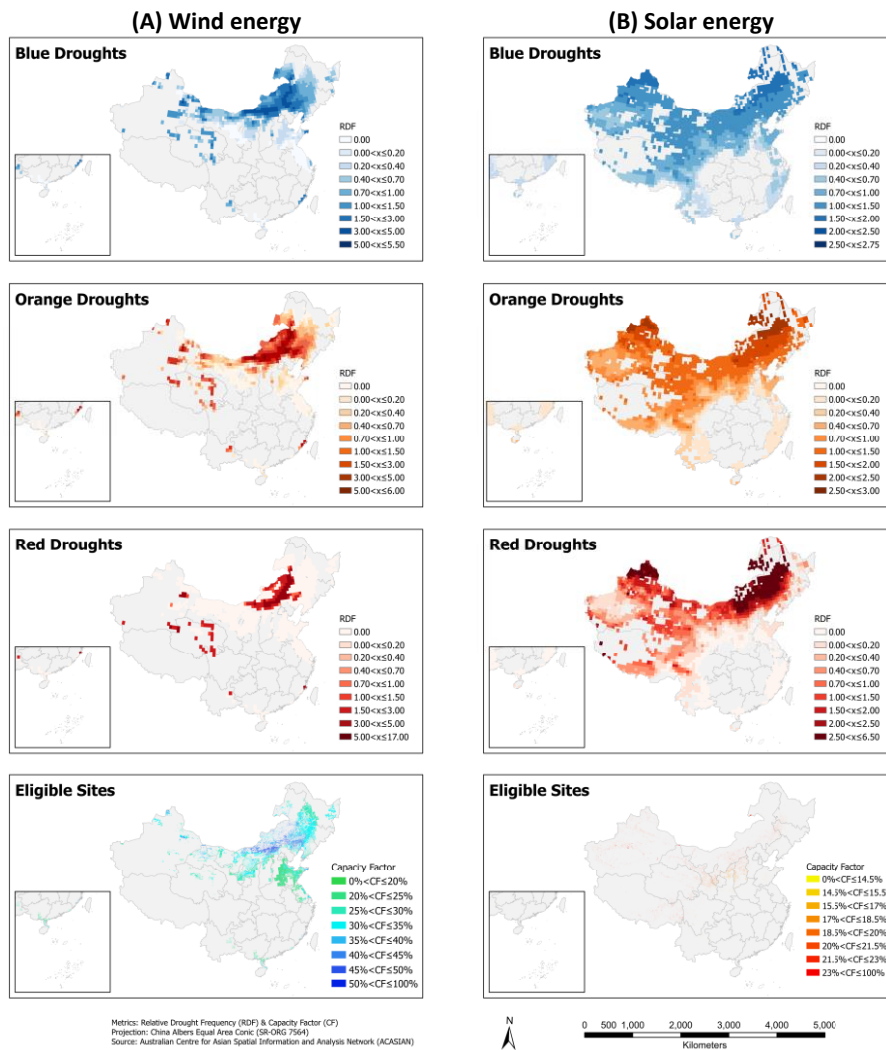


Figure 2. Spatial distribution of energy droughts and energy availability of wind and solar. (A) RDF index and capacity factor for each wind energy eligible site; (B) RDF index and capacity factor for each solar energy eligible site.

Comment 4: Lastly, it is unclear how the matrix can be used to guide investment or policy strategies. Perhaps the authors could discuss more about integrating their research findings into policy implications.

Response: We thank the reviewer for this helpful comment. In response, we have added to the discussion section the following paragraph, which clarifies how our findings can guide investment and its broad policy implications (Pages 23 and 25 of the manuscript):

“In China and many other countries, the resource availability has traditionally been the decisive metric for renewable energy project development. National governments and consulting companies publish resource availability maps to guide these projects. Over time, system planners have recognized the variability of these resources. Consequently,

Chinese local governments now require solar and wind power plants to be equipped with energy storage solutions. The minimum duration for storage is set at 1-4 hours, with a minimum power capacity of 10%-30% of the solar or wind power capacity, depending on the location. This study proposes a third metric, extremeness, which suggests that project developers should not only install short-duration energy storage but also consider long-duration energy storage technologies or alternative solutions. This recommendation is based on our map of extremeness, alongside the existing resource availability maps. Additionally, our findings on the spatial and temporal co-occurrence of energy droughts indicate that some regions could share their long-duration energy storage. If portable, these storage solutions could be rented and transported to specific sites during certain seasons. Also, regions where the droughts of solar and wind are not likely to coincide, could balance their approach with both resources.”

“The energy system is profoundly affected by climate change ⁵³. While most research focuses on the effects on generation or resource potential ⁵³⁻⁵⁶, the impact on the variability and extremeness of local resources is less understood. Recent studies have analyzed how historical climate change has affected long-duration energy supply shortages ⁵⁷, but they do not provide guidance for system planners on where to install renewable energy infrastructure to mitigate these impacts. Although our research does not project how future climate change may affect resource quality in three dimensions, it lays a strong foundation for future studies. It can help answer critical questions such as where to install renewable infrastructures to adapt to future climate conditions.”

We thank the reviewer for these valuable comments and suggestions.

Response to reviewer #2:

General Comment: Overview

The manuscript presents the findings of a statistical analysis of renewable energy production. The geographic focus is on the People's Republic of China. The analysis aims at changing the understanding of the reliability of energy production based on wind and solar energy. The focal point is renewable energy droughts, that is longer periods without or very little wind and/or solar energy production. On that basis, the authors suggest a way to assess the reliability of regions in that regard, and hence the needs in terms of power system design.

Major claims of the paper

The central argument of the manuscript is that literature on the security of renewable energy-based electricity systems suffers from a focus on the availability and short-term variability of energy resources (wind, solar). The authors suggest including the concept of energy droughts, that is extreme and prolonged reductions in renewable power generation to determine the outlines of a secure energy system based on renewables. The manuscript argues that the inclusion of energy droughts in the analysis allows to go beyond to narrow a view on energy security in a decarbonised electricity system. According to the authors, including energy droughts is suited to highlight a significant lack of sites with favorable renewable energy conditions, which in turn leaves system builders with important challenges.

Novelty and interest to others in the community and the wider field

The authors argue convincingly that the current premises of renewable energy system building are too narrow to understand potential supply gaps under the condition of a decarbonized electricity system based on wind and solar energy. I believe this paper will greatly stimulate research on energy security, as it puts into question certain assumptions in that field. For example, a standard argument in this field of study is the broad availability of renewable energy resources (in contrast to fossil fuel which is more geographically focused); on the basis of this premise, and with a positive outlook on technology development (for example in the area of storage), it is generally assumed that renewables will lead to higher energy security. The authors of this manuscript show convincingly that securing electricity supply can be more demanding than what is generally assumed. The lack of geographic regions that meet the three conditions of 'availability', 'low variability', and 'low extremeness' is one of the central points in that regard. If only a small minority of regions meet those conditions, energy security in a renewables-based system will have to be discussed in much more detail. Getting this issue wrong at the current point in time may come with great costs in the future (retroactively changing the energy system that has been built on wrong assumptions

about energy security). Moreover, the significance of individual regions for energy security may shift greatly, with potentially strong social, economic, and political implications.

Response: We thank the reviewer for these encouraging comments. We have significantly improved the text throughout the manuscript to follow the reviewer's suggestions.

Comment 1: *Conclusions: The conclusions are directly connected to the presented material. All in all, I find the manuscript convincing and believe it will be an important contribution to various fields. Despite it being located in a field of study that I am not directly part of (more statistical-oriented energy studies), the readability is high and it is generally possible to follow the argument. However, at times it is somewhat difficult to grasp how the different metrics used by the authors work. In particular, I was struggling to understand the definition of 'extremeness' and how it differs from droughts. After having read the manuscript several times I am still not quite sure whether this is the same concept or whether there are differences between the two. Possibly, these difficulties are connected to the structure of the text which first deals with droughts and subsequently deals with three energy metrics. Is it possible to explain both the definitions and the article structure a bit clearer from the start?*

Response: We thank the reviewer for this comment, which made us realize the need to clarify the definition of extremeness further. In response, we have added text to the introduction to make clear that an energy drought is an event, classified based on its duration and severity, while extremeness describes the likelihood of a site experiencing an energy drought. Extremeness is a key dimension of the resource's quality. Indeed, "extremeness" could also be called "droughtiness" without any loss of precision. We do not only focus on energy drought itself, but treat the frequency of energy drought as a part of the resource quality in a certain site. In other words, the research subject is not merely to characterize the energy drought but to characterize the resource quality in different sites.

We have added text to the introduction section for further clarification of the relationship between extremeness and drought.

In page 4, we say:

“...there is a lack of a metric to describe the resource quality in terms of its propensity to energy droughts. We term this attribute of proneness to droughts as “extremeness”.”

In page 5, we also say:

“Three: we propose new metrics to characterize renewable energy quality along three dimensions (availability, variability, and extremeness). The availability measures how much of the resource can be utilized at the site, as indicated by its average capacity factor. The variability measures how stable the resource is as indicated by the standard deviation of the capacity factor. This metric can guide the development of short-duration energy storage. The extremeness is proposed as a new dimension of resource quality to measure how likely the site is to experience energy droughts. This metric can guide the development of long duration energy storage and other backup resources. By using this triad of metrics, we improve existing understanding of renewable energy quality and identify the “ideal” sites for renewable energy development.”

We have also added the first two paragraphs of the results section (Pages 6-7 of the manuscript):

“We propose using a triad of indicators to assess renewable energy quality: availability, measured with the annual Capacity Factor; variability, measured with standard deviation; and extremeness, measured with the RDF index, an index we propose that measures the “droughtiness” of the resource. This droughtiness, which we term “extremeness”, measures the severity and frequency of episodes when wind power, solar power, or both are low relative to their expected value. Using these metrics, we find that no sites have the three desirable qualities of high availability, low variability, and low extremeness of wind or solar energy resources; only 2.8% of the suitable wind sites and 1% of the solar sites in China rank slightly above average in the three renewable energy quality dimensions, that is, have high energy quality.

While availability and variability are measured with commonly used metrics, assessing extremeness requires us to define a drought. We define a drought as an episode when the resource’s performance significantly deviates from its statistical expectation (more on the Methods section). Because renewable energy droughts differ in their severity, we define three (blue, orange, and red), each one denoting a higher level of severity...”

Comment 2: *On a more subjective note, do you feel that the paper will influence thinking in the field?*

As mentioned before, I tend to think that the text will greatly stimulate the debate, as it questions the accurateness of both system-building and the way we are currently conceiving its social, economic, and political implications. Having seen the study results in China, I immediately would like to know what the results of a similar study on my region would look like, and what the implications could be. In particular, I am wondering about how the paradoxes of high availability and high extremeness (which I understand as droughts) would translate into. Also, given the strong interactions

between regions in the electricity grid, I am wondering how the study results would look for an area with a generally smaller geography and current initiatives for increasing grid integration levels. Finally, I believe that the small number of regions with overall favorable conditions could stimulate discussions about the differences and similarities between fossil fuel-based energy systems and renewables-based systems.

Response: We thank the reviewer for these intellectually stimulating questions. We certainly hope that our paper dethrones CF as the king metric for renewable energy site selection and that our triad, or a similar one, replaces it. Nevertheless, there is a need for meticulous, detailed research that explores the economic and reliability tradeoffs of developing at sites with different scorings in the three metrics. The results will vary from one system to the next depending on the costs and availability of other load following resources and transmission capacity.

In response, we have added to the discussion section the following paragraph, which clarifies how our findings can guide investment and its broad policy implications (Pages 23 and 25 of the manuscript):

“In China and many other countries, the resource availability has traditionally been the decisive metric for renewable energy project development. National governments and consulting companies publish resource availability maps to guide these projects. Over time, system planners have recognized the variability of these resources. Consequently, Chinese local governments now require solar and wind power plants to be equipped with energy storage solutions. The minimum duration for storage is set at 1-4 hours, with a minimum power capacity of 10%-30% of the solar or wind power capacity, depending on the location. This study proposes a third metric, extremeness, which suggests that project developers should not only install short-duration energy storage but also consider long-duration energy storage technologies or alternative solutions. This recommendation is based on our map of extremeness, alongside the existing resource availability maps. Additionally, our findings on the spatial and temporal co-occurrence of energy droughts indicate that some regions could share their long-duration energy storage. If portable, these storage solutions could be rented and transported to specific sites during certain seasons. Also, regions where the droughts of solar and wind are not likely to coincide, could balance their approach with both resources.”

Open questions

There are also several open questions:

Comment 3: *Is 'extremeness' the same as 'droughts'? Can this be clarified?*

Response: We apologize for the confusion. In short, an energy drought is an event, classified based on its duration and severity, while extremeness describes the likelihood of a site experiencing an energy drought. As we realize that the reviewer's question is likely to be asked by readers, we have significantly improved the introduction section and the beginning of the results section to clarify the relationship between drought and extremeness.

We note that this comment is similar to Comment 1, and we direct the reviewer to our response to that comment for further information.

Comment 4: *How do 'resource availability', 'variability' and 'extremeness' compare in terms of their strength? Are these equally strong factors when it comes to determining the quality of a specific site? Could this be mentioned in the earlier parts of the text to help the reader seeing how these factors compare?*

Response: We thank the reviewer for the suggestion to clarify the hierarchy among the three metrics. We believe that the three dimensions are important, but their relative prioritization evolves over time as the power sector decarbonizes. To follow the reviewer's suggestion, we have added text to the introduction section, as follows (Page 5 of the manuscript):

“The three dimensions are important, but their relative prioritization will depend on how much the system is decarbonized. Resource availability is the most critical metric at low penetration levels of solar and wind resources. With low shares of electricity being generated by these sources, the system will have enough flexibility to accommodate their fluctuations and still meet the electrical load. Policymakers and project developers will prioritize maximizing renewable energy generation and reducing its Levelized Cost of Electricity, a function of the Capacity Factor or resource availability, with limited concern for system flexibility. As the penetration of variable renewable energy increases, system planners must consider these resources' variability to decide how to equip the system with the needed flexibility by installing dispatchable generation, energy storage, and increased power transmission capacity. At deeply decarbonized systems, energy droughts will pose serious threats to reliability, so planners will need to prioritize sites with low extremeness or sites where the mitigation measures, including large, long-duration storage are technically and economically feasible.”

Comment 5: *Why do the authors mention only blue droughts in Fig. 4 and 5, while red droughts are seemingly more significant?*

Response: We thank the reviewer for the comment. We agree with the reviewer that including results for the three categories of droughts in the manuscript would enrich the findings of our study. However, due to the length limit imposed by the journal, we have chosen to concentrate on presenting the results for blue droughts in Figures 4 and 5, with the outcomes for red and orange droughts provided in the Supplementary Information. For further details, please refer to Figures S22-S25 in Section S7 of the Supplementary Information.

Comment 6: *Is it possible to make clearer what the 'Spatial correlation matrices' in Fig. 4 and 5 are showing? I believe you are explaining mainly/only the nodes and links in Fig. 4 (C, D), but not the matrices on the left (A, B);*

Response: We thank the reviewer for pointing out we need to further explain how to interpret the correlation matrices. In response, we have significantly improved the captions of Figure 4 and Figure 5.

In Page 16, we say:

“Figure 4. Spatial dependence of wind and solar energy droughts (blue droughts). (A) and (B) Spatial correlation matrix and clusters of wind and solar blue droughts. We use the Pearson correlation coefficient to measure the spatial correlation of wind and solar energy droughts among provinces. Each coefficient reflects the strength and direction of the linear relationship between the occurrences of droughts in different provinces. A positive value indicates that the two provinces are positively correlated in terms of the prevalence of renewable energy droughts, suggesting that they tend to experience such events concurrently. Conversely, a negative value implies a negative correlation...”

In Page 18, we say:

“Figure 5. Spatial dependence of the coincident wind-solar energy droughts (blue droughts). It shows the spatial correlation matrix and clusters of coincident blue droughts. We use the Pearson correlation coefficient to measure the spatial correlation of coincident wind-solar energy droughts among provinces. Each coefficient reflects the strength and direction of the linear relationship between the occurrences of coincident droughts in different provinces. A positive value indicates that the two provinces are positively correlated in terms of the prevalence of coincident droughts. Conversely, a negative value implies a negative correlation.”

Comment 7: *Could mentioning how energy droughts come about make the text more accessible? It is probably well explained in the methods, yet explaining the causes in simple terms might help increase readability;*

Response: We thank the reviewer for the suggestion. To follow the reviewer's suggestion, we have added the text below to the introduction section to briefly explain how we define energy drought (Pages 2-3 of the manuscript):

“...In this study, we build upon the metrics used in previous studies to characterize energy droughts. We take the expected value as a key reference, similar to Rinaldi et al.²¹, and calculate the differences from the expected value. The expected value is critical for grid operators to plan dispatch decisions and thus should be considered. Then we, following Allen and Otero's approach, we set thresholds based on different quantiles of the distribution. We also adopt the system of binary variables used by Kapica et al. to mark whether a drought is occurring or not in a specific region and during a particular time period to analyze the spatial and temporal coincidence of energy droughts and the co-occurrence of droughts among different renewable resources.”

Comment 8: *In the 'One-Sentence Summary' it says 'No place has rich, less variable, and less extreme renewables'. Yet there are a number of purple circles in the lower left corners of Fig. 6; doesn't that suggest that there is a number of quality sites? Also, I find the word 'less' a bit problematic as it is not really intuitive*

Response: We thank the reviewer for the pointing out this problem. We agree with the reviewer that a minimal number of sites rank slightly above average in the three renewable energy quality dimensions, that is, have high energy quality. To address the reviewer's concern and clarify the findings, we now remove the “One-Sentence Summary”, and add the following text to the Results section (Pages 6-7 of the manuscript):

“... Using these metrics, we find that no sites have the three desirable qualities of high availability, low variability, and low extremeness of wind or solar energy resources; only 2.8% of the suitable wind sites and 1% of the solar sites in China rank slightly above average in the three renewable energy quality dimensions, that is, have high energy quality.”

***Comment 9:** What exactly is the 'trilemma'? I think it is important to get a bit more specific*

Response: We thank the reviewer for pointing out that we need to clarify what is the trilemma. Basically, the trilemma is the need to choose one of the three equally important objectives. The trilemma arises because these three attributes of renewable energy quality (availability, variability, and extremeness) present themselves in undesirable directions. Sites with higher resource availability have higher variability and more energy droughts; while areas with lower variability and fewer droughts have lower resource availability. Although a minimal number of sites rank slightly above average in the three renewable energy quality, no sites excel in all three quality attributes. The three objectives are in conflict with each other and difficult to reconcile. Stakeholders must prioritize one of the three attributes as renewable penetration grows.

In response, we have significantly improved the Abstract, Introduction, Results and Discussion sections to clarify what is the trilemma.

In the Abstract, we say (Page 1 of the manuscript):

“...It also finds a lack of sites that excel in all three quality attributes, which presents a trilemma to investors, system planners, and policymakers...”

In the introduction section, we have added text as follows (Page 5 of the manuscript):

“The three dimensions are important, but their relative prioritization will depend on how much the system is decarbonized. Resource availability is the most critical metric at low penetration levels of solar and wind resources. With low shares of electricity being generated by these sources, the system will have enough flexibility to accommodate their fluctuations and still meet the electrical load. Policymakers and project developers will prioritize maximizing renewable energy generation and reducing its Levelized Cost of Electricity, a function of the Capacity Factor or resource availability, with limited concern for system flexibility. As the penetration of variable renewable energy increases, system planners must consider these resources' variability to decide how to equip the system with the needed flexibility by installing dispatchable generation, energy storage, and increased power transmission capacity. At deeply decarbonized systems, energy droughts will pose serious threats to reliability, so planners will need to prioritize sites with low extremeness or sites where the mitigation measures, including large, long-duration storage are technically and economically feasible.”

In Page 6, we now say:

“... Using these metrics, we find that no sites have the three desirable qualities of high availability, low variability, and low extremeness of wind or solar energy resources; only 2.8% of the suitable wind sites and 1% of the solar sites in China rank slightly above average in the three renewable energy quality dimensions, that is, have high energy quality.”

In Page 19, we now say:

“...As the resource availability increases (i.e., as it changes from grey to purple dots in Figure 6), variability and extremeness also increase (i.e., they go from the bottom left to the top right corner in each panel in Figure 6). This indicates that the availability, variability, and extremeness of renewable energy present themselves in undesirable directions in the region observed. Sites with higher resource availability (the purple dots in Figure 6) generally have higher variability and more energy droughts; while areas with lower variability and fewer droughts generally have lower resource availability (the grey dots in Figure 6) ...”

In the Discussion section, we have added text as follows (Pages 22-23 of the manuscript):

“...Lack of sites that excel in all three quality attributes presents a trilemma to investors, system planners, and policymakers. This trilemma of renewable energy quality can help conceptualize three energy policy objectives, which are often difficult to reconcile and in conflict with each other. Stakeholders must prioritize one of the three attributes at different penetrations of variable renewables: at low penetration levels of variable renewables, resource availability will need to be prioritized; as the penetration of variable renewable energy increases, system planners must prioritize the attribute of resource variability at higher penetration levels; and at deeply decarbonized systems, planners will need to focus on the attribute of resource extremeness...”

Comment 10: *Could 'resource availability' be included in Fig. 3 (D, Spatial distribution)? I think this could make the graph more telling as you are saying that (paradoxically) resource endowments coincide largely with droughts occurring. I assume that would be difficult since then two graphs would be needed, one for solar and one for wind, but as it is now the text indicates that the benefits of certain regions are offset by droughts, but it doesn't really come across visually in this section (at least I don't see it). It would also connect sections 2.2 and 2.3 better*

Response: We thank the reviewer very much for this comment. In response, we have added to the results section in the manuscript the map of eligible sites and the capacity factors (representing resource availability) of these sites shown below (Figure 2 in Page 11 of the manuscript):

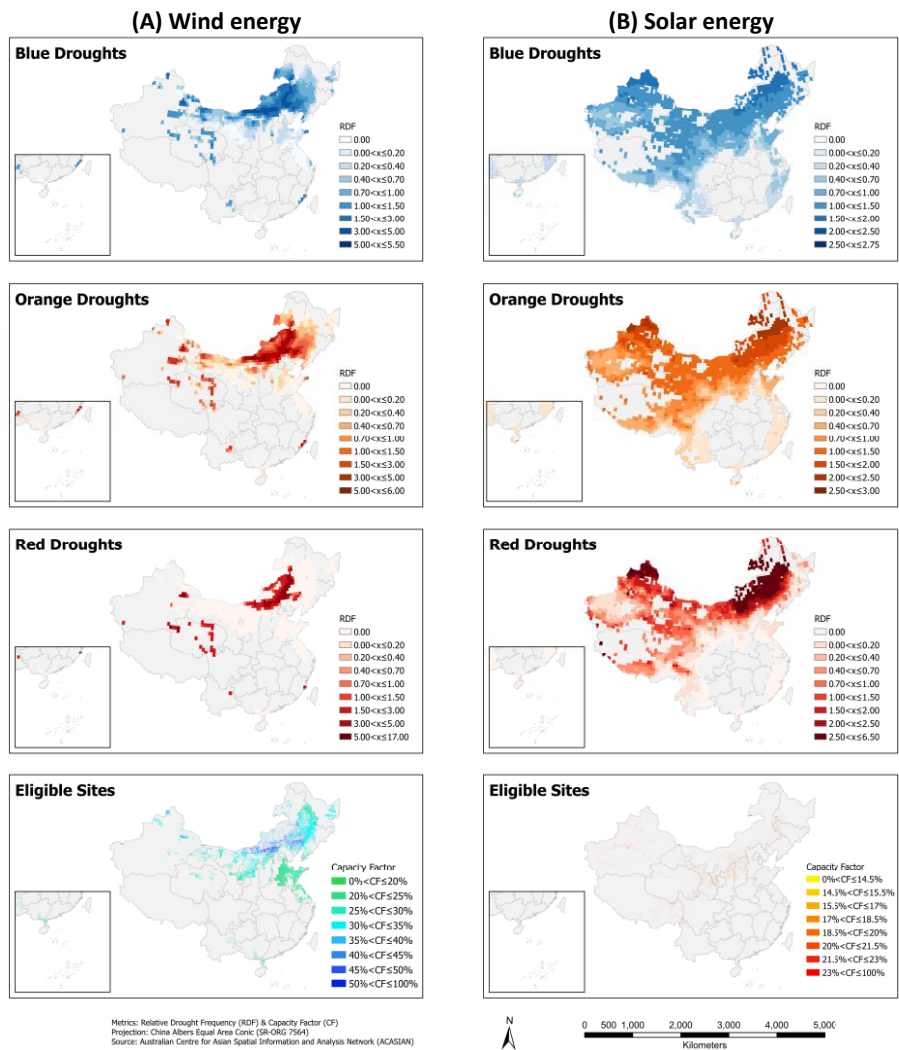


Figure 2. Spatial distribution of energy droughts and energy availability of wind and solar. (A) RDF index and capacity factor for each wind energy eligible site; (B) RDF index and capacity factor for each solar energy eligible site.

We thank the reviewer for these helpful comments and suggestions.

Response to reviewer #3:

***Comment 1:** This paper presents a statistical analysis on the occurrence of wind and solar droughts for the geographical area of China. My overall judgement is that, while there are some interesting insights, I am skeptical that there are sufficient new insights beyond what previous work has presented to justify publication.*

Response: We thank the reviewer for this comment, which made us realize the need to clarify this paper's novelty further. We agree with the reviewer that previous literature has characterized renewable energy droughts in different regions. However, the spatial dependence and temporal concurrence of renewable energy droughts remains understudied. The research subject is not merely to characterize the energy drought but to explore the spatial and temporal coincidence of wind and solar energy droughts. Also, we regard energy droughts as an intrinsic attribute of the resource. We define the attribute of proneness to droughts as "extremeness" and propose three metrics to comprehensively assess renewable energy quality: resource availability, variability, and extremeness. This is indeed an enrichment in how we understand the resource quality of the wind and solar.

In response to your suggestion that we clarify the contribution of this study, we have significantly improved the text throughout the manuscript as follows:

(1) In the Abstract, we say (see Page 1):

"...The spatial dependence and temporal concurrence of such extreme events remains understudied. Here we present a framework to characterize these events and to explore their spatial and temporal coincidence. Furthermore, we define the attribute of proneness to droughts as "extremeness" and propose three metrics to comprehensively assess renewable energy quality: resource availability, variability, and extremeness..."

(2) In the introduction section, we reviewed how the previous literature characterizes the energy drought and how we learned but differ from previous literature. We have added the following text to the Introduction section (Pages 2-3 of the manuscript):

"While there is an abundance of research analyzing how renewable energy droughts affect the power system ¹⁷⁻¹⁹, there is no consensus on the definition and characterization of renewable energy droughts. Raynaud et al. defined an energy drought as uninterrupted sequences of days with low power production or as sequences of days with a significant mismatch between production and demand ²⁰. Rinaldi et al. applied the energy drought concept on the production side, defining it as a solar or wind

capacity factor less than 50% of the daily mean for that day of the year ²¹. Kapica et al. built upon the definition of a drought as a capacity lower than a threshold and proposed measuring the duration of the drought as the number of time periods it occurs, represented by a sum of binary variables ²². Allen and Otero proposed standardized indices to describe energy droughts, adopting a quantile-based definition rather than a percentage of the mean. They defined moderate, severe, and extreme droughts using the distribution's 90th, 95th, and 97.5th percentiles. Furthermore, they defined the magnitude of the drought as the sum of their drought index over a certain period, considering both the duration and severity of the drought ²³. In this study, we build upon the metrics used in previous studies to characterize energy droughts. We take the expected value as a key reference, similar to Rinaldi et al. ²¹, and calculate the differences from the expected value. The expected value is critical for grid operators to plan dispatch decisions and thus should be considered. Then we, following Allen and Otero's approach, we set thresholds based on different quantiles of the distribution. We also adopt the system of binary variables used by Kapica et al. to mark whether a drought is occurring or not in a specific region and during a particular time period to analyze the spatial and temporal coincidence of energy droughts and the co-occurrence of droughts among different renewable resources.”

(3) Seeing drought propensity as an intrinsic property of a renewable energy site and proposing three metrics to comprehensively assess renewable energy quality is novel and a contribution. We have added text to the introduction section for further clarification.

In page 4, we say:

“...Still, there is a fundamental literature gap in understanding the resource drought at different sites. There is a notable difference between the impacts of resource variability, which can be managed with the installation of short-duration battery energy storage, and the impacts of resource droughts, which require backup generation and long-duration energy storage resources to prevent blackouts. Given this difference, there is a lack of a metric to describe the resource quality in terms of its propensity to energy droughts. We term this attribute of proneness to droughts as “extremeness”.”

In page 5, we have improved the text to clarify the contributions:

“...Two: we propose a method to examine the prevalence of spatial and temporal coincidence of these droughts. We determine in which regions these droughts are spatially correlated, jeopardizing large geographic areas. We also identify the regions and seasons where and when wind and solar energy extremes are likely to occur simultaneously. Three: we propose new metrics to characterize renewable energy quality along three dimensions (availability, variability, and extremeness). The

availability measures how much of the resource can be utilized at the site, as indicated by its average capacity factor. The variability measures how stable the resource is as indicated by the standard deviation of the capacity factor. This metric can guide the development of short-duration energy storage. The extremeness is proposed as a new dimension of resource quality to measure how likely the site is to experience energy droughts. This metric can guide the development of long-duration energy storage and other backup resources. By using this triad of metrics, we improve existing understanding of renewable energy quality and identify the “ideal” sites for renewable energy development.”

(4) Our proposed Relative Drought Frequency index to measure the extremeness in the resources of a specific site is indeed a new concept. Such a metric facilitates an increased understanding of energy droughts. We have added the following text to the Results section (Pages 6-7 of the manuscript):

“We propose using a triad of indicators to assess renewable energy quality: availability, measured with the annual Capacity Factor; variability, measured with standard deviation; and extremeness, measured with the RDF index, an index we propose that measures the “droughtiness” of the resource. This droughtiness, which we term “extremeness”, measures the severity and frequency of episodes when wind power, solar power, or both are low relative to their expected value. Using these metrics, we find that no sites have the three desirable qualities of high availability, low variability, and low extremeness of wind or solar energy resources; only 2.8% of the suitable wind sites and 1% of the solar sites in China rank slightly above average in the three renewable energy quality dimensions, that is, have high energy quality.

While availability and variability are measured with commonly used metrics, assessing extremeness requires us to define a drought. We define a drought as an episode when the resource’s performance significantly deviates from its statistical expectation (more on the Methods section). Because renewable energy droughts differ in their severity, we define three (blue, orange, and red), each one denoting a higher level of severity...”

Comment 2: *My main criticism of the work is that it merely presents a statistical analysis of the resource droughts. Explanations of the underlying meteorological and geographical conditions are not given, neither are measures for how a future energy system could bridge potential periods of resource scarcity compared (short-term and long-term storage, continental transmission grids, demand-side management).*

Response: We thank the reviewer for raising this point. We appreciate the acknowledgement of our statistical analysis of the resource drought. We would argue

that although we did not specify which technology to adapt to the energy droughts, the map we provided can guide the project developers where to avoid the energy droughts, where to avoid variability and where to gain a high average resource potential. Moreover, our map tells that it is challenging to find the ideal site that has high resource potential, stable energy output and not likely to experience energy drought.

We find that no sites excel in all three quality attributes: availability, variability, and extremeness of renewable energy. These attributes often manifest in undesirable directions. The meteorological and geographical mechanisms behind this trilemma are likely complex. Previous literature has shown that renewable energy droughts are often associated with large high-pressure systems over central Europe (see: Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall, <https://doi.org/10.1016/j.rser.2019.04.065>). After consultations with some climatologists, we have come to realize that while understanding the causes of individual drought events is feasible, unraveling the mechanisms behind such a trilemma poses a significant challenge. This endeavor necessitates an in-depth investigation and the development of sophisticated models that capture the interplay between geographical, meteorological, and atmospheric dynamics at high spatial and temporal resolutions. We concur with the reviewer's observation that the performances of the three quality attributes are fundamentally rooted in the meteorological and geographical conditions of the research area, and potentially, larger regions. Based on this understanding, we propose the following hypothesis: areas with abundant resources, such as regions with high solar radiation or wind speed, also exhibit a high momentum and potential for meteorological change. This energy imbalance may give rise to various weather conditions that affect the variability and extremeness of these resources. For instance, strong solar radiation can drive a more vigorous water cycle, resulting in increased evaporation, cloud formation, and potentially more intense and frequent precipitation events. These weather patterns can, in turn, impact the variability and extremeness of the local solar resource. Similarly, high wind speeds signify strong energy transfer, which influences the atmospheric energy balance and can lead to shifts in weather patterns. However, this remains a hypothesis. Credible analysis necessitates the foundation of granular climate modeling analysis. We hope this study will inspire meteorologists and climate scientists to delve into the mechanisms underlying this trilemma.

In response to your suggestion, we have added the following text to the Discussion section (Pages 24-25 of the manuscript):

“While this study has exposed that at many sites in China, the availability, variability, and extremeness of renewable energy tend to manifest in undesirable directions, similar

phenomena may occur at other locations worldwide. However, the underlying meteorological and geographical mechanisms driving this trilemma remain unclear and demand further investigation. Prior research has indicated a correlation between renewable energy droughts and the presence of extensive high-pressure systems over central Europe^{51,52}. Addressing the challenge of unraveling the mechanisms behind this trilemma requires a concerted effort to conduct in-depth investigations and to develop sophisticated models. These models should be capable of capturing the intricate interplay among geographical, meteorological, and atmospheric dynamics across high spatial and temporal resolutions. We hope this study will inspire meteorologists and climate scientists to delve deeper into the mechanisms underlying this phenomenon. The energy system is profoundly affected by climate change⁵³. While most research focuses on the effects on generation or resource potential^{53–56}, the impact on the variability and extremeness of local resources is less understood. Recent studies have analyzed how historical climate change has affected long-duration energy supply shortages⁵⁷, but they do not provide guidance for system planners on where to install renewable energy infrastructure to mitigate these impacts. Although our research does not project how future climate change may affect resource quality in three dimensions, it lays a strong foundation for future studies. It can help answer critical questions such as where to install renewable infrastructures to adapt to future climate conditions.”

Regarding the strategies to address potential future periods of resource scarcity, we agree with the reviewer that intermittent energy sources integration must be complemented by flexible power generators, short-term and long-term energy storage capacity, enhanced transmission grids, and effective demand-side management strategies to ensure a reliable electricity supply. The resource quality assessment provided in this paper can be used by system planners, along with representation of extant infrastructure as inputs into a capacity expansion and operational dispatch model. With these inputs, the model will prescribe the optimal capacity allocation and dispatch strategy of each resource type, including energy storage systems, transmission infrastructure, base-load generators, and demand side management initiatives. To make this clearer and address the reviewer’s concern, we have added a few statements to the manuscript as follows:

(1) In the introduction section, we add (Pages 5-6 of the manuscript):

“The three dimensions are important, but their relative prioritization will depend on how much the system is decarbonized. Resource availability is the most critical metric at low penetration levels of solar and wind resources. With low shares of electricity being generated by these sources, the system will have enough flexibility to accommodate their fluctuations and still meet the electrical load. Policymakers and project developers will prioritize maximizing renewable energy generation and reducing its Levelized Cost of Electricity, a function of the Capacity Factor or resource availability, with limited concern for system flexibility. As the penetration of variable

renewable energy increases, system planners must consider these resources' variability to decide how to equip the system with the needed flexibility by installing dispatchable generation, energy storage, and increased power transmission capacity. At deeply decarbonized systems, energy droughts will pose serious threats to reliability, so planners will need to prioritize sites with low extremeness or sites where the mitigation measures, including large, long-duration storage are technically and economically feasible.”

(2) To expand the policy implications of our findings, we have added the following text in the discussion section.

In Page 23, we add:

“In China and many other countries, the resource availability has traditionally been the decisive metric for renewable energy project development. National governments and consulting companies publish resource availability maps to guide these projects. Over time, system planners have recognized the variability of these resources. Consequently, Chinese local governments now require solar and wind power plants to be equipped with energy storage solutions. The minimum duration for storage is set at 1-4 hours, with a minimum power capacity of 10%-30% of the solar or wind power capacity, depending on the location. This study proposes a third metric, extremeness, which suggests that project developers should not only install short-duration energy storage but also consider long-duration energy storage technologies or alternative solutions. This recommendation is based on our map of extremeness, alongside the existing resource availability maps. Additionally, our findings on the spatial and temporal co-occurrence of energy droughts indicate that some regions could share their long-duration energy storage. If portable, these storage solutions could be rented and transported to specific sites during certain seasons. Also, regions where the droughts of solar and wind are not likely to coincide, could balance their approach with both resources.”

In Page 25, we add:

“The energy system is profoundly affected by climate change⁵³. While most research focuses on the effects on generation or resource potential^{53–56}, the impact on the variability and extremeness of local resources is less understood. Recent studies have analyzed how historical climate change has affected long-duration energy supply shortages⁵⁷, but they do not provide guidance for system planners on where to install renewable energy infrastructure to mitigate these impacts. Although our research does not project how future climate change may affect resource quality in three dimensions, it lays a strong foundation for future studies. It can help answer critical questions such as where to install renewable infrastructures to adapt to future climate conditions.”

Comment 3: Furthermore, I do not believe the authors' novelty claim is valid. There is just a lot of existing literature on this topic (also looking beyond resource quantification and into meteorological drivers and power system integration). It did not convince me that the authors' metrics go beyond the state of the art. Here are just a few examples from the literature:

<https://iopscience.iop.org/article/10.1088/1748-9326/ad374a/meta>

<https://iopscience.iop.org/article/10.1088/1748-9326/ab38d3/meta>

<https://arxiv.org/abs/2402.06758>

<https://doi.org/10.1016/j.rser.2019.04.065>

<https://doi.org/10.1002/met.2141>

<https://iopscience.iop.org/article/10.1088/1748-9326/11/12/124025/meta>

<https://arxiv.org/abs/2404.12178>

<https://www.nature.com/articles/nclimate3338>

Response: We appreciate the reviewer's comment and the provided literature. We have carefully reviewed and learned from these studies. Through an exhaustive literature review, we concur with the reviewer's observation that numerous researchers are investigating the impact of extreme events on energy systems and the methods to characterize such events. However, we adopt a distinct perspective by considering the proneness to extreme events occurring at a site as an inherent attribute of the local resource. Furthermore, we introduce this novel characteristic alongside the well-established metrics of resource availability and variability. In other words, the research subject is not merely to characterize the energy drought but to characterize the resource quality in different sites. This approach highlights the challenge of identifying an ideal resource site, as reflected in the title of our manuscript: 'The Renewable Energy Quality Trilemma.' This indeed enriches our comprehension of wind and solar resource quality.

To address the reviewer's concern, we now make a thorough review of literature on characterizing the energy drought and how we learned but differ from previous literature. We have added the following text to the Introduction section (Pages 2-3 of the manuscript):

“While there is an abundance of research analyzing how renewable energy droughts affect the power system ^{17–19}, there is no consensus on the definition and characterization of renewable energy droughts. Raynaud et al. defined an energy drought as uninterrupted sequences of days with low power production or as sequences of days with a significant mismatch between production and demand ²⁰. Rinaldi et al.

applied the energy drought concept on the production side, defining it as a solar or wind capacity factor less than 50% of the daily mean for that day of the year²¹. Kapica et al. built upon the definition of a drought as a capacity lower than a threshold and proposed measuring the duration of the drought as the number of time periods it occurs, represented by a sum of binary variables²². Allen and Otero proposed standardized indices to describe energy droughts, adopting a quantile-based definition rather than a percentage of the mean. They defined moderate, severe, and extreme droughts using the distribution's 90th, 95th, and 97.5th percentiles. Furthermore, they defined the magnitude of the drought as the sum of their drought index over a certain period, considering both the duration and severity of the drought²³. In this study, we build upon the metrics used in previous studies to characterize energy droughts. We take the expected value as a key reference, similar to Rinaldi et al.²¹, and calculate the differences from the expected value. The expected value is critical for grid operators to plan dispatch decisions and thus should be considered. Then we, following Allen and Otero's approach, we set thresholds based on different quantiles of the distribution. We also adopt the system of binary variables used by Kapica et al. to mark whether a drought is occurring or not in a specific region and during a particular time period to analyze the spatial and temporal coincidence of energy droughts and the co-occurrence of droughts among different renewable resources."

We have reviewed, added and cited the following studies:

17. Grochowicz, A., van Greevenbroek, K. & Bloomfield, H. C. Using power system modelling outputs to identify weather-induced extreme events in highly renewable systems. *Environmental Research Letters* 19, (2024).
18. Bloomfield, H. C., Brayshaw, D. J., Shaffrey, L. C., Coker, P. J. & Thornton, H. E. Quantifying the increasing sensitivity of power systems to climate variability. *Environmental Research Letters* 11, (2016).
19. Wörman, A., Pechlivanidis, I., Mewes, D., Rimpl, J. & Bertacchi Uvo, C. Spatiotemporal management of solar, wind and hydropower across continental Europe. *Communications Engineering* 3, (2024).
20. Raynaud, D., Hingray, B., François, B. & Creutin, J. D. Energy droughts from variable renewable energy sources in European climates. *Renew Energy* 125, 578–589 (2018).
21. Rinaldi, K. Z., Dowling, J. A., Ruggles, T. H., Caldeira, K. & Lewis, N. S. Wind and Solar Resource Droughts in California Highlight the Benefits of Long-Term Storage and Integration with the Western Interconnect. *Environ Sci Technol* 55, 6214–6226 (2021).
22. Kapica, J. et al. The potential impact of climate change on European renewable energy droughts. *Renewable and Sustainable Energy Reviews* 189, 114011 (2024).

51. van der Wiel, K. et al. Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall. *Renewable and Sustainable Energy Reviews* 111, 261–275 (2019).
52. Van Der Wiel, K. et al. The influence of weather regimes on European renewable energy production and demand. *Environmental Research Letters* 14, (2019).

In page 5, we have improved the text to clarify the contributions:

“...Two: we propose a method to examine the prevalence of spatial and temporal coincidence of these droughts. We determine in which regions these droughts are spatially correlated, jeopardizing large geographic areas. We also identify the regions and seasons where and when wind and solar energy extremes are likely to occur simultaneously. Three: we propose new metrics to characterize renewable energy quality along three dimensions (availability, variability, and extremeness). The availability measures how much of the resource can be utilized at the site, as indicated by its average capacity factor. The variability measures how stable the resource is as indicated by the standard deviation of the capacity factor. This metric can guide the development of short-duration energy storage. The extremeness is proposed as a new dimension of resource quality to measure how likely the site is to experience energy droughts. This metric can guide the development of long-duration energy storage and other backup resources. By using this triad of metrics, we improve existing understanding of renewable energy quality and identify the “ideal” sites for renewable energy development.”

We note that this comment resonates with comments 1 and 2, and we have addressed some of the concerns in our responses to those comments, which include revisions to the manuscript. We direct the reviewer to our response to those comments for further information.

We thank the reviewer for these helpful comments and suggestions.

<Title: Renewable energy quality trilemma and coincident wind and solar droughts>

October 14, 2024

Dear reviewers,

We want to thank you for the opportunity to resubmit a revised version of our manuscript entitled “*Renewable energy quality trilemma and coincident wind and solar droughts*”, to be considered for publication in *Communications Earth & Environment*. We appreciate the time and effort you invested in providing feedback on our manuscript.

We have improved the manuscript to address the comments and suggestions we received. We have responded to each of those comments and suggestions in our point-by-point response below. For clarity, we present our responses in blue font and the changes to the manuscript in red font. We have also included a revised manuscript in which we have tracked all the changes made in response to the feedback we received.

We thank you once again for providing us with valuable reviews and look forward to your response.

Sincerely Yours,

All authors

Response to reviewer #2:

General Comment: *The revised version of the text seems much clearer and readable to me. Compared to the original manuscript, the current version should also be suitable for a wider audience as it combines more technical insights with societal implications.*

Response: We thank the reviewer for these encouraging comments.

I only have two suggestions concerning the following points:

Comment 1: *The 'trilemma' and its representation in the text:*

Coming from Social science, the nature of the trilemma is much clearer to me now, as is its depth (explained in a new paragraph on pages 22 and 23). However, I do not fully see the implications of this trilemma yet. It reminds me of an article that is trying to capture another trilemma that system builders are confronted with (the 'impossible energy trinity' by Thaler and Hofman: <https://doi.org/10.1016/j.polgeo.2021.102579>). The authors of this article visualize the trilemma that they have researched. I think that could be an option here as well. What is more, they also include different courses of action that system builders, policy makers etc. can pursue (see section 2.3 of that article). To me, this is very intuitive and also very helpful for discussing the trade-offs of the energy transition. I am therefore wondering whether it may be possible to a) visualize the energy trilemma that you are about to establish, and b) whether you could also indicate certain options for decision-makers when facing the trilemma.

If it is not possible to add such a graph, then I am wondering whether the phenomenon that you are studying can be called a 'trilemma' (as this term suggests 'a state of things in which it is difficult to determine which one of three courses to pursue' - see <https://www.merriam-webster.com/dictionary/trilemma>). The question is whether the solution that you are presenting for the 'droughtiness' of certain regions - sharing storage capacity across regions through (new?) grids - conflicts with one or both of the other two 'corners' of the 'trilemma': variability and availability. This probably can only be answered if you go a little bit more into the questions that the trilemma poses for system builders and what the answers may be and whether there are conflicts between the answers (these could be technological, political, societal etc.). If there are no such conflicts, then the droughtiness merely adds another layer of difficulty on top of existing ones.

Response: We appreciate the reviewer's valuable suggestion. In response, we have enhanced the manuscript by: a) visualizing the renewable energy trilemma, and b) outlining various courses of action for decision-makers when confronting the trilemma.

As suggested by the reviewer, we have incorporated Figure 7 to graphically represent the renewable energy quality trilemma and to illustrate how the emphasis on the three quality attributes changes with different levels of variable renewable energy penetration.

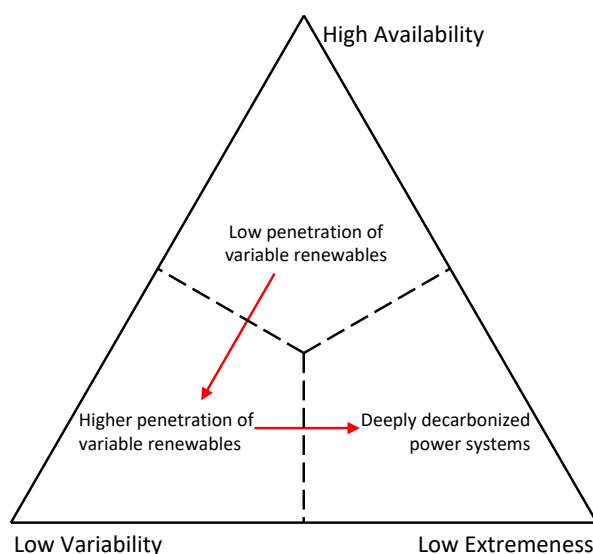


Figure 7. Renewable energy quality trilemma and relative prioritization of quality attributes across variable renewable penetration levels.

In the Results section of the revised manuscript, we now detail the relative prioritization of the three quality dimensions and outline the various courses of action that stakeholders can consider as the power sector progresses towards decarbonization. To this end, we have added the following text to the Results section (see Pages 11-12):

“As the power sector transitions towards decarbonization, the importance of the three key dimensions—resource availability, variability, and extremeness—shifts (Figure 7). At low penetration levels of solar and wind resources, resource availability is the most critical metric. With low shares of electricity being generated by these sources, the system retains sufficient flexibility to manage their inherent fluctuations while satisfying the electrical demand. In this context, policymakers and project developers prioritize increasing renewable energy production and reducing the Levelized Cost of Electricity (LCOE), which is largely dependent on the capacity factor or resource availability, with limited concern for system flexibility. As the penetration of variable renewable energy increases, system planners must shift their focus to resource variability. They will need to strategize how to enhance system flexibility through the deployment of dispatchable generation, short-duration energy storage, and power transmission infrastructure. At deeply decarbonized systems, the risk of energy droughts becomes a critical reliability concern. Consequently, planners must concentrate on the attribute of resource extremeness. They should give precedence to sites with lower extremeness or to locations where mitigation measures, such as large-

scale, long-duration energy storage, are technically feasible and economically justifiable.”

Comment 2: *Figure 2:*

The location of favorable sites for solar power generation is barely readable. Can this possibly be improved?

Response: We appreciate the reviewer’s comment. In response, we have made significant improvements to the map of eligible sites and the depiction of capacity factors, which represent resource availability, in Figure 2.

We thank the reviewer for these helpful comments and suggestions.

Response to reviewer #3:

General Comment: *With the current revision, I understand the contribution of the paper better. While I still feel that the paper somewhat exaggerates the research gap in the literature, based on the revisions and other reviewers' comments, I now believe that it would give sufficient new material for discussion and I would have no fundamental objection to this study being published, barring a few improvements.*

Response: We thank the reviewer for these encouraging comments.

Comment 1: *The study by Antonini et al. (2024) in 'Communications Earth & Environment' (<https://www.nature.com/articles/s43247-024-01260-7>) goes in a very similar direction, using three reliability indicators (mean power density, seasonal variability, weather variability). It might be that that paper came out after this manuscript was submitted, but I think it is worthwhile comparing and discussing the approach taken there to the one taken here.*

Response: We appreciate the reviewer's recommendation to consider the exciting research by Antonini et al. Their study shares a similar focus with ours in characterizing wind droughts, and it provides valuable insights into the identification of reliable sites for wind power generation. These sites are characterized by high power densities, low seasonal variability, and minimal weather fluctuations, which are crucial factors for the reliability and predictability of wind energy outputs. We have found Antonini et al.'s work to be particularly inspiring and have incorporated it into our literature review and Discussion and conclusions to enrich our discussion.

In the Introduction section, we say (see Page 3):

“...Antonini et al. ²⁴ proposed an energy deficit metric that integrates the depth and duration of low wind power, using power density, seasonal variability, and weather variability to identify reliable sites for wind power generation. Building on these, we characterize energy droughts by calculating deviations from expected values, crucial for grid planning, and using quantile-based thresholds and binary markers to analyze spatial and temporal patterns across different renewable resources.”

In the Discussion and conclusions section, we say (see Page 12):

“...Expanding on existing research, such as Antonini et al. ²⁴, our work uniquely considers both wind and solar resources simultaneously. Our findings, which build on the analysis of the spatial and temporal coincidence of these two resource types,

contribute novel insights valuable for the strategic deployment of decarbonized energy systems.”

***Comment 2:** One of the other reviewers also asked about whether 19 years would be enough to comprehensively capture variability. I found the line of argumentation in the response not very convincing. First, it's hard to argue for consistency with previous literature as a broader range of years has been evaluated in the literature, also pre-2000. Second, lack of data availability should be no issue, in principle, as ERA5 reanalysis data is provided from 1940 to 2024 at a 0.25 x 0.25 grid resolution. This would also allow further analysis of multi-decadal trends. Third, based on my impressions of the calculations required for the study, I find it hard to believe that the computational resource is a limiting factor. It will likely be possible to optimise the resource consumption with optimised code (e.g. using lazy memory allocation). Perhaps the authors can reconsider to expand the temporal scope of their analysis. The authors should upload the code and data used for their analysis under an open license. "Data availability on reasonable request" hinders reproducibility and transparency in research by creating barriers to data access, potentially leading to selective sharing, delays, or outright refusal, which prevents other researchers from independently verifying results or building upon the study's findings. Services like Github and Zenodo could be used for sharing.*

Response: We appreciate the reviewer’s insightful comment regarding data availability and computational demands. We concur that extensive datasets, such as NASA MERRA-2 (starting in 1980) and ECMWF ERA5 (starting in 1940), offer long time-series and high resolution data, making data availability a non-issue. Moreover, the method we employ to assess renewable energy availability and variability is not computationally intensive and can be efficiently processed on a personal computer.

However, the approach we propose in this study to identify renewable energy droughts is indeed more computationally demanding. The dataset for wind and solar energy analyzed in our study is approximately 40GB, which we do not consider a challenge. We have developed a quantile-based method to identify renewable energy droughts, focusing on two critical characteristics: intensity and duration. As detailed in the Methods section, to account for the duration of droughts, we segment the data into consecutive 3-hour intervals on a rolling basis and calculate the capacity factor for each segment. This method, compared to the daily or monthly averages used in previous studies, inherently increases the data volume by providing a more granular analysis.

Most importantly, our quantile-based approach necessitates a comprehensive comparison of actual energy generation against historical averages and a thorough understanding of the Cumulative Probability Distribution (CDF) of these deviations across all time periods and sites. This requirement compels us to load the entire dataset into memory during the analysis, rather than processing data for each site or year individually, which would otherwise reduce resource consumption.

Additionally, we designate drought conditions from a time segment to all hours within that segment, further amplifying the data volume. We recognize that this step could be optimized to minimize resource usage, and we have taken steps to enhance the efficiency of our code in this regard.

Following the reviewer's suggestion, now we upload the data and code and share them on GitHub for researchers to independently verify the results or building upon the study's findings. In the manuscript, we improved the Data availability and Code availability as follows:

In the Data availability, we say (see Page 22):

“The hourly reanalysis climatological MERRA-2 data, which are essential for calculating hourly wind and solar energy, include variables such as the eastward and northward components of wind speed at 50-meter, surface pressure, 2-meter temperature, surface incoming shortwave flux, total cloud area fraction, and surface albedo. These datasets can be accessed from the Global Environmental Data Service Information System (GES DISC) of NASA via the following link: <https://disc.gsfc.nasa.gov/datasets?page=1>. Additionally, postprocessed results, comprising capacity factors, standard deviations, and drought events for wind and solar energy, are freely available for download from the following GitHub repository: <https://github.com/qingyuann/Renewable-energy-droughts>.”

In the Code availability, we say (see Page 22):

“The R code utilized for characterizing renewable energy droughts, as well as for analyzing resource availability and variability, is publicly accessible on a GitHub repository. The repository can be accessed at the following link: <https://github.com/qingyuann/Renewable-energy-droughts>.”

Comment 3: Finally, I would note that through the detailed revisions, the manuscript got a bit wordy with low content density in parts (example: "Addressing the challenge of unraveling the mechanisms behind this trilemma requires a concerted effort to

conduct in-depth investigations and to develop sophisticated models."). I would suggest to edit for conciseness.

Response: We appreciate the reviewer's constructive feedback. In response, we have meticulously revised the manuscript to enhance both conciseness and readability. Here are some specific improvements we have made:

- **Abstract:** We have refined the content to ensure it is now under 150 words, making it more succinct while retaining the essence of our study.
- **Introduction:** We have condensed the literature review and streamlined other details to ensure the introduction is both concise and engaging.
- **Results:** We have removed some redundant statements in the initial paragraphs to focus on the key findings, thereby improving the section's clarity.
- **Discussion and conclusions:** We have eliminated some detailed explanations regarding the necessity of sophisticated models to interpret the meteorological and geographical nuances underlying our results. Additionally, we have removed other redundant statements to maintain a tight narrative.

These revisions have resulted in a manuscript that is more concise and easier to follow, while still effectively communicating our research findings and conclusions.

We thank the reviewer for these helpful comments and suggestions.