nature portfolio

Peer Review File

Globally Interconnected Solar-wind System Addresses Future Electricity Demands

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This paper aims to demonstrate the feasibility and potential benefits of a globally interconnected solar-wind system to address future electricity demands. While the modelling results are interesting, the structure is confusing, the model could use clarification and the added value of the paper remains unclear. I would hence advise a revise and resubmit. Please note, while I generally understand modelling efforts, I am not a modeler myself and must hence concede my shortcomings here. I hence urge the editor to include a modeler as one of the other reviewers.

Comments

• The article does not follow the common 'introduction, theory/literature, method, results/analysis, discussion, conclusion' structure. It is not explained why the authors deviate nor would I consider the current structure logical. I would greatly prefer more positioning of the article within the literature and a description of the method (what goes in and when) before moving to the results. I would hence ask the authors to restructure:
o Please add a theory/literature section that briefly summarizes the status of the field and what this article specifically adds to it. This will also help readers determine the added value of the paper. See also comment below.
o Please place the method section before the results. This way readers can understand what goes into the model when and how, before we discuss results. This is especially important for readership not directly working on similar models to understand what is going on.
o Please add a conclusion after the discussion section.

• The authors make it clear that it is the purpose of the study to evaluate "the global potential of solar and wind energy in term of their exploitability, accessibility, and interconnectability." This is done from a techno-economic optimization perspective that disregards global political realities (despite a brief mentioning of them in the discussion). This makes the added value of the paper questionable. First, economic theory would predict benefits to trade and efficiency gains through the global interconnection of energy systems (vis-a-vis more isolated energy systems). In that sense, the model outcome is in line with expectations, offering little new insights. Second, by not including great power rivalry into the equation, the results seem very naive and the paper does not really demonstrate the feasibility of global interconnection. Countries are likely to want more own production for the sake of energy security, even in the most optimistic global political environment. The added value hence lies more in how such interconnection might look like (the location of interconnectors) and how much interconnection can reduce generation and storage costs. I would hence ask the authors to clarify what they consider the main contribution of the study.
o In this respect, I personally found the most interesting result what is written on P14, lines 286-294: "We find that remaining at local interconnections is not conductive to maximizing benefits in terms of efficiency and cost. Relative to the S-I scenario, the reductions in overall installed capacities and associated costs are limited in the adjacent interconnections (S-N) and continental interconnections (S-C) scenarios (Table 1). Nonetheless, achieving global interconnection could markedly enhance the benefits of adjacent and continental interconnections. Such an insight highlights the importance of prioritizing global interconnection as the ultimate goal in the early planning of grid interconnection25,27. Complementary analyses targeting at the 2030s corroborate these findings (Supplementary Fig. S9)." -> I find it interesting to see that regional interconnection is not that efficient... this has major political and grid planning implications.

• The notion of energy security in the paper seems to be focused on reliability and resilience, not security of supply and other dimensions of energy security. This is a very limited (mostly engineering) conception of energy security. I would not conclude that energy security is enhanced (line 322), but nuance this finding, especially as geopolitics is largely ignored. More interconnection may enhance resilience as there are more rerouting possibilities (better score on the N-1 criterion), but also creates new dependencies.

• I am not sure if I agree with the results on energy access. In the paper, energy access is considered improved because cheaper energy is made available everywhere through interconnection, as mismatch is minimized. This assumes, however, an ability to buy/import energy, which may not be present in certain regions in reality. It also makes importing regions less secure in terms of security of supply and hence energy access. Finally, exporting regions may prioritize exports over servicing their own population if others pay more, leading to a situation where energy access remains poor in the exporting region. In all, there is more to energy access than the pure availability of it.

• The methods section is clear in terms of what was done on a granular level, but could use a discussion or figure that shows the overall model (variables in and out, processing steps). This would give readers a much needed overview of what goes on. At this point, I found it hard at times to understand what the model does when. How does the main algorithm decide (step by step) what comes out? In addition:
o Please elaborate a bit more on the 4 scenarios in the text: what exactly are the differences and how were they made/selected?
o Why do the authors envision growth from local to regional to continental to global interconnection? Why not immediately larger scale?
o What about long-distance losses in electricity transmission? How does that affect global interconnections and their costs? Would they not make global connections too costly? This seems to be a major omission in the model. How would, for example, the S-G scenario, with global interconnection between arbitrary regions work (in terms of computations)?
o Line 525: “In our analysis, we account for the construction costs of solar, wind, and energy storage infrastructures, excluding the costs pertaining to transmission infrastructure. This exclusion is underpinned by the premise that, irrespective of the scenario, establishing sufficient transmission capacity is a fundamental prerequisite for enabling global interconnection20,25.” I do not understand this choice. How can you optimize costs without taking transmission capacity into account. Isn’t this paper in the end about optimizing the trade-off between generation, storage and transmission costs? I don’t think the transmission costs are the same in every scenario. Please clarify.
o Line 560: “We target at completely flexible power grids, which implies the absence of baseload generation. In this context, the generation units are classified into three categories: real-time solar-wind generation, stored solar-wind generation, and other flexible units.” -> No baseload? I know this is noted in the discussion section but still... how does this impact the utility/results of the study? Moreover, what if more hydropower and a bit of natural gas with ccs were to be used?
o In how far is existing infrastructure taken into account?

• There are some minor spelling issues here and there. Most notable is that the authors put the footnotes before (instead of after) the dots at the end of sentences.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)
Noteworthy Results.
The research highlights some significant findings about the potential of a globally interconnected solar-wind power system:
1. The system could generate approximately 237.33×10^3 TWh per year, which exceeds projected global electricity demand for the 2050s.
2. Strategic optimization of plant placements, combined with regional storage and transmission, could lower costs and minimize energy curtailment.
3. A phased global interconnection approach, starting with storage expansion and followed by transmission upgrades, is proposed.
4. Global interconnection could improve power supply stability and resilience, especially during extreme weather events.
5. The system could ensure equitable access to renewable resources and balance the energy decarbonization burden across regions.

Significance, Comparison to Established Literature and Originality.
The research presented in this paper marks a significant advancement in the field of renewable energy by offering a detailed roadmap for implementing a globally interconnected solar-wind power system. Unlike previous studies by Jacobson et al. (2017) and Chen et al. (2021) that explored renewable energy potentials and pathways to carbon neutrality, this study stands out with its comprehensive and actionable approach. It not only evaluates the theoretical potential of solar and wind energy but also addresses practical aspects of implementation, such as optimizing plant deployment, storage capacities, and transmission infrastructure. This holistic roadmap, which considers both technical and socio-economic factors, distinguishes it from earlier work and provides a concrete pathway toward global energy interconnection.
Additionally, the study's originality lies in its multi-faceted methodology, which integrates spatial analysis, power generation modeling, and multi-objective optimization. This thorough approach enables a nuanced evaluation of the feasibility and benefits of global interconnection, moving beyond the theoretical concepts of earlier research. By tackling practical

challenges and offering a detailed implementation plan, this study significantly contributes to the existing body of knowledge and provides valuable insights for policymakers and stakeholders in the renewable energy sector.

Study's conclusions and claims are well-supported by:
Simulation and Modeling: Extensive simulations and modeling estimate the potential electricity generation of a globally interconnected solar-wind system, demonstrating its capacity to exceed projected future demand. The optimized placement of power plants and storage/transmission infrastructure provides concrete evidence for the feasibility and cost-effectiveness of their proposed approach.
Data Analysis: Real-world data on land use, terrain, solar radiation, wind speed, and existing transmission lines identify suitable locations for solar and wind farms, strengthening the validity of their findings regarding renewable resources' potential.
Explanation: Detailed explanations of their methodology, including data sources, model parameters, and optimization algorithms, allow for scrutiny and potential replication, enhancing the credibility of their conclusions.

Limitations.
1. Overestimation of Interconnectable Potential: The analysis may overestimate potential due to factors like rural road capacity for wind turbine transport and low-voltage transmission line limitations.
2. Cost Estimation Limitations: The cost analysis uses a unified pricing benchmark, not fully accounting for regional variations or potential cost reductions from technological advancements.
3. Assumption of Non-Existent Baseload Generation: The simulation models assume no baseload generation, which may not accurately reflect current power grids.
4. Limited Focus on Environmental Impacts: The study does not thoroughly evaluate the environmental impacts of large-scale deployment.

These limitations do not invalidate the study's findings.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
This paper provides a simple mapping calculation of solar and wind production potentials in comparison with demand. By allowing for ideal global interconnectedness, the authors estimate the potential for global electricity trade and related investments.

This is an oddly simple back-of-the-envelope paper, in a field where multiple detailed model studies exist. The authors do not even cite the modeling studies such as Brinkerink et al., 2018 (https://www.sciencedirect.com/science/article/pii/S2096511718300446) and Guo et al., 2022 (https://www.nature.com/articles/s41560-022-01136-0).

The method ignores the techno-economic aspects of the power system outside the solar/wind/interconnection system (e.g. competition of GEI with fossil power generation, competition of GEI with storage or PtX options, the role of demand side responses) that the more advanced studies in this field have explored. Also the details of the grid requirements are not taken into account (e.g. becomes the world one large load balancing area, or are these interconnections only for specific bottlenecks).

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The paper is much improved. The authors made a noticeable and serious effort to address my comments as best as possible within the boundaries of their model and purpose of the paper. I especially commend the new resilience section, scenario elaboration, and the added workflow chart. The latter will aid greatly in appealing to a larger audience, even though it is not in the main text itself. The many clarifications throughout add up as well. Despite understandable limitations, there is clear value in what the paper does.

While I consider the paper ok as is, I would also not mind a clearer statement of the paper's objective in the introduction. The abstract reads "we demonstrate the potential of a globally interconnected solar-wind system to address future electricity demands." Something this explicit is missing in the introduction. It would just be about adding a sentence that sums it up: This paper aims to / shows …". The current one at lines 86-88 just does not quite do it. I would also simply replace the wording of 'equitable energy access' with that of energy availability, to avoid the connotations usually associated with the term access in energy access and equity literature, which the paper does not quite cover. If possible, a few final words by the authors that sum up the core findings in the text (like in the abstract) and then interpret them for science and society/policy, would also be appreciated. The discussion sticks very close to the model, but it is left to the reader to interpret the broader implications of the findings. None of these three comments need delay the review process, but they would be a welcome addition.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)
I commend the authors for significantly enhancing the technical rigor of their analysis. The inclusion of stress tests, which simulate the system's performance under challenging conditions like extreme weather events and geopolitical tensions, demonstrates a commendable effort to consider real-world vulnerabilities and uncertainties. This approach effectively captures the stochastic nature of renewable energy resources and the potential for disruptions in a globally interconnected grid. Furthermore, the incorporation of regional cost variations for solar and wind deployment, accounting for factors such as levelized cost of energy (LCOE) differentials, adds a layer of nuance and accuracy to the data analysis, reflecting the complexities of global energy markets.

The improved documentation of baseload and flexible power sources, particularly the integration with the IEA's Net Zero Emissions (NZE) scenario, strengthens the study's applicability to real-world energy transition pathways.

Furthermore, the comprehensive description of computational methods for trans-regional interconnections, including explicit descriptions of the algorithms and parameters used, enhances the reproducibility of the study. The clear presentation of assumptions and limitations, along with the inclusion of sensitivity analyses exploring the impact of key parameters, strengthens the robustness of the findings and allows for a more nuanced interpretation of the results within the context of the study's scope.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
The authors have revised the paper in response to the review comments in a truly impressive fashion. The manuscript is now much clearer about the goal and limitations of the work and where it contributes beyond the existing literature. The stronger focus on the modeling work really shows the added value much stronger than the earlier version of the paper.

While reading the text, I had three main comments that eventually were addressed later in the text or in the Methods section, but that would be good to address earlier on:
- The first few pages only discuss solar and wind, but do not mention hydro at all, even though this is also widely considered a major contributor to non-biomass renewable energy and flexible technology that is complementary with intermittent renewables. Also, the main paper barely mentions that the model evaluates solar and wind in the context of the full power system, leaving the question to be answered in the Methods section. Around Line 624, the four generation categories are described, but it remains unclear whether the technologies mentioned in these categories are resolved in the model or whether these four categories are treated a aggregate characteristic power generation options.
- Line 203 introduces transcontinental corridors across northern America-Eurasia and southern America-Africa, which raises the question about capacity of such backbone interconnections. I found the answer in Figure 2, but would help to clarify such information in the text.
- The GEIDCO proposed plan for global energy interconnection does not rely on HVDC cables as discussed in this paper but rather of Ultra-HVDC cables, which have lower losses (but probably higher investment costs) than the ones described around Line 640. It might be worth exploring the GEI plans in more detail and update some of the assumptions.

(Remarks on code availability)

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I have no further comments. The authors have addressed my concerns and suggestions.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
The authors have responded to my final concerns in a thorough fashion and improved the manuscript further. No further comments from my side other than congratulating the authors with an interesting study.

(Remarks on code availability)

Dear Reviewers,

We greatly appreciate your insights and constructive feedback on our manuscript titled "**Globally Interconnected Solar-wind System Addresses Future Electricity Demands**". We have carefully considered each comment and have made corresponding revisions to the manuscript. Below, we provide a point-by-point response to each comment. Changes to the manuscript text are highlighted in red in the revised document, and our responses to the comments are noted in blue below for clarity. Please note that the line numbers refer to the version with accepted revisions (no revision marks) that was uploaded into the system.

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

General Comment

This paper aims to demonstrate the feasibility and potential benefits of a globally interconnected solar-wind system to address future electricity demands. While the modelling results are interesting, the structure is confusing, the model could use clarification and the added value of the paper remains unclear. I would hence advise a revise and resubmit. Please note, while I generally understand modelling efforts, I am not a modeler myself and must hence concede my shortcomings here. I hence urge the editor to include a modeler as one of the other reviewers.

Response: Thank you for your constructive comments on our manuscript. We appreciate the time and effort you have dedicated to reviewing our work, and also note your concerns regarding the structure of the paper, model clarification, and the added value of the research. We have carefully considered your feedback and made significant revisions to the manuscript from the following three aspects.

First, regarding the structure of the manuscript, we change the ordering of presented items to ensure they followed the submission guidelines of *Nature Communications*. To address your feedback, **we restructure the *Results* section,** where the contents on costs, energy trade, and other benefits of global interconnection are merged into one subsection. In addition, **we add a new subsection titled *Resilience of a globally interconnected system*** to present the results of our stress tests in response to your concerns on geopolitics, energy access, and supply dependence.

Second, on the model clarification, **we add a framework diagram** (Supplementary Fig. S12) to illustrate the entire process and workflow. We also supplement the following details to the models: 1) using current wind-solar-storage-transmission capacities as initial conditions; 2) focusing on optimization for the International Energy Agency (IEA)'s Net Zero Emissions (NZE) scenario; 3) considering transmission costs and losses in power dispatch; and 4) considering baseload power generation and contributions of other sources.

Third, following your suggestions, we **clarify the following added values of this study in the revised Introduction and Discussion sections**: 1) addressing the gap in previous studies regarding the geographic and temporal specifics of resource allocation and utilization; 2) demonstrating the important role of spatiotemporal optimization in establishing a globally interconnected power system and the benefits in terms of energy efficiency and cost reduction; and 3) conducting detailed analyzes of the potential risks associated with global interconnection, providing new insights into the integration of renewable energy on a global scale.

Despite these efforts, we recognize some limitations in our analysis, which are summarized **in the *Limitations* subsection** of the revised *Methods* section.

Comments #1

The article does not follow the common 'introduction, theory/literature, method, results/analysis, discussion, conclusion' structure. It is not explained why the authors deviate nor would I consider the current structure logical. I would greatly prefer more positioning of the article within the literature and a description of the method (what goes in and when) before moving to the results. I would hence ask the authors to restructure:

Response: Thank you for your valuable feedback. We would like to clarify that the original manuscript was organized following the guidelines of *Nature Communications* (https://www.nature.com/ncomms/submit/article).

However, your insights have helped us recognize the need for adjustments to enhance the manuscript's clarity and ensure it is accessible to a broader audience. **Based on your suggestions, we have made several significant improvements to the revised manuscript.** For example, regarding theory/literature, we have enriched the introduction by briefly reviewing recent research advances and identifying existing knowledge gaps. As for the methodology, we have included a concise summary at the beginning of the results section to aid readers in understanding the methods before moving to the results. Further details on these and other specific revisions are outlined in subsequent responses.

Specific comment #1.1

Please add a theory/literature section that briefly summarizes the status of the field and what this article specifically adds to it. This will also help readers determine the added value of the paper.

Response: Thank you for your valuable suggestions. We recognize the need to better situate our work within the current literature and articulate the contributions our paper makes to the field.

In light of your comment, **we have expanded the *Introduction* section to provide a brief overview of the current status of the field in the revised manuscript.** We briefly summarize key developments in global energy interconnection, including both practical implementations and recent theoretical advances. We highlight the evolution of the concept, from Buckminster Fuller's initial vision to contemporary examples of interconnections at varying scales. Additionally, we discuss recent studies that explore the benefits of global interconnection, including Brinkerink et al.'s modeling of interconnected power systems and Guo et al.'s investigation of the environmental and economic benefits of renewable electricity trade via ultra-high-voltage direct-current lines. We also acknowledge existing gaps, particularly regarding the geographic and temporal specifics of resource allocation and utilization—issues to be addressed in this study.

The updated sections, specifically the **third paragraph of the *Introduction*** section, now read as follows: "Trans-regional interconnection of power systems is a promising solution for achieving high penetration of variable renewable energy (VRE) sources[16,17]. Initially envisioned by Buckminster Fuller[18] as a global energy grid to facilitate spatial integration of distributed generation[9,19], global interconnections has evolved from an idealistic vision to practical implementations at small scales. These include sub-regional, regional, and intercontinental interconnections[16,20-22]. For example, Spain and Morocco are connected via three 400 kV 700 MW submarine power cables traversing the Mediterranean[22], and the Central American Electrical Interconnection System exemplifies regional integration by interlinking six countries with a 300 MW backbone grid[21]. Building on these pioneering implementations, recent studies have further explored the potential benefits of global energy interconnection. Brinkerink et al.[23] developed a high-resolution model to simulate globally interconnected power systems, providing initial proof-of-concept results that showcase the viability and additional benefits of integrating European and North American power grids. Similarly, Guo et al.[24] examined the implications of renewable electricity trade facilitated by ultra-high-voltage direct-current (UHVDC) lines, finding that such interconnections could significantly reduce CO_2 emissions and air pollutant levels while offsetting investments in other generation options. While these studies underscore the importance of interconnection strategies, they also highlight gaps in addressing geographic and temporal specifics of resource allocation and utilization." (Lines 54-70).

On this basis, we briefly summarize the contributions of our study, which are mainly reflected in the insights into the geographic and temporal allocation of solar-wind resources, the optimal configurations of transmission and storage systems, and the benefits of cost savings, curtailment reduction, and efficiency improvements. The updated parts, **at the end of the *Introduction*** section, read as follows: "…establishing a globally interconnected solar-wind system oriented towards net-zero emissions still needs to be clarified. Some scenarios proposed for this objective explored renewable energy potentials and national pathways to carbon neutrality, but they represent a macroscopic perspective that lacks essential geographic details[6,8,14,31]. The practical implementation requires a holistic evaluation of various aspects, including the feasibility of delivering PV and wind generation to the grid, the dynamics of demand fluctuations, the balance between supply and demand, the strategic configuration of transmission and storage systems, and comprehensive assessments of costs and benefits[4,13,16,32]. (Lines 78-85).

To address the existing geographic and temporal gaps[4,7,32,33], we integrate high-resolution spatial (500-meter) and temporal (hourly) data to comprehensively evaluate the global potential of solar and wind energy regarding their exploitability, accessibility, and interconnectability. We develop a multi-objective optimization framework to identify cost-effective and resource-efficient interconnection strategies that balance investment costs, renewable energy penetration, and power curtailment. Here, we outline an optimized, phased pathway to establish a globally interconnected solar-wind power system, and provide valuable insights into the spatial distribution and deployment timeline of solar-wind power plants, the allocation of storage and transmission capacities, and potential benefits and risks of global interconnection. Our work advances a more nuanced understanding of global energy interconnection and offers a concrete pathway to realize this vision." (Lines 86-95).

Specific comment #1.2

Please place the method section before the results. This way readers can understand what goes into the model when and how, before we discuss results. This is especially important for the readership not directly working on similar models to understand what is going on.

Response: Thank you for your suggestions.

While we have adhered to the structure guidelines provided by *Nature Communications*, which place the methodological details (Methods) after the Results, we acknowledge the significance of placing a quick overview of the methodology that guides readers to the detailed results. In this regard, **we have incorporated brief descriptions of the methods at the beginning of each relevant Results subsection.**

For example, at the beginning of **the *Interconnectable solar-wind potential* subsection**, we have added the following texts: "Theoretically, the potential of solar and wind resources on Earth vastly surpasses human demand[33,34]. In our pursuit of a globally interconnected solar-wind system, we have focused solely on the potentials that are exploitable, accessible, and interconnectable (see Methods). Through spatial filtering at a 500-meter resolution, we first mapped the suitability factors for deploying solar/wind power plants within each 0.25°×0.25° grid-box (Supplementary Fig. S1). Subsequently, the combination of suitability and simulated power generation efficiency (Supplementary Fig. S2) determines the spatial distribution of global potential for power generation (Fig. 1a)." (Lines 98-104).

Similarly, **in the *Optimal configuration and pathway* subsection**, we begin with: "The optimization of developmental paths for a globally interconnected solar-wind power system necessitates balancing global power supply and demand, coordinating system-wide costs, ensuring efficient energy utilization, and guaranteeing uninterrupted power supply[4,13,32], as well as considering numerous geographic details, including the topology of interconnections, the spatiotemporal variations of generation and loads, and constraints in storage and transmission capacities pertinent to trans-regional dispatch. To address these complexities, we design a comprehensive multi-objective optimization framework to identify the optimal pathway for global interconnection (see Methods). Central to this framework is a simplified trans-regional electricity dispatch model (Supplementary Fig. S5), which enables hourly analysis of electricity generation, transmission, storage, consumption, and curtailment. We optimized the placement and timeline for installing PVs and wind turbines (Figs. 2a–b), the phased configuration of storage capacities across regions (Fig. 2c), and the transmission power between interconnected grids during different phases (Fig. 2d), aiming at maximizing solar-wind penetration while minimizing power curtailment and overall costs. Our envisioned scenario evolves from adjacent interconnections in the 2030s to continental interconnections in the 2040s, culminating in a global interconnection by the 2050s (Supplementary Fig. S4), in accordance with the low-emission scenario of the Shared Socioeconomic Pathway 1–2.6 (Supplementary Fig. S6). Employing the Non-dominated Sorting Genetic Algorithm-II[38] to solve the multi-objective optimization problem, we obtained a set of the Pareto-efficient solutions (Fig. 2e). The optimal one was selected based on meeting the minimum solar-wind penetration of 68%, as specified by the International Energy Agency (IEA)'s Net Zero Emissions (NZE) scenario (Supplementary Table S1) while achieving a curtailment close to 5% and minimizing costs." (Lines 164-184).

Specific comment #1.3

Please add a conclusion after the discussion section.

Response: Thank you for your valuable suggestion. We agree on the need to provide a concise conclusion to clearly summarize the main findings and implications of the paper. However, to comply with the guidelines of *Nature Communications*, we have not included a separate "Conclusion" section, but instead **included the key conclusions in the *Discussion* section.**

At the beginning of the *Discussion* section, we briefly recap the main findings of the study, such as the critical role of global interconnection in achieving net-zero emissions and promoting renewable electricity exchange. The relevant texts read as follows: "Achieving net-zero emissions by 2050 necessitates transformative strategies to scale up renewable energy penetration. Both the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) advocate for solar-wind energy to constitute at least 68% of the global energy mix by mid-century[40,47]. Global grid interconnection represents a compelling pathway to accelerate this transition, particularly given the uneven geographic distribution of solar-wind potential (Fig. 1a). By enabling regions with abundant solar-wind resources that are exploitable, accessible, and interconnectable to export surplus power generation (Fig. 3c), global interconnection facilitates the development of an international market for renewable electricity exchanges[28]. Such exchange significantly enhances energy utilization efficiency and reduces the costs associated with achieving high penetration levels of variable generation, outperforming traditional decarbonization strategies[6,31]. Our estimates indicate that exploiting only 29.4% of the interconnectable potential (Figs. 1d, 2a, and 2b) could suffice to fulfill the projected electricity demand for the 2050s[34], at approximately 84.2% of the cost required under self-sufficiency prioritization strategies (Table 1). While regional policies may deviate from the optimal pathway, diverse, cost-effective alternatives ensure flexibility and resilience to such uncertainties (Fig. 2e)." (Lines 381-395).

At the end of the *Discussion* section, we emphasize our contributions and the importance of global-scale integration of solar-wind energy. The texts read as follows: "These findings advance the understanding of global interconnection as a transformative approach to integrating solar and wind energy into the global energy mix. Unlike previous research[6,31] that explored renewable energy potentials and pathways to carbon neutrality, this study offers a comprehensive and actionable roadmap for implementing a globally interconnected solar-wind power system. Moving beyond proof-of-concept[23,27] or regional studies[16,20,21], we provide spatial estimates of interconnectable solar-wind potential, identifying critical regions of surplus and deficit while emphasizing the necessity of global-scale energy exchanges. Our analysis highlights the importance of delineating cost-effective configurations and development paths through multi-objective optimization, demonstrating its value in achieving balanced resource allocation, curtailment reduction, and efficiency improvements. Furthermore, we provide new insights into the potential benefits of enhancing equitable energy access and alleviating economic pressures on energy decarbonization while also examining potential risks under uncertainties. These thorough analyses enable a more nuanced perception of the feasibility of global interconnection, moving beyond the theoretical concepts of earlier research. By tackling practical challenges and offering alternative implementation plans, this study would contribute to the existing body of knowledge and provide valuable insights for policymakers and stakeholders in the renewable energy sector." (Lines 451-466).

Comments #2

The authors make it clear that it is the purpose of the study to evaluate "the global potential of solar and wind energy in term of their exploitability, accessibility, and interconnectability." This is done from a techno-economic optimization perspective that disregards global political realities (despite a brief mentioning of them in the discussion). This makes the added value of the paper questionable. First, economic theory would predict benefits to trade and efficiency gains through the global interconnection of energy systems (vis-a-vis more isolated energy systems). In that sense, the model outcome is in line with expectations, offering little new insights. Second, by not including great power rivalry into the equation, the results seem very naive, and the paper does not really demonstrate the feasibility of global interconnection. Countries are likely to want more of their own production for the sake of energy security, even in the most optimistic global political environment. The added value hence lies more in how such interconnection might look like (the location of interconnectors) and how much interconnection can reduce generation and storage costs. I would hence ask the authors to clarify what they consider the main contribution of the study.

Response: Thank you for your insightful comments. We have attempted to address your concerns through the following improvements, structured into **three** points.

First, we agree with you that economic theory predicts benefits to trade and efficiency gains through global energy interconnection, and indeed, our findings align with these expectations. However, the added value of our study is not limited to these aspects. We also provide essential insights into the geographic and temporal specifics of solar-wind resource allocation, the optimal configurations of transmission and storage systems, and the benefits of cost savings, curtailment reduction, and efficiency improvements. These insights address gaps in the existing literature, which focuses on proof-of-concept studies or regional analyses. **We briefly summarize previous advances and our added values** in the revised *Introduction* section as follows: "Building on these pioneering implementations, recent studies have further explored the potential benefits of global energy interconnection. Brinkerink et al.[23] developed a high-resolution model to simulate globally interconnected power systems, providing initial proof-of-concept results that showcase the viability and additional benefits of integrating European and North American power grids. Similarly, Guo et al.[24] examined the implications of renewable electricity trade facilitated by ultra-high-voltage direct-current (UHVDC) lines, finding that such interconnections could significantly reduce CO_2 emissions and air pollutant levels while offsetting investments in other generation options. While these studies underscore the importance of interconnection strategies, they also highlight gaps in addressing geographic and temporal specifics of resource allocation and utilization. (Lines 61-70).

To address the existing geographic and temporal gaps[4,7,32,33], we integrate high-resolution spatial (500-meter) and temporal (hourly) data to comprehensively evaluate the global potential of solar and wind energy regarding their exploitability, accessibility, and interconnectability. We develop a multi-objective optimization framework to identify cost-effective and resource-efficient interconnection strategies that balance investment costs, renewable energy penetration, and power curtailment. Here, we outline an optimized, phased pathway to establish a globally interconnected solar-wind power system, and provide valuable insights into the spatial distribution and deployment timeline of solar-wind power plants, the allocation of storage and transmission capacities, and potential benefits and risks of global interconnection. Our work advances a more nuanced understanding of global energy interconnection and offers a concrete pathway to realize this vision." (Lines 86-95).

We further summarize and discuss our main contributions (which are listed in the response to your general comment) in the revised *Discussion* sections as follows: "…this study offers a comprehensive and actionable roadmap for implementing a globally interconnected solar-wind power system. Moving beyond proof-of-concept[23,27] or regional studies[16,20,21], we provide spatial estimates of interconnectable solar-wind potential, identifying critical regions of surplus and deficit while emphasizing the necessity of global-scale energy exchanges. Our analysis highlights the importance of delineating cost-effective configurations and development paths through multi-objective optimization, demonstrating its value in achieving balanced resource allocation, curtailment reduction, and efficiency improvements. Furthermore, we provide new insights into the potential benefits of enhancing equitable energy access and alleviating economic pressures on energy decarbonization while also examining potential risks under uncertainties. These thorough analyses enable a more nuanced perception of the feasibility of global interconnection, moving beyond the theoretical concepts of earlier research. By tackling practical challenges and offering alternative implementation plans, this study would contribute to the existing body of knowledge and provide valuable insights for policymakers and stakeholders in the renewable energy sector." (Lines 453-466).

Second, we fully recognize the importance of geopolitical realities and their potential barriers to global interconnection. To this end, we have included a resilience analysis in our revised manuscript to explore the impact of geopolitical disruptions on the globally interconnected grid. Specifically, **we simulated a scenario where transmission capacities from a critical node are reduced to zero due to regional conflicts.** The results, shown in **Fig. R1**, reveal that disruptions in generation hubs (e.g., North America, Australia) or demand centers (e.g., Eastern and Southern Asia) would increase global solar-wind curtailment and reduce penetration, but the absolute change would not exceed 15%. In addition, the change due to the failure of a single transmission line is small, with changes in penetration or curtailment remaining below 1% (**Fig. R2**). These findings demonstrate the resilience of a globally interconnected system in the face of geopolitical tensions.

The scenario is described **in the *Stress tests* subsection of the revised *Methods* section** as follows: "…Geopolitical tensions[46] could disrupt the transmission capacities of critical nodes and lines within the interconnected grid, thereby impacting global power exchange. We simulated scenarios in which all transmission capacities associated with a specific node were reduced to zero and analyzed the resulting changes in global solar-wind curtailment and penetration. These simulations provide insights into the vulnerability of a globally interconnected grid to geopolitical disturbances (Fig. 4d) ..." (Lines 787-792).

The modelling results are presented in the ***Resilience of a globally interconnected system* subsection** as follows: "…Geopolitical tensions[46] further threaten the stability of transmission nodes and lines that underpin global interconnections. Failures at generation hubs like northern America, southern America, and Australia, or demand centers like eastern Asia, southern Asia, and southeastern Asia would sharply increase global solar-wind curtailment and reduce penetration (Fig. 4d). By contrast, nodes like northern Africa and western Asia, which primarily serve as transregional transmission bridges exhibit relatively localized impacts when disrupted individually due to rerouting flexibility[27] in the interconnected grid. In an extreme scenario of a complete grid collapse, global solar-wind curtailment (penetration) would rise (drop) by an absolute 41.2% (22.9%). Although individual line failures generally have minimal global impacts, with changes in penetration or curtailment remaining below 1% (Supplementary Fig. S10) …" (Lines 343-352).

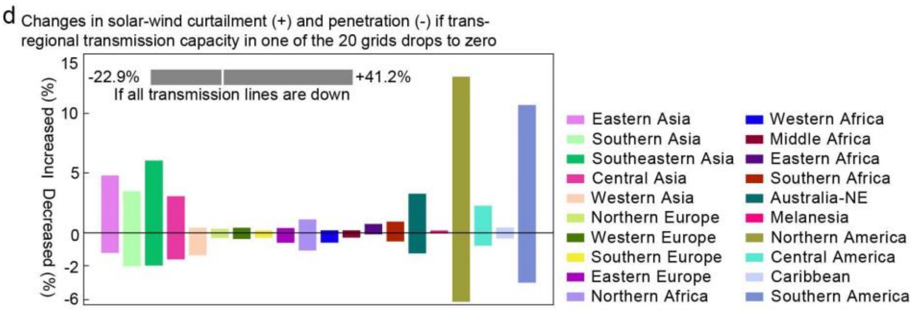


Fig. R1 (also appears as Fig. 4d in the revised manuscript). Changes in global solar-wind curtailment and penetration when all transmission lines associated with a single regional grid (denoted by bar colors) are disrupted. The horizontal gray inset depicts the extreme scenario where all transmission lines fail simultaneously.

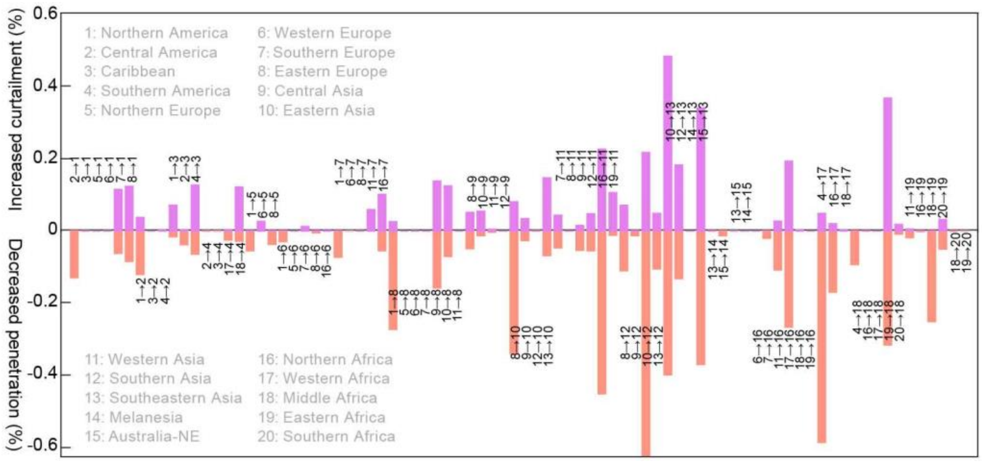


Fig. R2 (also appears as Fig. S10 in the revised SI). Impact of individual transmission line failures on solar-wind generation curtailment and penetration. Labels with arrows indicate the start and end points of the disrupted transmission lines.

Third, we recognize the critical role of incorporating great power rivalry into the optimization framework, as countries are likely to want more of their own production for energy security. While we did not find a feasible way to include great power rivalry directly into the equation, we address this concern by introducing a stress test that simulates the impact of great power rivalry. Specifically, **we ran a simulation where regions prioritize energy self-sufficiency strategies instead of optimized interconnection** to observe how global electricity consumption and supply would be affected. The results, shown in **Fig. R3**, reveal that the imbalance caused by self-sufficiency strategies exerts widespread impacts. Such impacts are considered manageable because none of the absolute changes exceed 10%.

The scenario is described **in the *Stress tests* subsection of the revised *Methods* section** as follows: "Incompatible regional energy policies lead to deviations from the optimal pathways toward global interconnection[17]. We designed scenarios where individual grids independently achieve 68% solar-wind penetration to analyze how regional overexploitation of solar and wind resources alters global electricity supply structures. In addition, an extreme scenario in which all regional grids adopt self-sufficiency prioritization strategies is modeled to uncover potential risks of power curtailment and the pressures exerted on alternative energy sources (Fig. 4c) …" (Lines 782-787).

The modelling results are presented in the ***Resilience of a globally interconnected system* subsection** as follows: "…However, the globally interconnected power system remains susceptible to disruptions from incompatible regional policies, geopolitical tensions, and aggressive market competition. For instance, economically advanced nations may prioritize energy self-sufficiency, particularly in response to geopolitical crises like the Russia-Ukraine conflict, which has heightened concerns over energy independence[45]. Our analysis indicates that such self-sufficiency strategies—resembling the S-I scenario—drive overexploitation of solar and wind resources (Table 1), undermining the global electricity supply balance enabled by optimized interconnection. The resulting imbalance exerts widespread impacts. Specifically, policy incompatibilities in southern Asia, western Asia, northern Africa, and eastern Asia lead to the largest increases in solar-wind curtailment. In contrast, those in northern America, southern Asia, eastern Asia, and southern

America cause the most significant declines in demand for alternative energy sources (Fig. 4c). In an extreme scenario where all regional grids adopt self-sufficiency prioritization strategies, absolute increases in curtailment (reductions in demand) would reach 34.6% (13.5%) …" (Lines 330-342).

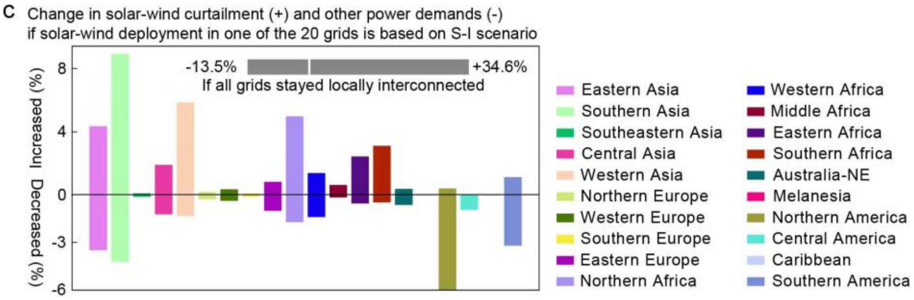


Fig. R3 (also appears as Fig. 4c in the revised manuscript). Changes in solar-wind curtailment and alternative energy supplies when one of the 20 regional grids (denoted by bar colors) deploys solar-wind resources based on the S-I scenario. The horizontal gray inset illustrates the extreme case where all 20 grids remain locally interconnected.

Specific comment #2.1

In this respect, I personally found the most interesting result what is written on P14, lines 286-294: "We find that remaining at local interconnections is not conductive to maximizing benefits in terms of efficiency and cost. Relative to the S-I scenario, the reductions in overall installed capacities and associated costs are limited in the adjacent interconnections (S-A) and continental interconnections (S-C) scenarios (Table 1). Nonetheless, achieving global interconnection could markedly enhance the benefits of adjacent and continental interconnections. Such an insight highlights the importance of prioritizing global interconnection as the ultimate goal in the early planning of grid interconnection25,27. Complementary analyses targeting at the 2030s corroborate these findings (Supplementary Fig. S9)." -> I find it interesting to see that regional interconnection is not that efficient... this has major political and grid planning implications.

Response: Thank you for your encouraging feedback.

In our study, we did find that regional interconnections (adjacent interconnections, S-A, or continental interconnections, S-C) offer limited reductions in installed capacities and associated costs compared to the global interconnection (S-G). This finding underscores the importance of global interconnection as the most effective strategy for maximizing efficiency and reducing costs. In this revision, **we further deepened the analysis of these findings** in the *Potential benefits of global interconnection* subsection as follows: "Remaining at local interconnections is not conducive to fully capitalizing on the efficiency and cost benefits. Relative to the S-I scenario, the adjacent (S-A) and continental (S-C) interconnection scenarios yield only modest reductions in installed capacities and associated costs (Table 1). Achieving global interconnection markedly amplifies the benefits of these intermediate scenarios, underscoring the importance of prioritizing global interconnection as the ultimate goal in early planning of grid interconnection[27,29]. Complementary analyses for the 2030s support these findings (Supplementary Table S2). The positive amplifying effects of global interconnection become increasingly pronounced in later stages of development with higher solar-wind penetration. Compared to the baseline scenario, accelerating global interconnection by the 2030s results in only a 4% increase in penetration (Fig. 3a). However, if development lags and only adjacent interconnections are achieved by the 2050s, solar-wind penetration could decrease by 15.2%. Moreover, accelerating global interconnection offers advantages in investment allocation. In the baseline scenario, the investment burden is disproportionately concentrated in the early stages, whereas global interconnection by the 2030s leads to a more balanced cost distribution across different phases." (Lines 258-271).

Additionally, we strongly agree with you that these findings have major political and grid planning implications. Achieving global interconnection requires careful consideration of geopolitical realities, regional energy policies, and the complex dynamics of infrastructure development across multiple jurisdictions. Overcoming political and economic barriers will require substantial international cooperation and strategic investments in infrastructure. In this revision, **we further emphasized these implications in the *Discussion* section** as follows: "We recognize that the implementation of global interconnections remains fraught with challenges. Transitioning from localized, self-sufficient modes to a broad, unified global paradigm necessitates robust international agreements and a supranational entity[30] to facilitate stakeholder communications, coordinate cross-regional investments, and ensure competitive and equitable transnational energy flows. Developing transcontinental and transoceanic infrastructure under diverse geographical and environmental conditions demands innovative engineering solutions alongside substantial investment in labor, materials, and financial resources[21,22]. Geopolitical instability might be the greatest uncertainty for uninterrupted cross-border energy flows[21,25], particularly in the context of intense international competition. Furthermore, concerns over energy sovereignty, political pressures to safeguard domestic energy infrastructures, resistance from incumbent market participants toward new entrants, and local opposition to interconnection projects all pose potential barriers to the progress of global interconnection[28]. Nevertheless, our stress tests demonstrate that a globally interconnected system exhibits substantial resilience to unforeseen disruptions (Fig. 4), with risks to generation, transmission, and consumption largely mitigated through diversified transmission routes and reinforced critical infrastructure. Even under extreme conditions, the likelihood of cascading failures remains exceptionally low." (Lines 435-450).

Comments #3

The notion of energy security in the paper seems to be focused on reliability and resilience, not security of supply and other dimensions of energy security. This is a very limited (mostly engineering) conception of energy security. I would not conclude that energy security is enhanced (line 322), but nuance this finding, especially as geopolitics is largely ignored. More interconnections may enhance resilience as there are more rerouting possibilities (better score on the N-1 criterion), but also creates new dependencies.

Response: Thank you for your insightful comments.

We agree with you that the conception of energy security in the original manuscript was limited. In this revision, we have removed the terminology "energy security" to avoid misrepresentation and to focus the content on reliability and resilience. In response to your suggestion to nuance our findings, **we have introduced a new subsection dedicated to the resilience of a globally interconnected power system. Specifically, we conducted stress tests for five critical scenarios: climate change, extreme weather events, incompatible regional policies, geopolitical tensions, and market competition.** Details of these scenarios are provided in the *Stress tests* subsection of the revised *Methods* section, and the key results are presented in the *Resilience of a globally interconnected system* subsection of the revised *Results* section. Regarding the two aspects you mentioned here—geopolitics and new dependencies—our findings suggest the following:

First, geopolitical disruptions can significantly affect the stability of transmission nodes and lines, threatening the resilience of global interconnections (**Fig. R4**). For example, failures at major generation hubs such as North America, South America, and Australia, or demand centers like Eastern and Southern Asia, result in substantial increases in solar-wind curtailment and reduced penetration. Nonetheless, individual line failures generally have minimal global impacts, with changes in penetration or curtailment remaining below 1%. In the revised manuscript, we have included these findings in **the *Resilience of the Globally Interconnected System* subsection of the *Results* section** as follows: "Geopolitical tensions[46] further threaten the stability of transmission nodes and lines that underpin global interconnections. Failures at generation hubs like northern America, southern America, and Australia, or demand centers like eastern Asia, southern Asia, and southeastern Asia would sharply increase global solar-wind curtailment and reduce penetration (Fig. 4d). By contrast, nodes like northern Africa and western Asia, which primarily serve as transregional transmission bridges exhibit relatively localized impacts when disrupted individually due to rerouting flexibility[27] in the interconnected grid. In an extreme scenario of a complete grid collapse, global solar-wind curtailment (penetration) would rise (drop) by an absolute 41.2% (22.9%) …" (Lines 343-350).

This scenario is described in the revised *Methods* section as follows: "…Geopolitical tensions[46] could disrupt the transmission capacities of critical nodes and lines within the interconnected grid, thereby impacting global power exchange. We simulated scenarios in which all transmission capacities associated with a specific node were reduced to zero and analyzed the resulting changes in global solar-wind curtailment and penetration. These simulations provide insights into the vulnerability of a globally interconnected grid to geopolitical disturbances (Fig. 4d) …" (Lines 787-792).

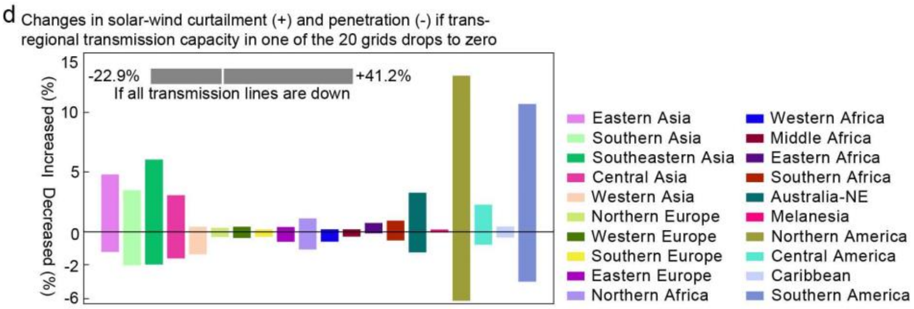


Fig. R4 (also appears as Fig. 4d in the revised manuscript). Changes in global solar-wind curtailment and penetration when all transmission lines associated with a single regional grid (denoted by bar colors) are disrupted. The horizontal gray inset depicts the extreme scenario where all transmission lines fail simultaneously.

Second, increased interconnection can create new dependencies, and our findings highlight that regions heavily reliant on external power supplies are particularly vulnerable to disruptions (**Fig. R5**). For example, disruptions in the connection between Eastern Asia and Eastern Europe could create a supply gap of nearly 15% for Eastern Asia. This deficit would double in the extreme case of severing all transmission lines into Eastern Asia. We have included these results into **the *Resilience of the Globally Interconnected System* subsection of the revised *Results* section** as follows: "…Although individual line failures generally have minimal global impacts, with changes in penetration or curtailment remaining below 1% (Supplementary Fig. S10), regions heavily reliant on external power supplies are particularly susceptible to such disruptions (Fig. 4e). For example, a disruption in the connection between eastern Asia and eastern Europe would create a supply gap of nearly 15% for eastern Asia, and severing all transmission lines into eastern Asia would double this deficit..." (Lines 350-355).

This scenario is described in the revised *Methods* section as follows: "…Furthermore, we explored regional dependencies in the interconnected grid by quantifying power supply gaps in a specific grid when one or all of its interconnected grids ceased supply (Fig. 4e)." (Lines 797-799).

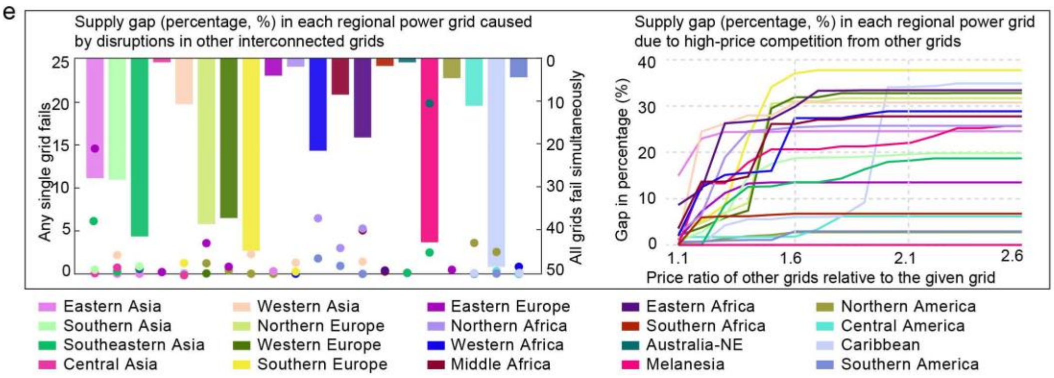


Fig. R5 (also appears as Fig. 4e in the revised manuscript). Power supply gaps resulting from supply interruptions from interconnected grids (left panel) and aggressive market competition (right panel). Circles represent scenarios of a single grid disruption, while bars indicate simultaneous disruptions across all interconnected grids. Circle colors denote disrupted grids, while bar colors indicate affected grids.

Comments #4

I am not sure if I agree with the results on energy access. In the paper, energy access is considered improved because cheaper energy is made available everywhere through interconnection, as mismatch is minimized. This assumes, however, an ability to buy/import energy, which may not be present in certain regions in reality. It also makes importing regions less secure in terms of security of supply and hence energy access. Finally, exporting regions may prioritize exports over servicing their own population if others pay more, leading to a situation where energy access remains poor in the exporting region. In all, there is more to energy access than the pure availability of it.

Response: Thank you for your valuable comments. We agree with you that our original analysis focused on the availability of renewable energy through interconnection. As you point out, this does not account for the critical issues of financial accessibility and supply security. This highlights the need for a more nuanced understanding of energy access. Below, we present our improvements in this revision, which are structured into **two points**.

First, we agree that interconnection could increase vulnerability for energy-importing regions, as they may become more dependent on energy imports. While our study emphasizes the increased resilience of the system through interconnection, this inevitably introduces new dependencies and vulnerabilities. In this revision, **we add an analysis of the potential risks of energy dependence. Specifically, we analyze power supply gaps resulting from disruptions in interconnected grids.** Our findings show that regions that are heavily reliant on external power supplies are particularly susceptible to such disruptions (**Fig. R5, left panel**). In the revised manuscript, we have added these findings to the *Resilience of the Globally Interconnected System* subsection of the *Results* section as follows: "…Although individual line failures generally have minimal global impacts, with changes in penetration or curtailment remaining below 1% (Supplementary Fig. S10), regions heavily reliant on external power supplies are particularly susceptible to such disruptions (Fig. 4e). For example, a disruption in the connection between eastern Asia and eastern Europe would create a supply gap of nearly 15% for eastern Asia, and severing all transmission lines into eastern Asia would double this deficit..." (Lines 350-355).

Second, we understand your concern regarding exporting regions prioritizing exports over domestic needs. In this revision, **we have expanded our analysis to include market competition and pricing dynamics. We model a scenario of market competition in which economically dominant regions may outbid the local grid for surplus power.** We introduce a weighting adjustment to the transmission loss matrix to reflect pricing dynamics, which allows us to estimate potential energy losses in disadvantaged regions. Our results show that even regions not directly affected by disruptions can experience adverse effects through aggressive market competition (**Fig. R5, right panel**). We have presented the results in the *Resilience of the Globally Interconnected System* subsection of the revised *Results* section as follows: "…Furthermore, regions not directly connected to disruptions can still experience adverse effects through aggressive market competition (Fig. 4e). In Melanesia, for instance, if eastern Asia and southern Asia offered 1.6 times the baseline price to secure priority access to surplus power from Australia and southeastern Asia, Melanesia would face a supply gap exceeding 20%..." (Lines 355-359).

For the above-mentioned two scenarios, we have outlined the simulation process **in the *Stress tests* subsection of the revised *Methods* section** as follows: "…Lastly, we examined regional market competition, where economically dominant regions influence electricity flows by outbidding local grids. To simulate such dynamics, we introduced weighted adjustments to the transmission loss matrix (Supplementary Fig. S4c), creating scenarios where competitive regions gained a cost advantage. This allowed us to estimate the potential energy losses experienced by disadvantaged regions. Furthermore, we explored regional dependencies in the interconnected grid by quantifying power supply gaps in a specific grid when one or all of its interconnected grids ceased supply (Fig. 4e)." (Lines 792-799).

Comments #5

The methods section is clear in terms of what was done on a granular level, but could use a discussion or figure that shows the overall model (variables in and out, processing steps). This would give readers a much needed overview of what goes on. At this point, I found it hard at times to understand what the model does when. How does the main algorithm decide (step by step) what comes out?

Response: Thank you for your valuable feedback.

In this revision, **we have supplemented a framework diagram (Fig. R6)** to provide a visual overview of the model. This figure outlines the key variables, processing steps, and outputs of the optimization framework, showing how different components of the model interact. **The framework consists of four steps. First,** the workflow begins by screening suitable locations for photovoltaic (PV) and wind turbine deployment and assessing their theoretical generation potential. **Second,** a multi-objective optimization model is employed to derive the optimal configuration of wind, solar, storage, and transmission capacities. This process uses trans-regional electricity dispatch to evaluate objective function values under specific candidate configurations for the 2050s. **Third,** the same multi-objective optimization is applied to determine the optimal phased configurations for the 2030s and 2040s. These results are designed to align with the 2050 configuration, forming a progressive development path. **Fourth,** experiments are conducted to assess the sensitivity of the globally interconnected system to external environmental changes, as well as the potential benefits and risks under global interconnection.

In the revised manuscript, **we have added a descriptive introduction at the beginning of the *Methods* section.** The accompanying text reads: "An overview of our workflow for global interconnected solar-wind system optimization and analysis is illustrated in Supplementary Fig. S12. The process begins by identifying suitable locations for solar PV and wind turbine deployment and assessing their theoretical generation potential. A multi-objective optimization model is then utilized to derive the optimal configuration of solar, wind, storage, and transmission capacities. This process involves trans-regional electricity dispatch to determine the objective function values for specific configurations. Subsequently, the optimization approach is applied to optimize phased configurations for the 2030s and 2040s, ensuring alignment with the 2050 configuration to establish a development path. Finally, comparative experiments are conducted to analyze the potential benefits and the resilience of a globally interconnected system." (Lines 476-484).

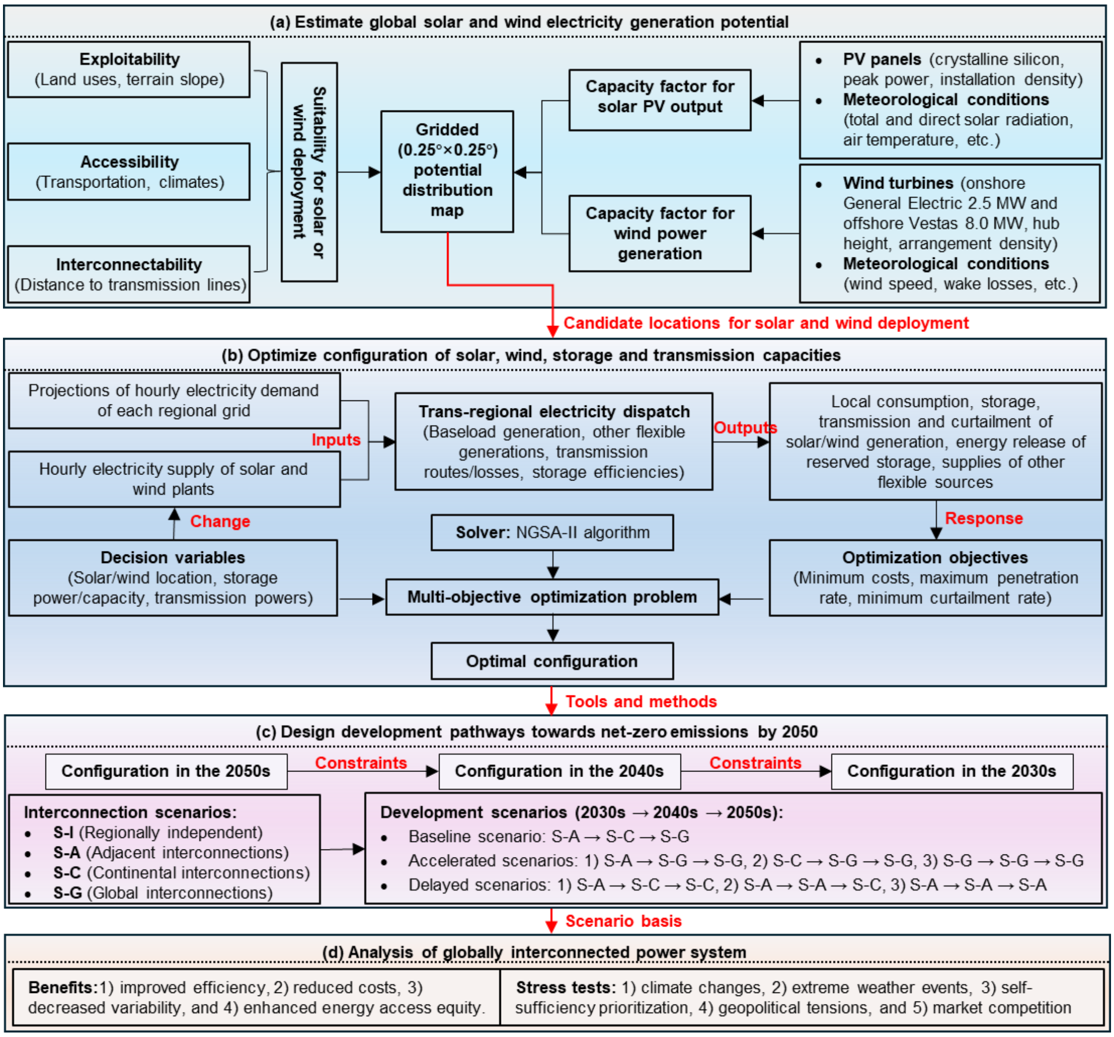


Fig. R6 (also appears as Fig. S12 in the revised SI). Optimization workflow for a global

interconnected solar-wind system. This workflow begins by screening suitable locations for photovoltaic and wind turbine deployment, followed by an assessment of their theoretical generation potential. A multi-objective optimization model is then employed to derive the optimal configuration of wind, solar, storage, and transmission capacities. This process relies on trans-regional electricity dispatch to determine the objective function values under specific candidate configurations. Next, the multi-objective optimization is applied to determine the optimal phased configurations for the 2030s and 2040s, ensuring alignment with the 2050 configuration to form a progressive development path. Different interconnection and development scenarios are compared. Finally, experiments are conducted to analyze the potential benefits and the resilience of a globally interconnected power system.

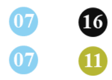
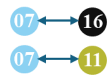
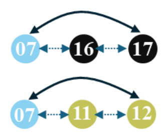
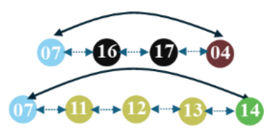
Additionally, we have reorganized and adjusted the sequence of the *Methods* section to align it with this overall framework, ensuring a more coherent flow and clear links between the model steps and the corresponding subsections. More details on specific aspects of the methodology will be elaborated in subsequent responses.

Specific comment #5.1

Please elaborate a bit more on the 4 scenarios in the text: what exactly are the differences and how were they made/selected?

Response: Thank you for your constructive feedback. We designed four interconnection scenarios to represent varying degrees of power grid integration, ranging from completely independent regional grids to a fully interconnected global grid. **The differences between these scenarios are primarily reflected in the scope and extent of power grid integration, as shown in Table R1**:

Table R1. Differences between the four interconnection scenarios.

Scenario	Definition	Purpose	Example
Regionally Independent (S-I)	The 20 regional grids operate independently without trans-regional power transmission	It represents the current state of largely isolated power markets at the country or regional level.	
Adjacent Interconnections (S-A)	This scenario allows for power exchange between geographically adjacent regions	It simulates practical trans-border electricity sharing, such as the European interconnection system.	
Continental Interconnections (S-C)	This scenario assumes the establishment of complete interconnection within continents. The grids of different continents are connected through intermediate grids that are spatially adjacent to both	It reflects a medium degree of power grid integration, such as the interconnections between Europe and North Africa, and West Asia and North Africa.	
Global Interconnections (S-G)	This scenario envisions an idealized global grid where all regions are interconnected with no limit on the number of intermediate nodes.	It explores the theoretical limits of solar and wind generation sharing on a global scale.	

These scenarios were selected to progressively expand the scope of grid interconnection, enabling a systematic assessment of how increasing levels of integration affect energy system performance and efficiency. In the revised manuscript, we have made **two major improvements:**

First, we have revised the *Interconnection Scenarios* subsection of the *Methods* section to clarify the differences between the scenarios and their purpose. The updated descriptions read as follows: "**Interconnection scenarios.** We designed four interconnection scenarios, each reflecting different degrees of regional and global power grid integration (Supplementary Fig. S4). In the S-I (regionally independent) scenario, the world is divided into 20 regions, each operating as an independent energy system with no trans-regional power transmission. This scenario represents the current state of largely isolated country- or regional-level power markets. The S-A (adjacent interconnections) scenario allows power exchange between geographically adjacent regions, simulating practical cross-border electricity sharing, such as the European interconnected power grid system[71]. In the S-C (continental interconnections) scenario, full interconnection is established within each continent, enabling power exchange across larger geographic areas. In this scenario, two grids on different continents can connect through an intermediate grid that is spatially adjacent to both, facilitating the balancing of variable renewable resources[10], such as solar and wind, across diverse climatic zones. Finally, the S-G (global interconnections) scenario envisions an idealized global load balancing framework, where all regions are interconnected without constraints on the number of intermediate nodes, and four transoceanic transmission lines are introduced to enable broader electricity exchange. This scenario aims to explore the theoretical limits of global solar and wind generation sharing. These progressively expansive scenarios allow us to assess the potential benefits and challenges of increasing grid interconnection levels on energy system resilience, efficiency, and costs." (Lines 705-721).

Second, we have revised Supplementary Fig. S4 to better illustrate the differences among the scenarios. Specifically, Fig. S4a shows the spatial division of the 20 regional grids; Fig. S4b presents the topological networks of spatial connections; and Fig. S4c illustrates the transmission losses between grid nodes. The revised Supplementary Fig. S4 are shown below:

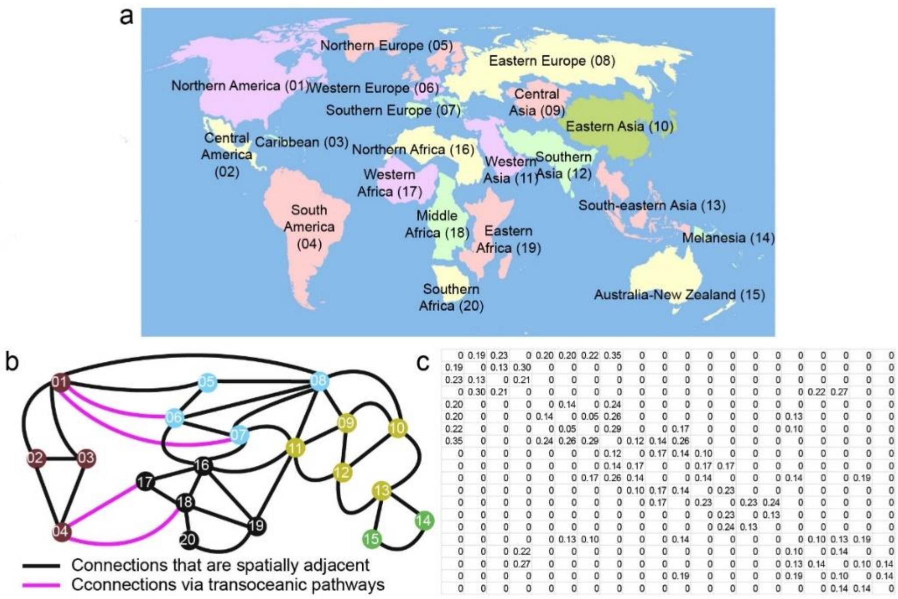


Fig. R7 (also appears as Fig. S4 in the revised SI). Illustration of different global interconnection scenarios. a, Spatial division of 20 regional power grids based on the United

Nations geoscheme, with the number in parentheses representing the grid index. **b,** Topological network of the spatial connections between the 20 regional grids, where black lines indicate spatial adjacency while purple lines represent connection via transoceanic pathways. In the S-I scenario (regionally independent), the 20 grids are independent, without trans-regional power exchange. In the S-A scenario (adjacent interconnections), spatially adjacent grids are interconnected, enabling trans-regional power transmission along the black connections. In the S-C scenario (continental interconnections), grids within the same continent are fully interconnected, while grids on different continents connect through an intermediate grid that is spatially adjacent to both. The S-G scenario (global interconnections) introduces four transoceanic pathways (purple lines) and permits any two grids to interconnect without constraints on the number of intermediate nodes. **c,** Transmission loss matrix corresponding to the network in (**b**), where the element in row i and column j represents the relative transmission loss between grid i and grid j. On land, losses over long distances are about 3% per 1,000 kilometers for high-voltage direct-current (HVDC) lines and about 7% per 1,000 kilometers for high-voltage alternating-current (HVAC) lines[64]. For HVDC sea cables, losses are similar but can reach 60% per 100 km for HVAC sea cables. Here, we assume a 50/50 split between HVDC and HVAC on land, with HVDC dominating at sea. Therefore, losses are calculated based on 5% per 1,000 km on land and 3% per 1,000 km over sea routes. In our power dispatch simulations, a network path search algorithm identifies all possible routes between two grids, prioritizing the least-cost path or multiple paths (depending on the required transmission power and the capacity of each route) for actual power flow.

Specific comment #5.2

Why do the authors envision growth from local to regional to continental to global interconnection? Why not immediately larger scale?

Response: Thank you for your insightful feedback.

The scenario from local to global interconnection was **initially designed to reflect real-world challenges associated with large-scale grid integration**. These challenges include infrastructure availability, policy coordination, economic and cost, as well as evolving dynamics of energy demand and supply. A stepwise approach to interconnection allows for progressive development, reducing potential risks and providing a more robust strategy. Existing success stories, such as the European energy market interconnection, also suggest that progressive interconnection is a more feasible and realistic pathway. In the revised manuscript, we have **explained the rationale in the D*evelopment Scenarios* subsection** of the *Methods* section as follows: **"Development scenarios.** We designed one baseline and six (three accelerated and three delayed) alternative development scenarios (Supplementary Fig. S12) to explore how interconnection progressions affect global electricity supply. Factors such as technological and infrastructure maturity, policy and coordination complexities, economic feasibility, cost-effectiveness, and dynamic balance between energy demand and supply may hinder the development of grid interconnection. Successful cases, such as the European power market integration[22], demonstrate that a stepwise approach—from local to regional, to continental, and ultimately to global interconnection—is a more robust and feasible pathway. This approach progressively addresses technical, policy, and economic challenges, optimizes grid stability and efficiency, and mitigates potential risks. Therefore, our baseline scenario assumes a phased approach to global energy interconnections, with interconnections initially designed to address regional bottlenecks and then gradually transitioning to a unified global load-balancing framework…" (Lines 722-733).

In our original optimization strategy, we first derived the layout for the 2030s and then optimized the layouts for expansion in the 2040s and 2050s based on the 2030s configuration. However, your comments prompted us to reconsider the potential drawbacks of this strategy, particularly the risk that the 2030 and 2040 layouts may not align well with the dynamic demands of the 2050s. In this revision, **we have adjusted the optimization process**. Specifically, we now directly optimize the 2050 layout based on the IEA's NZE projections for solar-wind penetration in the 2050s. Using the optimized 2050 configuration as a constraint, we derive the phased optimal layouts for the 2040s and 2030s. In the revised manuscript, we have **clarified this adjustment in the D*evelopment Scenarios* subsection** of the *Methods* section as follows: "…we envision a transition from S-A in the 2030s to S-C in the 2040s, culminating in S-G by the 2050s. For each scenario, we optimized the configuration in line with the IEA's NZE scenario[47] and selected the most cost-effective solution that meets the minimum solar-wind penetration of 68% and a curtailment close to 5%, based on alternatives provided by the NSGA-II algorithm. In addition, we optimized configurations for the 2040s and 2030s to form a development pathway consistent with the 2050 configurations. The rationale behind optimizing these phased targets is to account for the gradual increase in global electricity demand from the 2030s to the 2050s. Designing the system solely for 2050 demand from the outset could result in significant energy waste in previous years of lower demand. Therefore, setting phased goals provides a more strategic approach to guiding global grid interconnection effectively." (Lines 733-742).

Specific comment #5.3

What about long-distance losses in electricity transmission? This seems to be a major omission in the model. How does that affect global interconnections and their costs? Would they not make global connections too costly? How would, for example, the S-G scenario, with global interconnection between arbitrary regions work (in terms of computations)?

Response: Thank you for your insightful comments. We agree with you that transmission losses and their impact on overall costs are important aspects to consider and that it is important to ensure the computations are clearly stated. Below, we describe the improvements in this revision, which are structured into **three points**.

First, we improved our model to explicitly account for transmission losses. Specifically, the transmission loss is modeled as a proportion of power transmitted over each transmission line, increasing as a function of distance. In our study, we use a loss rate of 5% per 1,000 km for land-based transmission and 3% per 1,000 km for undersea transmission by referring to the Energy Technology Systems Analysis Program of the International Energy Agency. Based on the grid topology (**Fig. R7b**) and the geographic distances between interconnected nodes (the centroids of the 20 regional grids), we derive the transmission loss matrix (**Fig. R7c**). The matrix is incorporated into the transregional power dispatch model, enabling the optimization framework to determine the optimal allocation of generation, storage, and transmission capacities.

In the revised manuscript, we have detailed **this improvement in the *Trans-regional electricity dispatch* subsection** of the *Methods* section as follows: "…According to the Energy Technology Systems Analysis Program (ETSAP) of the IEA, long-distance transmission losses on land are about 3% per 1,000 kilometers for high-voltage direct-current (HVDC) lines, and about 7% per 1,000 kilometers for high-voltage alternating-current (HVAC) lines[64]. For sea cables, HVDC losses are similar, but HVAC losses can reach 60% per 100 kilometers. Here, we assume a 50/50 split between HVDC and HVAC on land, while HVDC dominates for cross-sea transmission. As a result, transmission losses are calculated at 5% per 1,000 kilometers on land and 3% per 1,000 kilometers at sea. The centroid of each regional grid is used to calculate the average distances between grids, forming the transmission loss matrix shown in Supplementary Fig. S4c…" (Lines 637-645).

Second, transmission losses impact total costs by raising the capacity required for solar-wind deployment. Nevertheless, global interconnection still offers advantages over relatively independent scenarios. As shown in **Table R2**, compared to the regionally independent (S-I) scenario, the installed capacities of solar and wind power plants are reduced by 22.1%, while the corresponding power outputs are reduced by 25.2% under the global interconnection (S-G) scenario. The power requirements for storage systems are reduced by 41.6%, and the capacity requirements decrease by 37.0%. The initial investment required for constructing solar PVs, wind turbines, storage, and transmission facilities under the S-G scenario is 84.2% of the cost required for the S-I scenario. These results highlight that while transmission losses add to costs, the benefits of global interconnection outweigh the challenges through optimizing resource utilization efficiency.

In the revised manuscript, we have **updated these results in the *Potential Benefits of Global Interconnection* subsection** of the *Results* section as follows: "…Using the regionally independent (S-I) scenario as a reference, the global interconnection (S-G) scenario reduces the installed capacities (and corresponding power outputs) of wind and solar power plants by 22.1% (25.2%) and lowers the power (and capacity) requirements for storage systems by 41.6% (37.0%). Driven by a 33.6% reduction in curtailment, this streamlined solar-wind-storage configuration achieves a 5.1% increase in solar-wind penetration. The initial investment for constructing solar PVs, wind turbines, storage, and transmission facilities under the S-G scenario amounts to 84.2% of the cost required for the S-I scenario, translating to potential savings of around 22.47 trillion US$..." (Lines 247-254).

Table R2 (also appears as Table 1 in the revised manuscript). Anticipated capacities, costs and utilization rates for PV, wind, storage, and transmission facilities by the 2050s across different interconnection scenarios.

Scenario	Installed solar capacity (TWp)	Installed wind capacity (TWp)	Energy storage power (TW)	Energy storage capacity (TWh)	Electricity transmission power (TW)	Annual solar generation ($\times 10^3$ TWh)
S-I	55.43	3.41	8.44	144.31	/	89.38
S-A	54.36	3.38	7.92	115.46	235.51	87.63
S-C	47.15	3.34	5.74	106.69	341.44	73.57
S-G	42.52	3.27	4.93	90.88	384.49	65.24

Scenario	Annual wind generation ($\times 10^3$ TWh)	Storage utilization rate (%)	Transmission utilization rate (%)	Total initial investment (trillion US$)	Curtailment rate (%)	Penetration rate (%)
S-I	7.73	4.53	/	142.32	41.30	72.02
S-A	7.63	3.21	0.48	133.34	32.20	73.68
S-C	7.58	0.70	0.74	123.12	23.46	74.20
S-G	7.42	0.52	1.15	119.85	8.65	77.08

Third, regarding the computation under interconnection, the process is as follows. **1)** At each time step, we calculate the surplus and deficit of electricity across all grids. **2)** A path-finding algorithm is applied to identify all potential transmission routes based on the network topology (Supplementary Fig. S4b). **3)** For each route, transmission losses are calculated as the sum of losses from all sub-connections along the route. **4)** All routes are sorted by loss, and power dispatch decisions are made sequentially. For each route, power transmission occurs if the connected grids have one in surplus and the other in deficit. The transmission amount depends on the surplus/deficit of power and the maximum capacity of the transmission route. Once a route is in operation, the remaining transmission capacity between nodes is updated. This process continues until all routes have been processed.In the revised manuscript, we **provided the following descriptions of these processes in the *Trans-regional electricity dispatch* subsection** of the *Methods* section as follows: "…When surplus power exists in any one grid, a path-finding algorithm identifies all potential transmission routes based on the network topology (Supplementary Fig. S4b), where each grid acts as a node. In the S-A scenario, transmission routes are limited to direct connections without intermediate nodes; in the S-C scenario, a single intermediate node is allowed; and in the S-G scenario, multiple intermediate nodes are permitted. Transmission losses for each route are calculated as the sum of losses from all sub-connections, and the least costly routes are prioritized for electricity transmission. Once a route is in operation, the remaining transmission capacity between nodes is updated. The usable capacity of a route is determined by the smallest remaining capacity among its sub-connections." (Lines 645-653).

Specific comment #5.4

Line 525: "In our analysis, we account for the construction costs of solar, wind, and energy storage infrastructures, excluding the costs pertaining to transmission infrastructure. This exclusion is underpinned by the premise that, irrespective of the scenario, establishing sufficient transmission capacity is a fundamental prerequisite for enabling global interconnection20,25." I do not understand this choice. How can you optimize costs without taking transmission capacity into account. Isn't this paper in the end about optimizing the trade-off between generation, storage and transmission costs? I don't think the transmission costs are the same in every scenario. Please clarify.

Response: Thank you for your constructive feedback.

In the original analysis, the cost estimates did not include transmission costs. This decision was made based on the premise that establishing sufficient transmission capacity is a fundamental prerequisite for global interconnection. Therefore, our initial focus was on optimizing generation and storage configurations, with transmission costs evaluated in a subsequent comparison. **In the original manuscript, we discussed this point in *Discussion* section as follows:** "*Referring to the construction cost of the southeastern Asia-Australia 3GW transmission line at 0.64 million US$ per kilometer*[41]*, these economized funds could support the construction of 31,000 lines spanning more than 30.5 million kilometers, which could cumulatively provide a maximum power capacity exceeding 90.21 TW. Such an expansive coverage would adequately fulfill the requirements for global interconnection*[27,28]*, signaling that the savings could offset or even surpass the additional investment required for trans-regional power transmission*."

However, we recognize the limitation of excluding transmission costs and agree with you that this affects the trade-offs between generation, storage, and transmission costs. In this revision, **we have refined the optimization framework to include transmission costs in the cost calculations.**

In the absence of global transmission cost data, we referenced ERCOT's report on construction costs of transmission lines (**Fig. R8d**). Additionally, following Reviewer 2's suggestion, we incorporated region-specific solar and wind installation costs based on IRENA's report to account for spatial variations in deployment expenses (**Fig. R8a-b**). In the revised manuscript**,** we have detailed these adjustments in the *Multi-objective problem definition* subsection of the *Methods* section as follows: "In our analysis, we account for the construction costs of deploying solar, wind, storage, and transmission infrastructures. The total investment costs are encapsulated by the equation:

$$T_{inv} = \sum_{i=1}^{13296} \xi_{sol} I_s^i C_s^i + \xi_w \sum_{i=1}^{8477} \xi_w I_w^i C_w^i + \xi_{sto} \sum_{i=1}^{20} V_s^i + \xi_{tran} \sum_{i=1}^{42} P_t^i \quad (8)$$

Here, C_s and C_w correspond to the maximum installation capacities for solar and wind facilities within each grid-box. The terms ξ_{sol}, ξ_w, ξ_{sto}, and ξ_{tran} denote the unit costs of installing solar panels, wind turbines, storage facilities, and new transmission projects, respectively (see Supplementary Fig. S8). For onshore wind and solar PV, continental averages were calculated based on available country-level data from the IRENA to reflect regional cost differences. Due to data limitations, global averages of all available records were applied for offshore wind, energy storage, and transmission. Our cost optimization focuses on strategically allocating limited investments across solar, wind, storage, and transmission facilities to realize the most effective solution..." (Lines 584-594).

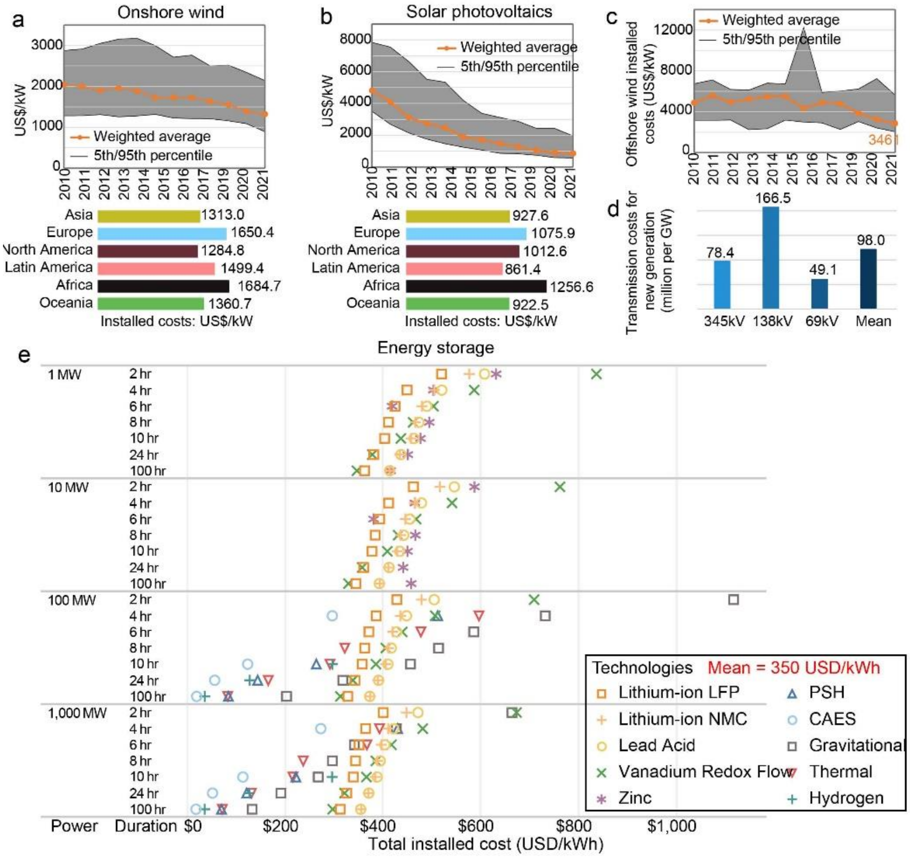


Fig. R8 (also appears as Fig. S8 in the revised SI). Pricing benchmarks for deployment of onshore wind turbines (a), solar PV (b), offshore wind turbines (c), new transmission lines (d), and energy storage systems (e). The installed cost data for solar PV and wind turbine are extracted from reports issued by the International Renewable Energy Agency (IRENA) (https://www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022). The cost of new transmission lines is based on statistical analyses by the Energy Institute for the Electric Reliability Council of Texas, Inc. (ERCOT) transmission projects (https://energy.utexas.edu/sites/default/files/UTAustin_FCe_TransmissionCosts_2017.pdf). Energy storage cost data come from the U.S. Department of Energy (https://www.pnnl.gov/ESGC-cost-performance). For onshore wind and solar PV, continental averages were calculated based on country-level data from IRENA to reflect regional cost differences. Due to limitations in data availability, global averages of all available records were applied for offshore wind (3,461 USD/kW), energy storage (350 USD/kWh), and onshore transmission (98 million per GW). Considering the difficulty of constructing transoceanic transmission lines, we take the maximum value for the cost of offshore transmission (166.5 million per GW).

Specific comment #5.5

Line 560: "We target at completely flexible power grids, which implies the absence of baseload generation. In this context, the generation units are classified into three categories: real-time solar-wind generation, stored solar-wind generation, and other flexible units." -> No baseload? I know this is noted in the discussion section but still... how does this impact the utility/results of the study? Moreover, what if more hydropower and a bit of natural gas with ccs were to be used?

Response: Thank you for your feedback on the assumption that there is no baseload. While this assumption allows us to explore the feasibility and challenges of a fully flexible power grid reliant on solar, wind, storage, and transmission, we recognize that it oversimplifies the practical evolution of future power grids and may affect the utility/results of the study. In this revision, we have refined the baseload settings and conducted additional analyses to better reflect the reality. Below, we summarize these adjustments and additional findings in **three points.**

First, we adjust the baseload settings to align with the International Energy Agency's (IEA) ***Net Zero Emissions by 2050*** **(NZE) scenario (Table R3).** Specifically, baseload generation (including nuclear, geothermal, and unabated fossil fuels) is set to decline gradually from 36% in the 2030s to 11% in the 2040s and further to 9% by the 2050s. **Hydropower and fossil fuels with CCUS are included** as flexible power sources to maintain system stability. In the revised manuscript, we have added a description of these adjustments in the *Trans-regional electricity dispatch* subsection of the revised *Methods* section as follows: "…We categorize power generation units into four types: baseload generation (including nuclear, geothermal, and unabated fossil fuels), real-time solar-wind generation, stored solar-wind generation, and other flexible units (such as hydropower, hydrogen-based, and fossil fuels with CCUS). During electricity dispatch, baseload generation is always prioritized, followed by solar and wind generation (to maximize their penetration), with any remaining gap filled by flexible units. Referring to the IEA's NZE scenario (Supplementary Table S1), we set the share of baseload generation to decline gradually from 36% in the 2030s to 11% in the 2040s and further to 9% by the 2050s…" (Lines 621-628).

Table R3 (also appears as Table S1 in the revised SI). International Energy Agency Net-Zero Emissions by 2050 Roadmap.

	Electricity Generation (TWh)			**Shares (%)**		
	2030s	**2040s**	**2050s**	**2030s**	**2040s**	**2050s**
Total generation	**37,316**	**56,553**	**71,164**	**100**	**100**	**100**
Renewables	22,817	47,521	62,333	61	84	88
Solar PV	6,970	17,031	23,469	19	30	33
Wind	8,008	18,787	24,785	21	33	35
Hydropower	5,870	7,445	8,461	16	13	12
Bioenergy	1,407	2,676	3,279	4	5	5

Concentrated solar power	204	880	1,386	1	2	2
Geothermal	330	625	821	1	1	1
Marine	27	77	132	0	0	0
Nuclear	3,777	4,855	5,497	10	9	8
Hydrogen-based	875	1,857	1,713	2	3	2
Fossil fuels with CCUS	459	1,659	1,332	1	3	2
Coal with CCUS	289	966	663	1	2	1
Natural gas with CCUS	170	694	669	0	1	1
Unabated fossil fuels	9,358	632	259	25	1	0
Coal	2,947	0	0	8	0	0
Natural gas	6,222	626	253	17	1	0
Oil	189	6	6	1	0	0

Second, to evaluate the impact of baseload generation, we retain the idealized scenario with no baseload and introduce an alternative scenario with a baseload share of 9%. As shown in **Fig. R9**, grids with lower baseload proportions have greater flexibility and fault tolerance in their development path. However, this flexibility requires increased reliance on flexible power sources to maintain grid stability. This reliance decreases over time, from 30% in the 2030s to 17% in the 2050s, as transregional solar-wind power consumption increases from 15% to 53%. This analysis highlights the trade-offs between baseload generation and system flexibility, providing a more comprehensive understanding of future grid evolution. In the revised manuscript, we have **updated these analyzes in the *Optimal configuration and pathway* subsection** of the *Results* section as follows: "…In grids with a lower proportion of baseload generation, a wider range of development pathways becomes feasible (Fig. 2e), enhancing flexibility and fault tolerance during system evolution. However, this enhancement necessitates a higher reliance on flexible power sources to maintain grid stability. Under an NZE scenario, where baseload generation is close to zero, the average proportion of flexible power required is approximately 18.7%. From the 2030s to the 2050s, a substantial transition in the electricity supply and consumption structures is anticipated (Figs. 2f–g), reducing reliance on flexible power reserves from 30% to 17% and increasing the share of trans-regional solar-wind power consumption from 15% to 53%." (Lines 220-227).

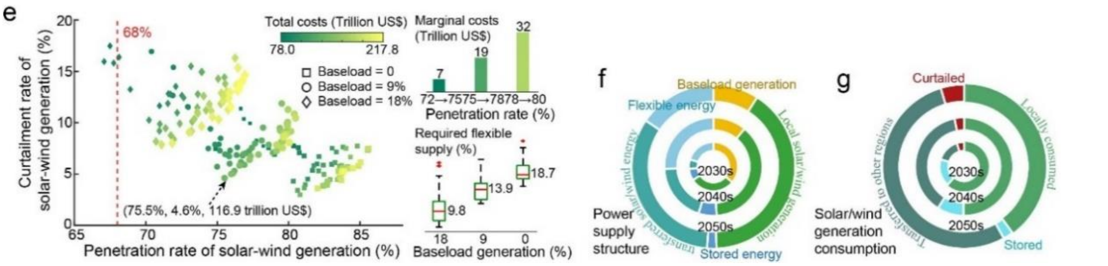


Fig. R9 (also appears as Fig. 2e-g in the revised manuscript). e, Multi-objective optimization results highlighting trade-offs among maximizing penetration, minimizing curtailment, and reducing overall costs. Different symbol shapes indicate the impact of varying baseload generation levels. The insets illustrate the marginal cost of increased penetration and flexible power requirements under different baseload scenarios. **f–g**, Evolution of power supply (**f**) and consumption (**g**) structures under the optimal spatial configuration and development pathway.

Third, we revise our projections of future electricity demand to ensure consistency with the IEA's NZE scenario. After projecting future load profiles (**Fig. R10**), a linear ratio was applied to align the forecasted total electricity demand with NZE's projections. In the revised manuscript, we have described this revision **in the *Projections of future generation and demand* subsection of the *Methods* section** as follows: "…We first fit the parameters in Eq. 12 using historical data from Toktarova et al.[34], and then incorporate future projections of influencing factors to derive future load profiles (Supplementary Fig. S14). To address the inconsistency between our projections and the IEA's NZE scenario (Supplementary Table S1), we calibrate the forecasted hourly loads by applying a linear ratio based on their total generation forecasts" (Lines 698-702).

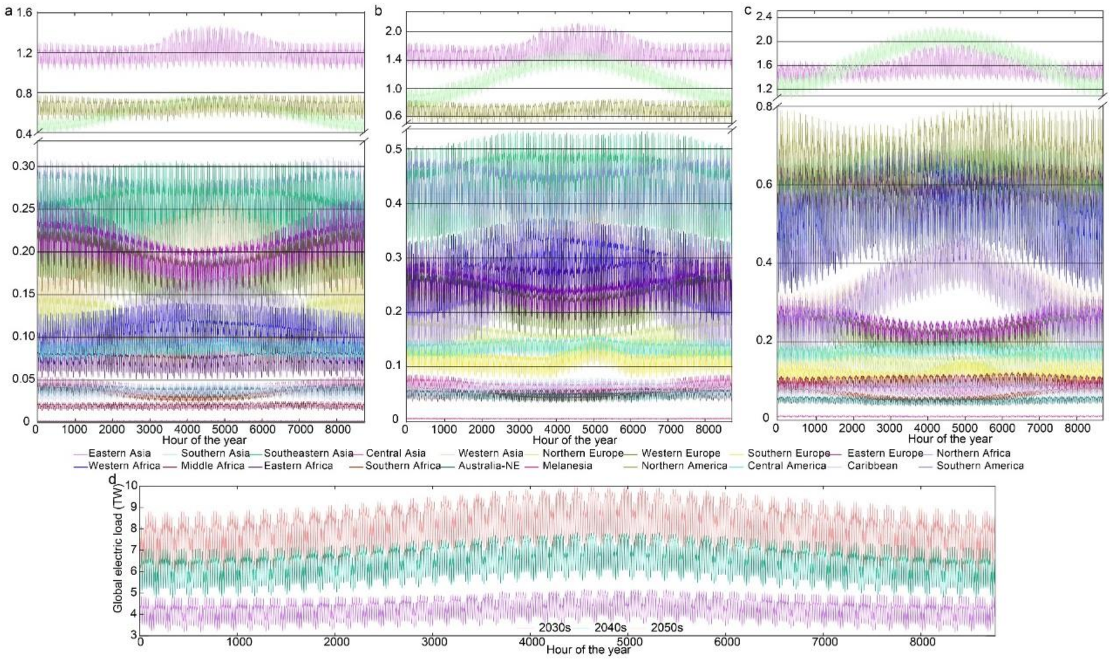


Fig. R10 (also appears as Fig. S14 in the revised SI). Future projections of load profiles. (**a–c**) Load profiles of the 20 regional grids in the 2030s (**a**), 2040s (**b**) and 2050s (**c**). (**d**) Comparison of global load profiles in the 2030s, 2040s and 2050s.

Specific comment #5.6

In how far is existing infrastructure taken into account?

Response: Thank you for your insightful question.

In this revision, we explicitly incorporated current solar, wind, storage, and transmission capacities into the refined optimization model. This ensures that the optimized configurations are compatible with ongoing or planned developments. Specifically, the installed capacities for solar, wind, and storage (primarily pumped storage) are sourced from the Renewable Energy Statistics 2024 report by IRENA, and the trans-regional transmission capacities are based on Brinkerink et al.'s study. In the optimization model (Eq. 7), the decision variables—$\mathbf{I}_s$(solar capacity), $\mathbf{I}_w$ (wind capacity), $\mathbf{P}_s$ (storage capacity), $\mathbf{V}_s$ (storage power), and $\mathbf{P}_t$ (transmission power)—are constrained by their current states, as detailed in Table R4. In the revised manuscript, we have added a description to **the revised *Multi-objective problem definition* subsection** of the *Methods* section as follows: "…The decision variables—$\mathbf{I}_s$, $\mathbf{I}_w$, $\mathbf{P}_s$, $\mathbf{V}_s$, and $\mathbf{P}_t$—are subject to their current states (Supplementary Table S4) to ensure that the optimized future configuration keeps compatible with ongoing or planned efforts. Specifically, the designed capacities for solar, wind, or storage in each regional grid should exceed existing installed capacities, and the transmission power for each connection should surpass the current capacity." (Lines 578-583).

Table R4 (also appears as Table S4 in the revised SI). Current states of regional solar, wind and storage capacities, as well as existing trans-regional transmission projects.

Regions	Wind (MW)	Solar (MW)	Storage (MW)	Transmission (MW)
01	165,009	143,609	19,107	1840 (01→02)
02	8,644	12,825	6	1,500 (02→01), 400 (02→04)
03	10,857	13,406	0	0
04	39,785	49,076	974	400 (04→02)
05	72,524	27,172	3,652	22,815 (05→06), 1,600 (05→08)
06	110,807	147,453	10,329	22,815 (06→05), 23,375 (06→07), 9,800 (06→08), 2,000 (06→16)
07	56,193	71,890	8,584	23,375 (07→06), 9,353 (07→08), 3,260 (07→11), 7,250 (07→16)
08	18,449	40,239	7,661	2,100 (08→05), 9,300 (08→06), 10,880 (08→07), 350 (08→09),1,295 (08→10), 3,950 (08→11)
09	1,441	1,555	0	350 (09→08), 4,380 (09→12)
10	451,717	734,202	80,139	1,295 (10→08), 50 (10→12), 2,158 (10→13)
11	13,440	29,577	540	3,260 (11→07), 3,950 (11→08), 3,860 (11→12), 5,800 (11→16)
12	47,215	74,017	5,825	3,630 (12→09), 50 (12→10), 3,860 (12→11), 3 (12→13)
13	8,006	25,748	1,296	2,158 (13→10), 3 (13→12)
14	72	324	0	0
15	13,970	32,972	810	0
16	4,003	3,084	464	2,000 (16→06), 12,250 (16→07), 5,800 (16→11), 4,182 (16→19)
17	297	901	0	0
18	1.1	374	0	997 (18→09), 600 (18→20)
19	905	1,188	0	4,182 (19→16), 997 (19→08), 7,185 (19→20)
20	3,447	5,846	2,732	600 (20→18), 7,185 (20→19)

*The numbers in the first column correspond to Supplementary Fig. S4a. Data on installed capacities for solar, wind, and storage (primarily pumped storage) are sourced from the *Renewable Energy Statistics 2024* report issued by IRENA (https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024). Trans-regional transmission capacities are based on the study by Brinkerink et al.[76], with the numbers representing the maximum transmission power and the contents in parentheses indicating the starting and ending regions of the transmission routes. Please note that the transmission is directional.

Comments #6

There are some minor spelling issues here and there. Most notable is that the authors put the footnotes before (instead of after) the dots at the end of sentences.

Response: Thank you for your comments. We have carefully reviewed the manuscript for any spelling errors and have made corrections where necessary. Regarding the placement of footnotes, we have reviewed the journal guidelines and ensured that placing footnotes before bullet points is in line with the journal guidelines. We would like to express our thanks again for your careful review and constructive comments on our manuscript.

Reviewer #2 (Remarks to the Author):

Comments #1

Noteworthy Results.

The research highlights some significant findings about the potential of a globally interconnected solar-wind power system:

1. The system could generate approximately 237.33×10^3 TWh per year, which exceeds projected global electricity demand for the 2050s.
2. Strategic optimization of plant placements, combined with regional storage and transmission, could lower costs and minimize energy curtailment.
3. A phased global interconnection approach, starting with storage expansion and followed by transmission upgrades, is proposed.
4. Global interconnection could improve power supply stability and resilience, especially during extreme weather events.
5. The system could ensure equitable access to renewable resources and balance the energy decarbonization burden across regions.

Response: Thank you for recognizing the results of our study and for highlighting the key findings. We appreciate your summary and are delighted that the potential of a globally interconnected solar-wind power system resonates with you.

In this revision, we have further refined our analysis to improve the robustness of these results based on your summary and suggestions from other reviewers. Most notably, we conduct stress tests to validate the outcomes related to supply stability and resilience under extreme or unforeseen conditions, including climate change, extreme weather events, incompatible regional policies, geopolitical tensions, and market competition. These improvements are detailed **in the new subsection *Resilience of a globally interconnected system* in the *Results* section.**

Additionally, we have expanded the discussion of the broader implications of these results, particularly their relevance to achieving a sustainable global energy system. This expanded analysis is presented **in the revised *Discussion* section.**

We sincerely thank you for your positive feedback. Your comments encourage us to further refine our results and their implications for advancing global renewable energy integration.

Comments #2

Significance, Comparison to Established Literature and Originality.

The research presented in this paper marks a significant advancement in the field of renewable energy by offering a detailed roadmap for implementing a globally interconnected solar-wind power system. Unlike previous studies by Jacobson et al. (2017) and Chen et al. (2021) that explored renewable energy potentials and pathways to carbon neutrality, this study stands out with its comprehensive and actionable approach. It not only evaluates the theoretical potential of solar and wind energy but also addresses practical aspects of implementation, such as optimizing plant deployment, storage capacities, and transmission infrastructure. This holistic roadmap, which considers both technical and socio-economic factors, distinguishes it from earlier work and provides a concrete pathway toward global energy interconnection.

Additionally, the study's originality lies in its multi-faceted methodology, which integrates spatial analysis, power generation modeling, and multi-objective optimization. This thorough approach enables a nuanced evaluation of the feasibility and benefits of global interconnection, moving beyond the theoretical concepts of earlier research. By tackling practical challenges and offering a detailed implementation plan, this study significantly contributes to the existing body of knowledge and provides valuable insights for policymakers and stakeholders in the renewable energy sector.

Response: Thank you for your positive comments on the significance, comparison to established literature, and originality of our work. We are pleased that you consider our research a significant advancement in the field of renewable energy and that the comprehensive and actionable roadmap we present is different from earlier studies.

We greatly appreciate your recognition of our study's multi-faceted methodology. Integrating spatial analysis, power generation modeling, and multi-objective optimization is a key focus of our work, as we aim to explore practical pathways for global energy interconnection based on previous theoretical assessments. In this revision, **we update the *Introduction* and *Discussion* sections to better situate our research within the context of prior research**, and especially emphasize our advancement to the established literature (e.g., Jacobson et al. (2017) and Chen et al. (2021)). The added texts in the **revised *Introduction* section** are as follows: "…Following these pivotal events, the theoretical concept of GEI has evolved to tangible politics and practices[27], with several studies proposing various alternative pathways for its implementation[28-30]. Yet, establishing a globally interconnected solar-wind system oriented towards net-zero emissions still needs to be clarified. Some scenarios proposed for this objective explored renewable energy potentials and national pathways to carbon neutrality, but they represent a macroscopic perspective that lacks essential geographic details[6,8,14,31]. The practical implementation requires a holistic evaluation of various aspects, including the feasibility of delivering PV and wind generation to the grid, the dynamics of demand fluctuations, the balance between supply and demand, the strategic configuration of transmission and storage systems, and comprehensive assessments of costs and benefits[4,13,16,32]." (Lines 76-85).

In addition, we **highlight the added value of this study** in the revised *Discussion* section as follows: "These findings advance the understanding of global interconnection as a transformative approach to integrating solar and wind energy into the global mix. Unlike previous research[6,31] that explored renewable energy potentials and pathways to carbon neutrality, this study offers a comprehensive and actionable roadmap for implementing a globally interconnected solar-wind power system. Moving beyond proof-of-concept[23,27] or regional studies[16,20,21], we provide spatial estimates of interconnectable solar-wind potential, identifying critical regions of surplus and deficit while emphasizing the necessity of global-scale energy exchanges. Our analysis highlights the importance of delineating cost-effective configurations and development paths through multi-objective optimization, demonstrating its value in achieving balanced resource allocation, curtailment reduction, and efficiency improvements. Furthermore, we provide new insights into the potential benefits of enhancing equitable energy access and alleviating economic pressures on energy decarbonization while also examining potential risks under uncertainties. These thorough analyses enable a more nuanced perception of the feasibility of global interconnection, moving beyond the theoretical concepts of earlier research. By tackling practical challenges and offering alternative implementation plans, this study would contribute to the existing body of knowledge and provide valuable insights for policymakers and stakeholders in the renewable energy sector." (Lines 451-466).

Comments #3

Study's conclusions and claims are well-supported by:

Simulation and Modeling: Extensive simulations and modeling estimate the potential electricity generation of a globally interconnected solar-wind system, demonstrating its capacity to exceed projected future demand. The optimized placement of power plants and storage/transmission infrastructure provides concrete evidence for the feasibility and cost-effectiveness of their proposed approach.

Data Analysis: Real-world data on land use, terrain, solar radiation, wind speed, and existing transmission lines identify suitable locations for solar and wind farms, strengthening the validity of their findings regarding renewable resources' potential.

Explanation: Detailed explanations of their methodology, including data sources, model parameters, and optimization algorithms, allow for scrutiny and potential replication, enhancing the credibility of their conclusions.

Response: Thank you for your positive comments on our study's conclusions and claims. We are pleased that you found the simulations, data analysis, and detailed methodological explanations to be well-aligned with our research objectives and supportive of the study's conclusions.

In this revision, we have further refined these aspects based on your feedback and suggestions from other reviewers. Specifically:

1) Simulation and Modeling: We incorporated the current capacities of solar, wind, storage, and transmission as initial conditions of the optimization model (Eq. 7), ensuring compatibility with ongoing or planned efforts. Transmission costs have been integrated into the cost estimation (Eq. 8) to enable balancing among regional generation, storage, and transmission investments. In addition, we accounted for transmission losses during electricity dispatch, enhancing the robustness of our cost and feasibility analyses.

2) Data Analysis: We introduced stress tests to analyze the stability and resilience of a globally interconnected system under extreme or unforeseen conditions, including climate change, extreme weather events, incompatible regional policies, geopolitical tensions, and market competition. These additions strengthen our understanding of the potential risks under global interconnection.

3) Methodological Explanations: We expanded the descriptions of interconnection scenarios, baseload and flexible power sources, and computational details of trans-regional interconnections. These refinements provide greater clarity and transparency to our methodologies.

We sincerely appreciate your encouragement. Your feedback has guided us to make significant improvements in the rigor and comprehensiveness of our analysis.

Comments #4

Limitations. These limitations do not invalidate the study's findings.

Response: Thank you for your acknowledgement that these limitations do not invalidate the study's findings. In this revision, we have made efforts to address these limitations and have further clarified their scope and impact. More details are given in the following responses.

Specific comment #4.1

Overestimation of Interconnectable Potential: The analysis may overestimate potential due to factors like rural road capacity for wind turbine transport and low-voltage transmission line limitations.

Response: Thank you for pointing out the potential overestimation of interconnectable potential. We recognize these aspects as limitations of our analysis and explain them in the revised manuscript.

First, in the *Limitations* subsection of the *Methods* section, we note: "We recognize that our analysis has certain limitations. First, the classification of roads and transmission lines was not considered in assessing the solar-wind potential. For instance, the inability of certain rural roads to accommodate large wind turbine transport and the inadequacy of low-voltage transmission lines for long-distance power transmission might lead to an overestimation of the interconnectable potential…" (Lines 802-806).

Second, in the *Interconnectable solar-wind potential* subsection of the *Results* section, we the range of uncertainty due to climate fluctuations as follows: "Our estimates suggest that the total electricity generation from global interconnectable solar-wind potential could reach a staggering level of [237.33±1.95] $\times 10^3$ TWh/year (mean ± standard deviation; the standard deviation is due to climatic fluctuations)…" (Lines 121-123).

Specific comment #4.2

Cost Estimation Limitations: The cost analysis uses a unified pricing benchmark, not fully accounting for regional variations or potential cost reductions from technological advancements.

Response: Thank you for your comments. We agree with you that incorporating regional differences and potential cost reductions from technological advances would further strengthen our analysis.

In the revised manuscript, we have **incorporated regional cost variations for onshore wind and solar PV deployment** by calculating continental values based on available data from IRENA (Fig. R11). Due to data limitations, we applied global unified benchmarks for offshore wind, energy storage, and transmission infrastructure. We emphasized that a more granular analysis that accounts for variations in land and labor costs, transportation conditions, and other factors would further improve accuracy. These points are clarified in the revised ***Multi-objective problem definition* subsection of the *Methods* section** as follows: "…For onshore wind and solar PV, continental averages were calculated based on available country-level data from the IRENA to reflect regional cost differences. Due to data limitations, global averages of all available records were applied for offshore wind, energy storage, and transmission. Our cost optimization focuses on strategically allocating limited investments across solar, wind, storage, and transmission facilities to realize the most effective solution. A more refined estimation would further encompass a variety of complex factors[4,13], including variations in land and labor costs, discrepancies in transportation conditions, and the influence of proximity to the coast on offshore wind turbine installations…" (Lines 590-597).

Despite the explicit consideration of cost variations, we acknowledge that our cost estimates do not account for potential reductions due to dynamic learning and technological advances. This limitation is stated in **the *Optimal configuration and pathway* subsection** of the revised *Results* section as follows: "…While our cost estimation does not account for potential reductions due to dynamic learning[40] and technological advances[4], it provides a practical basis for identifying cost-effective pathways. The initial investment for our preferred scenario is estimated at 116.9 trillion US$, based on current pricing benchmarks (Supplementary Fig. S8), representing only 54% of the highest estimated cost of 217.8 trillion US$...." (Lines 215-219). We also discuss this limitation **in the *Limitations* subsection** of the revised *Methods* section as follows: "We recognize that our analysis has certain limitations…Second, while we considered cost differences in deploying solar, wind, and storage facilities, our analysis did not account for regional cost variations and temporal cost reductions due to dynamic learning[73] and technological advancements[4], which may undermine the reliability of our cost estimates in guiding investment decisions...” (Lines 802-809).

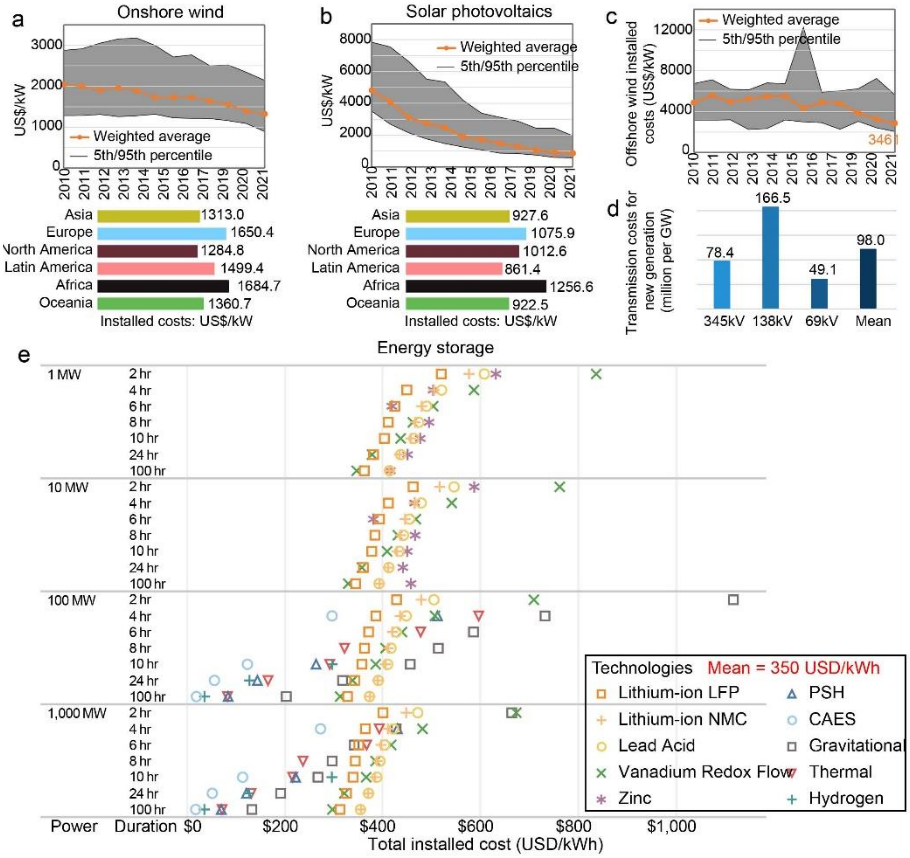


Fig. R11 (also appears as Fig. S8 in the revised SI). Pricing benchmarks for deployment of onshore wind turbines (a), solar PV (b), offshore wind turbines (c), new transmission lines (d), and energy storage systems (e). The installed cost data for solar PV and wind turbine are extracted from reports issued by the International Renewable Energy Agency (IRENA) (https://www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022). The cost of new transmission lines is based on statistical analyses by the Energy Institute for the Electric Reliability Council of Texas, Inc. (ERCOT) transmission projects (https://energy.utexas.edu/sites/default/files/UTAustin_FCe_TransmissionCosts_2017.pdf). Energy storage cost data come from the U.S. Department of Energy (https://www.pnnl.gov/ESGC-cost-performance). For onshore wind and solar PV, continental averages were calculated based on country-level data from IRENA to reflect regional cost differences. Due to limitations in data availability, global averages of all available records were applied for offshore wind (3,461 USD/kW), energy storage (350 USD/kWh), and onshore transmission (98 million per GW). Considering the difficulty of constructing transoceanic transmission lines, we take the maximum value for the cost of offshore transmission (166.5 million per GW).

Specific comment #4.3

Assumption of Non-Existent Baseload Generation: The simulation models assume no baseload generation, which may not accurately reflect current power grids.

Response: Thank you for your insightful comments on our assumption of non-existent baseload generation. This assumption was intended to explore the possibility of a fully flexible power grid reliant on solar, wind, storage, and transmission. However, we recognize that it does not accurately reflect the current or near-future state of power grids. In this revision, **we have refined the baseload settings and conducted additional analyses to better reflect the reality.**

First, we adjusted the baseload settings to align with the International Energy Agency's (IEA) *Net Zero Emissions by 2050* (NZE) scenario (Table R5). Specifically, baseload generation (including nuclear, geothermal, and unabated fossil fuels) is now set to decline gradually, from 36% in the 2030s to 11% in the 2040s, and further to 9% by the 2050s. The revised ***Trans-regional electricity dispatch* subsection** of the *Methods* section describes this adjustment as follows: "…We categorize power generation units into four types: baseload generation (including nuclear, geothermal, and unabated fossil fuels), real-time solar-wind generation, stored solar-wind generation, and other flexible units (such as hydropower, hydrogen-based, and fossil fuels with CCUS). During electricity dispatch, baseload generation is always prioritized, followed by solar and wind generation (to maximize their penetration), with any remaining gap filled by flexible units. Referring to the IEA's NZE scenario (Supplementary Table S1), we set the share of baseload generation to decline gradually from 36% in the 2030s to 11% in the 2040s and further to 9% by the 2050s…" (Lines 621-628).

Table R5 (also appears as Table S1 in the revised SI). International Energy Agency Net-Zero Emissions by 2050 Roadmap.

	Electricity Generation (TWh)			Shares (%)		
	2030s	**2040s**	**2050s**	**2030s**	**2040s**	**2050s**
Total generation	**37,316**	**56,553**	**71,164**	**100**	**100**	**100**
Renewables	22,817	47,521	62,333	61	84	88
Solar PV	6,970	17,031	23,469	19	30	33
Wind	8,008	18,787	24,785	21	33	35
Hydropower	5,870	7,445	8,461	16	13	12
Bioenergy	1,407	2,676	3,279	4	5	5
Concentrated solar power	204	880	1,386	1	2	2
Geothermal	330	625	821	1	1	1
Marine	27	77	132	0	0	0
Nuclear	3,777	4,855	5,497	10	9	8
Hydrogen-based	875	1,857	1,713	2	3	2
Fossil fuels with CCUS	459	1,659	1,332	1	3	2
Coal with CCUS	289	966	663	1	2	1
Natural gas with CCUS	170	694	669	0	1	1
Unabated fossil fuels	9,358	632	259	25	1	0
Coal	2,947	0	0	8	0	0
Natural gas	6,222	626	253	17	1	0
Oil	189	6	6	1	0	0

Second, we retain the idealized scenario with no baseload generation and introduce an alternative scenario with a baseload share of 9% to assess the impact of baseload generation. Our results indicate that grids with lower baseload proportions have greater flexibility and fault tolerance in development pathways. However, this increased flexibility requires a higher proportion of flexible power sources (e.g., hydropower, hydrogen-based energy, and fossil fuels with CCUS) to maintain grid stability (Fig. R12). These results are presented in **the *Optimal configuration and pathway* subsection** of the revised manuscript as follows: "…In grids with a lower proportion of baseload generation, a wider range of development pathways becomes feasible (Fig. 2e), enhancing flexibility and fault tolerance during system evolution. However, this enhancement necessitates a higher reliance on flexible power sources to maintain grid stability. Under an NZE scenario, where baseload generation is close to zero, the average proportion of flexible power required is approximately 18.7%. From the 2030s to the 2050s, a substantial transition in the electricity supply and consumption structures is anticipated (Figs. 2f–g), reducing reliance on flexible power reserves from 30% to 17% and increasing the share of trans-regional solar-wind power consumption from 15% to 53%." (Lines 220-227).

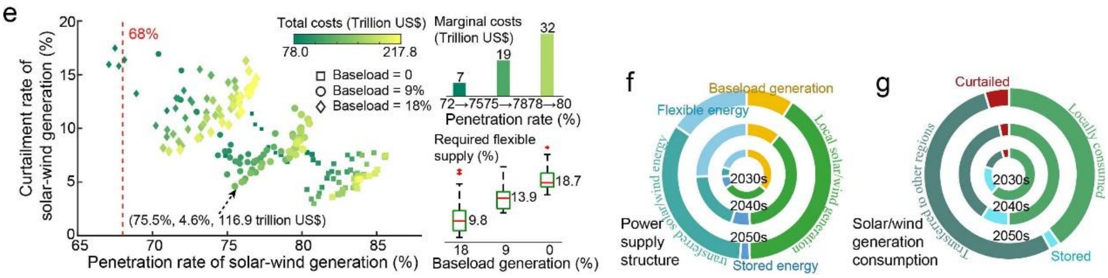


Fig. R12 (also appears as Fig. 2e–g in the revised manuscript). e, Multi-objective optimization results highlighting trade-offs among maximizing penetration, minimizing curtailment, and reducing overall costs. Different symbol shapes indicate the impact of varying baseload generation levels. The insets illustrate the marginal cost of increased penetration and flexible power requirements under different baseload scenarios. **f–g**, Evolution of power supply (**f**) and consumption (**g**) structures under the optimal spatial configuration and development pathway.

Specific comment #4.4

Limited Focus on Environmental Impacts: The study does not thoroughly evaluate the environmental impacts of large-scale deployment.

Response: Thank you for your comments.

We agree with you that evaluating the environmental implications of large-scale solar-wind deployment is crucial for comprehensively assessing its feasibility and sustainability. We recognize this as a key direction for future research. However, this topic does not fit within the scope of this study's focus on the interconnectable potential and optimization of global interconnection. Therefore, we have only emphasized the importance of environmental evaluation **in the *Limitations* subsection of the revised manuscript**: "…Fourth, our analysis primarily focused on the technical and socio-economic benefits without evaluating the potential environmental impacts of large-scale solar-wind deployment[74]...Given these limitations, our analysis should be interpreted as providing foundational insights for conceptualizing and advancing a globally interconnected solar-wind power system. Future research should address these issues, striving to develop more nuanced, feasible, and actionable implementation strategies." (Lines 814-821).

Reviewer #3 (Remarks to the Author):

Comments #1

This paper provides a simple mapping calculation of solar and wind production potentials in comparison with demand. By allowing for ideal global interconnectedness, the authors estimate the potential for global electricity trade and related investments.

Response: Thank you for your insightful comments. We appreciate your recognition of the study's main works and the opportunity to introduce revisions to enhance its practical applicability. Below, we provide a detailed response, structured into **two points.**

First, our research maps solar and wind production potentials in comparison with demand. This work provides an important foundation for us to explore the optimal roadmap for implementing a globally interconnected solar-wind power system. By integrating mapping calculation, generation modeling, and multi-objective optimization, we address critical practical aspects such as solar-wind power plant deployment, storage capacity allocation, and transmission configuration. These efforts address gaps in existing literature, which focuses on proof-of-concept studies or regional analyses. In the revised manuscript, we have **emphasized these advancements to the established literature in the revised *Introduction* section** as follows:

"…Building on these pioneering implementations, recent studies have further explored the potential benefits of global energy interconnection. Brinkerink et al.[23] developed a high-resolution model to simulate globally interconnected power systems, providing initial proof-of-concept results that showcase the viability and additional benefits of integrating European and North American power grids. Similarly, Guo et al.[24] examined the implications of renewable electricity trade facilitated by ultra-high-voltage direct-current (UHVDC) lines, finding that such interconnections could significantly reduce CO_2 emissions and air pollutant levels while offsetting investments in other generation options. While these studies underscore the importance of interconnection strategies, they also highlight gaps in addressing geographic and temporal specifics of resource allocation and utilization. (Lines 61-70).

…Following these pivotal events, the theoretical concept of GEI has evolved to tangible politics and practices[27], with several studies proposing various alternative pathways for its implementation[28-30]. Yet, establishing a globally interconnected solar-wind system oriented towards net-zero emissions still needs to be clarified. Some scenarios proposed for this objective explored renewable energy potentials and national pathways to carbon neutrality, but they represent a macroscopic perspective that lacks essential geographic details[6,8,14,31]. The practical implementation requires a holistic evaluation of various aspects, including the feasibility of delivering PV and wind generation to the grid, the dynamics of demand fluctuations, the balance between supply and demand, the strategic configuration of transmission and storage systems, and comprehensive assessments of costs and benefits[4,13,16,32]." (Lines 78-85).

Second, your comments have prompted us to recognize that an ideal global interconnection is not the best option. Over-idealization would limit our understanding of practical interconnections and affect the utility of our study. In this revision, **we have made efforts to improve our models and scenarios to better align with reality.** Specifically, we take into count existing infrastructure, transmission costs and losses, baseload, and flexible power sources in our optimization framework. We also add an analysis of the resilience of the global interconnected grid under extreme conditions. More details are provided below:

1) Incorporating real-world constraints: Current wind, solar, storage, and transmission capacities (Table R6) are incorporated into the optimization model as initial conditions to ensure alignment with ongoing plans. This adjustment is described in the revised ***Multi-objective problem definition*** **subsection** of the *Methods* section as follows: "…The decision variables—$\mathbf{I}_s$, $\mathbf{I}_w$, $\mathbf{P}_s$, $\mathbf{V}_s$, and $\mathbf{P}_t$—are subject to their current states (Supplementary Table S4) to ensure that the optimized future configuration keeps compatible with ongoing or planned efforts. Specifically, the designed capacities for solar, wind, or storage in each regional grid should exceed existing installed capacities, and the transmission power for each connection should surpass the current capacity." (Lines 578-583).

Table R6 (also appears as Table S4 in the revised SI). Current states of regional solar, wind and storage capacities, as well as existing trans-regional transmission projects.

Regions	Wind (MW)	Solar (MW)	Storage (MW)	Transmission (MW)
01	165,009	143,609	19,107	1840 (01→02)
02	8,644	12,825	6	1,500 (02→01), 400 (02→04)
03	10,857	13,406	0	0
04	39,785	49,076	974	400 (04→02)
05	72,524	27,172	3,652	22,815 (05→06), 1,600 (05→08)
06	110,807	147,453	10,329	22,815 (06→05), 23,375 (06→07), 9,800 (06→08), 2,000 (06→16)
07	56,193	71,890	8,584	23,375 (07→06), 9,353 (07→08), 3,260 (07→11), 7,250 (07→16)
08	18,449	40,239	7,661	2,100 (08→05), 9,300 (08→06), 10,880 (08→07), 350 (08→09),1,295 (08→10), 3,950 (08→11)
09	1,441	1,555	0	350 (09→08), 4,380 (09→12)
10	451,717	734,202	80,139	1,295 (10→08), 50 (10→12), 2,158 (10→13)
11	13,440	29,577	540	3,260 (11→07), 3,950 (11→08), 3,860 (11→12), 5,800 (11→16)
12	47,215	74,017	5,825	3,630 (12→09), 50 (12→10), 3,860 (12→11), 3 (12→13)
13	8,006	25,748	1,296	2,158 (13→10), 3 (13→12)
14	72	324	0	0
15	13,970	32,972	810	0
16	4,003	3,084	464	2,000 (16→06), 12,250 (16→07), 5,800 (16→11), 4,182 (16→19)
17	297	901	0	0
18	1.1	374	0	997 (18→09), 600 (18→20)
19	905	1,188	0	4,182 (19→16), 997 (19→08), 7,185 (19→20)
20	3,447	5,846	2,732	600 (20→18), 7,185 (20→19)

*The numbers in the first column correspond to Supplementary Fig. S4a. Data on installed capacities for solar, wind, and storage (primarily pumped storage) are sourced from the *Renewable Energy Statistics 2024* report issued by IRENA (https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024). Trans-regional transmission capacities are based on the study by Brinkerink et al.[76], with the numbers representing the maximum transmission power and the contents in parentheses indicating the starting and ending regions of the transmission routes. Please note that the transmission is directional.

2) Accounting for transmission costs: We refine the optimization framework to explicitly include transmission investments in the cost calculation. This refinement is described in the revised ***Multi-objective problem definition*** **subsection** of the *Methods* section as follows: "In our analysis, we account for the construction costs of deploying solar, wind, storage, and transmission infrastructures. The total investment costs are encapsulated by the equation:

$$T_{inv} = \sum_{i=1}^{13296} \xi_{sol} I_s^i C_s^i + \xi_w \sum_{i=1}^{8477} \xi_w I_w^i C_w^i + \xi_{sto} \sum_{i=1}^{20} V_s^i + \xi_{tran} \sum_{i=1}^{42} P_t^i \quad (8)$$

Here, C_s and C_w correspond to the maximum installation capacities for solar and wind facilities within each grid-box. The terms ξ_{sol}, ξ_w, ξ_{sto}, and ξ_{tran} denote the unit costs of installing solar panels, wind turbines, storage facilities, and new transmission projects, respectively (see Supplementary Fig. S8) ..." (Lines 584-590).

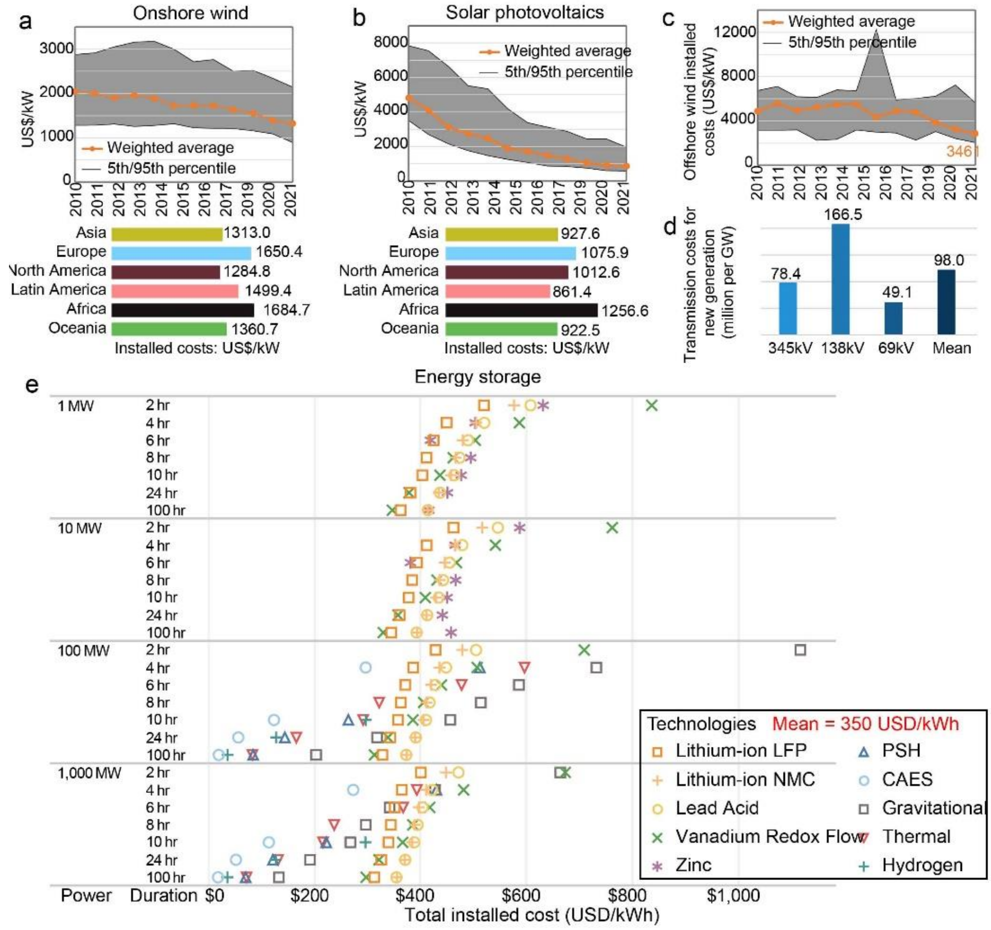


Fig. R13 (also appears as Fig. S8 in the revised SI). Pricing benchmarks for deployment of onshore wind turbines (a), solar PV (b), offshore wind turbines (c), new transmission lines (d), and energy storage systems (e). The installed cost data for solar PV and wind turbine are extracted from reports issued by the International Renewable Energy Agency (IRENA) (https://www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022). The cost of new transmission lines is based on statistical analyses by the Energy Institute for the Electric Reliability Council of Texas, Inc. (ERCOT) transmission projects (https://energy.utexas.edu/sites/default/files/UTAustin_FCe_TransmissionCosts_2017.pdf). Energy storage cost data come from the U.S. Department of Energy (https://www.pnnl.gov/ESGC-cost-performance). For onshore wind and solar PV, continental averages were calculated based on country-level data from IRENA to reflect regional cost differences. Due to limitations in data availability, global averages of all available records were applied for offshore wind (3,461

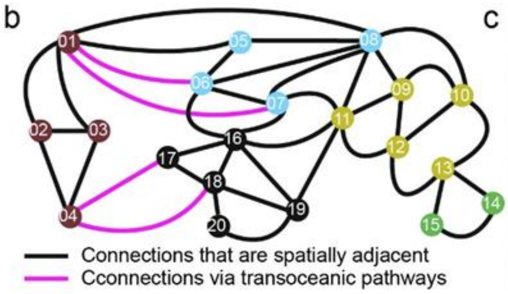
USD/kW), energy storage (350 USD/kWh), and onshore transmission (98 million per GW). Considering the difficulty of constructing transoceanic transmission lines, we take the maximum value for the cost of offshore transmission (166.5 million per GW).

3) Refining electricity dispatch model: Baseload and flexible power sources are included in the dispatch model, with their proportions adjusted over time to reflect realistic grid dynamics. This adjustment is described in the revised ***Trans-regional electricity dispatch*** **subsection** of the *Methods* section as follows: "…We categorize power generation units into four types: baseload generation (including nuclear, geothermal, and unabated fossil fuels), real-time solar-wind generation, stored solar-wind generation, and other flexible units (such as hydropower, hydrogen-based, and fossil fuels with CCUS). During electricity dispatch, baseload generation is always prioritized, followed by solar and wind generation (to maximize their penetration), with any remaining gap filled by flexible units. Referring to the IEA's NZE scenario (Supplementary Table S1), we set the share of baseload generation to decline gradually from 36% in the 2030s to 11% in the 2040s and further to 9% by the 2050s…" (Lines 621-628).

Table R7 (also appears as Table S1 in the revised SI). International Energy Agency Net-Zero Emissions by 2050 Roadmap.

	Electricity Generation (TWh)			Shares (%)		
	2030s	**2040s**	**2050s**	**2030s**	**2040s**	**2050s**
Total generation	**37,316**	**56,553**	**71,164**	**100**	**100**	**100**
Renewables	22,817	47,521	62,333	61	84	88
Solar PV	6,970	17,031	23,469	19	30	33
Wind	8,008	18,787	24,785	21	33	35
Hydropower	5,870	7,445	8,461	16	13	12
Bioenergy	1,407	2,676	3,279	4	5	5
Concentrated solar power	204	880	1,386	1	2	2
Geothermal	330	625	821	1	1	1
Marine	27	77	132	0	0	0
Nuclear	3,777	4,855	5,497	10	9	8
Hydrogen-based	875	1,857	1,713	2	3	2
Fossil fuels with CCUS	459	1,659	1,332	1	3	2
Coal with CCUS	289	966	663	1	2	1
Natural gas with CCUS	170	694	669	0	1	1
Unabated fossil fuels	9,358	632	259	25	1	0
Coal	2,947	0	0	8	0	0
Natural gas	6,222	626	253	17	1	0
Oil	189	6	6	1	0	0

4) Modeling transmission losses: Transmission losses are modeled as a proportion of power transmitted over each transmission line, increasing as a function of distance. This improvement is detailed in the revised ***Trans-regional electricity dispatch*** **subsection**: "…According to the Energy Technology Systems Analysis Program (ETSAP) of the IEA, long-distance transmission losses on land are about 3% per 1,000 kilometers for high-voltage direct-current (HVDC) lines, and about 7% per 1,000 kilometers for high-voltage alternating-current (HVAC) lines[64]. For sea cables, HVDC losses are similar, but HVAC losses can reach 60% per 100 kilometers. Here, we assume a 50/50 split between HVDC and HVAC on land, while HVDC dominates for cross-sea transmission. As a result, transmission losses are calculated at 5% per 1,000 kilometers on land and 3% per 1,000 kilometers at sea. The centroid of each regional grid is used to calculate the average distances between grids, forming the transmission loss matrix shown in Supplementary Fig. S4c. When surplus power exists in any one grid, a path-finding algorithm identifies all potential transmission routes based on the network topology (Supplementary Fig. S4b), where each grid acts as a node." (Lines 637-647).



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0	0.19	0.23	0	0.20	0.20	0.22	0.35	0	0	0	0	0	0	0	0	0	0	0	0
0.19	0	0.13	0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.23	0.13	0	0.21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.30	0.21	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22	0.27	0	0
0.20	0	0	0	0	0.14	0	0.24	0	0	0	0	0	0	0	0	0	0	0	0
0.20	0	0	0	0.14	0	0.05	0.26	0	0	0	0	0	0	0	0.13	0	0	0	0
0.22	0	0	0	0	0.05	0	0.29	0	0	0.17	0	0	0	0	0.10	0	0	0	0
0.35	0	0	0	0.24	0.26	0.29	0	0.12	0.14	0.26	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0.12	0	0.17	0.14	0.10	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0.14	0.17	0	0	0.17	0.17	0	0	0	0	0	0	0
0	0	0	0	0	0	0.17	0.26	0.14	0	0	0.14	0	0	0	0.14	0	0	0.19	0
0	0	0	0	0	0	0	0	0.10	0.17	0.14	0	0.23	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.17	0	0.23	0	0.23	0.24	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.23	0	0.13	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.24	0.13	0	0	0	0	0	0
0	0	0	0	0	0.13	0.10	0	0	0	0.14	0	0	0	0	0	0.10	0.13	0.19	0
0	0	0	0.22	0	0	0	0	0	0	0	0	0	0	0	0.10	0	0.14	0	0
0	0	0	0.27	0	0	0	0	0	0	0	0	0	0	0	0.13	0.14	0	0.10	0.14
0	0	0	0	0	0	0	0	0	0	0.19	0	0	0	0	0.19	0	0.10	0	0.14
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0.14	0

Fig. R14 (also appears as Fig. S4b-c in the revised SI). b, Topological network of the spatial connections between the 20 regional grids, where black lines indicate spatial adjacency while purple lines represent connection via transoceanic pathways. In the S-I scenario (regionally independent), the 20 grids are independent, without trans-regional power exchange. In the S-A scenario (adjacent interconnections), spatially adjacent grids are interconnected, enabling trans-regional power transmission along the black connections. In the S-C scenario (continental interconnections), grids within the same continent are fully interconnected, while grids on different continents connect through an intermediate grid that is spatially adjacent to both. The S-G scenario (global interconnections) introduces four transoceanic pathways (purple lines) and permits any two grids to interconnect without constraints on the number of intermediate nodes. **c,** Transmission loss matrix corresponding to the network in (**b**), where the element in row *i* and column *j* represents the relative transmission loss between grid *i* and grid *j*. On land, losses over long distances are about 3% per 1,000 kilometers for high-voltage direct-current (HVDC) lines and about 7% per 1,000 kilometers for high-voltage alternating-current (HVAC) lines[64]. For HVDC sea cables, losses are similar but can reach 60% per 100 km for HVAC sea cables. Here, we assume a 50/50 split between HVDC and HVAC on land, with HVDC dominating at sea. Therefore, losses are calculated based on 5% per 1,000 km on land and 3% per 1,000 km over sea routes. In our power dispatch simulations, a network path search algorithm identifies all possible routes between two grids, prioritizing the least-cost path or multiple paths (depending on the required transmission power and the capacity of each route) for actual power flow.

5) Conducting resilience analysis: Stress tests were introduced to assess system performance under extreme conditions, providing insights into the potential risks of a globally interconnected solar-wind system. These tests address five key scenarios: climate change, extreme weather events, incompatible regional policies, geopolitical tensions, and market competition. These stress tests are detailed in **the *Stress tests* subsection** of the revised *Methods* section as follows: "**Stress tests.** To evaluate the resilience and reliability of a globally interconnected power system, we conducted stress tests under extreme or unforeseen conditions, including climate change, extreme weather events, incompatible regional policies, geopolitical tensions, and market competition. Based on the optimal configurations identified for the S-G scenario, we introduced targeted stressors and assessed their impacts by observing the resulting changes in regional or global electricity supply dynamics…" (Lines 765-770). The results of stress tests are presented **in the new subsection *Resilience of a***

globally interconnected system of the revised *Results* section as follows:

"…Our simulations show that uncertainties in global power supply associated with changes in solar radiation (±5%)[43], wind speed (±2%)[4], and electrical loads (±10%)[34] remain consistently below 0.1% within the interconnected grid (Fig. 4a). Notably, these uncertainties decrease as the degree of interconnection increases. Extreme weather events—exemplified by the 2021 Texas Winter Storm—pose significant threats to power supply[44] by triggering frequent and severe regional generation failures. The globally interconnected grid exhibits exceptional robustness in addressing such disruptions. Under the S-G scenario, the decline in solar-wind electricity supply caused by the complete outage of a single regional grid averages only 2.6% (ranging from 0.7% to 11.7%), compared to declines of 5.8%, 15.1%, and 26.4% under the S-C, S-A, and S-I scenarios, respectively (Fig. 4b) ... (Lines 318-327).

However, the globally interconnected power system remains susceptible to disruptions from incompatible regional policies, geopolitical tensions, and aggressive market competition. For instance, economically advanced nations may prioritize energy self-sufficiency, particularly in response to geopolitical crises like the Russia-Ukraine conflict, which has heightened concerns over energy independence[45]. Our analysis indicates that such self-sufficiency strategies—resembling the S-I scenario—drive overexploitation of solar and wind resources (Table 1), undermining the global electricity supply balance enabled by optimized interconnection. The resulting imbalance exerts widespread impacts. Specifically, policy incompatibilities in southern Asia, western Asia, northern Africa, and eastern Asia lead to the largest increases in solar-wind curtailment. In contrast, those in northern America, southern Asia, eastern Asia, and southern America cause the most significant declines in demand for alternative energy sources (Fig. 4c). In an extreme scenario where all regional grids adopt self-sufficiency prioritization strategies, absolute increases in curtailment (reductions in demand) would reach 34.6% (13.5%). (Lines 330-342).

Geopolitical tensions[46] further threaten the stability of transmission nodes and lines that underpin global interconnections. Failures at generation hubs like northern America, southern America, and Australia, or demand centers like eastern Asia, southern Asia, and southeastern Asia would sharply increase global solar-wind curtailment and reduce penetration (Fig. 4d). By contrast, nodes like northern Africa and western Asia, which primarily serve as transregional transmission bridges exhibit relatively localized impacts when disrupted individually due to rerouting flexibility[27] in the interconnected grid. In an extreme scenario of a complete grid collapse, global solar-wind curtailment (penetration) would rise (drop) by an absolute 41.2% (22.9%). Although individual line failures generally have minimal global impacts, with changes in penetration or curtailment remaining below 1% (Supplementary Fig. S10), regions heavily reliant on external power supplies are particularly susceptible to such disruptions (Fig. 4e). For example, a disruption in the connection between eastern Asia and eastern Europe would create a supply gap of nearly 15% for eastern Asia, and severing all transmission lines into eastern Asia would double this deficit. Furthermore, regions not directly connected to disruptions can still experience adverse effects through aggressive market competition (Fig. 4e). In Melanesia, for instance, if eastern Asia and southern Asia offered 1.6 times the baseline price to secure priority access to surplus power from Australia and southeastern Asia, Melanesia would face a supply gap exceeding 20%. These findings underscore the importance of coordinated global planning, stable geopolitical environments, and equitable market conditions to ensure the long-term reliability and resilience of a globally interconnected power system[27,28]." (Lines 343-361).

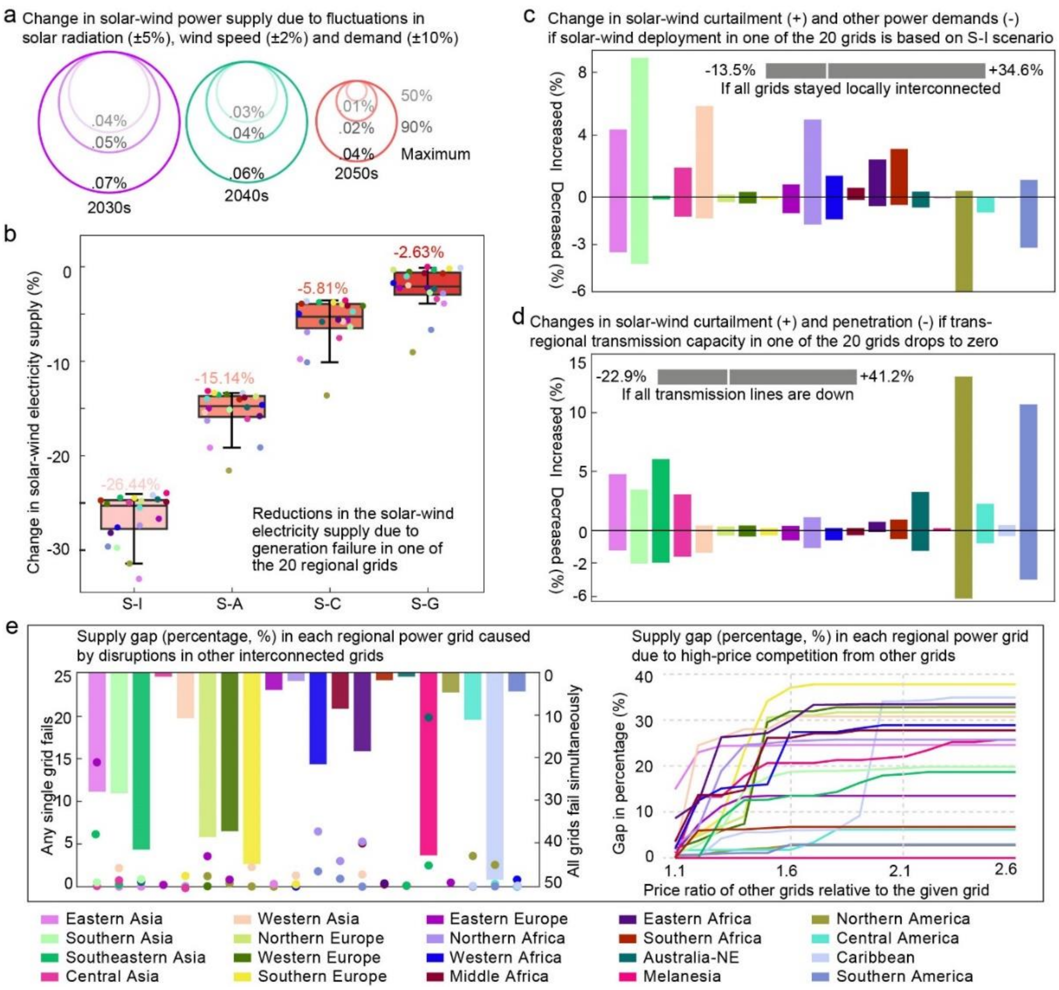

Fig. R15 (also appears as Fig. 4 in the revised manuscript. Resilience of a globally interconnected system to extreme or unforeseen conditions. a, Impact of climate-induced variations in power generation and demand on solar-wind penetration at different stages. Maximum, 90th, and 50th percentiles of changes observed across 10,000 simulations are presented. **b**, Reduction in global solar-wind penetration under S-I, S-A, S-C, and S-G scenarios when one of the 20 regional grids experiences a complete outage. Each circle represents the grid experiencing the outage. **c**, Changes in solar-wind curtailment and alternative energy supplies when one of the 20 regional grids (denoted by bar colors) deploys solar-wind resources based on the S-I scenario. The horizontal gray inset illustrates the extreme case where all 20 grids remain locally interconnected. **d**, Changes in global solar-wind curtailment and penetration when all transmission lines associated with a single regional grid (denoted by bar colors) are disrupted. The horizontal gray inset depicts the extreme scenario where all transmission lines fail simultaneously. **e**, Power supply gaps resulting from supply interruptions from interconnected grids (left panel) and aggressive market competition (right panel). Circles represent scenarios of a single grid disruption, while bars indicate simultaneous disruptions across all interconnected grids. Circle colors denote disrupted grids, while bar colors indicate affected grids. The colors of circles in (**b**) and (**e**), bars in (**c**), (**d**), and (**e**), and lines in (**e**) correspond to the legend at the bottom.

Despite these efforts, we recognize some limitations in our analysis. These limitations are summarized **in the *Limitations* subsection of the revised *Methods* section**. We hope that these improvements will meet with your approval. Thank you again for your constructive comments.

Comments #2

This is an oddly simple back-of-the-envelope paper, in a field where multiple detailed model studies exist. The authors do not even cite the modeling studies such as Brinkerink et al., 2018 (https://www.sciencedirect.com/science/article/pii/S2096511718300446) and Guo et al., 2022 (https://www.nature.com/articles/s41560-022-01136-0).

Response: Thank you for bringing the two modeling studies to our attention. We acknowledge that global interconnection is not a novel concept introduced in this study, and numerous prior works, including the two you mentioned—Brinkerink et al., 2018 and Guo et al., 2022—have explored this topic from various perspectives. We sincerely apologize for the oversight in not citing these key references in our original manuscript. In the revised manuscript, **we have incorporated these studies into the *Introduction* section and have briefly evaluated their contributions** as follows: "…recent studies have further explored the potential benefits of global energy interconnection. Brinkerink et al.[23] developed a high-resolution model to simulate globally interconnected power systems, providing initial proof-of-concept results that showcase the viability and additional benefits of integrating European and North American power grids. Similarly, Guo et al.[24] examined the implications of renewable electricity trade facilitated by ultra-high-voltage direct-current (UHVDC) lines, finding that such interconnections could significantly reduce CO_2 emissions and air pollutant levels while offsetting investments in other generation options..." (Lines 62-68).

We would also like to emphasize the additional values of our study compared to previous studies. We seek to build upon previous research and take a step further by providing a detailed roadmap for implementing a globally interconnected solar-wind power system. By integrating potential mapping, power generation modeling, and multi-objective optimization, we aim to tackle critical practical aspects such as solar and wind plant deployment, storage capacity allocation, and transmission configuration. We have emphasized these points **in the revised *Introduction* section** as follows: "To address the existing geographic and temporal gaps[4,7,32,33], we integrate high-resolution spatial (500-meter) and temporal (hourly) data to comprehensively evaluate the global potential of solar and wind energy regarding their exploitability, accessibility, and interconnectability. We develop a multi-objective optimization framework to identify cost-effective and resource-efficient interconnection strategies that balance investment costs, renewable energy penetration, and power curtailment. Here, we outline an optimized, phased pathway to establish a globally interconnected solar-wind power system, and provide valuable insights into the spatial distribution and deployment timeline of solar-wind power plants, the allocation of storage and transmission capacities, and potential benefits and risks of global interconnection. Our work advances a more nuanced understanding of global energy interconnection and offers a concrete pathway to realize this vision." (Lines 86-95).

Comments #3

The method ignores the techno-economic aspects of the power system outside the solar/wind/interconnection system (e.g. competition of GEI with fossil power generation, competition of GEI with storage or PtX options, the role of demand side responses) that the more advanced studies in this field have explored.

Response: Thank you for your insightful comments regarding other techno-economic aspects. We agree that these aspects are essential in comprehensively evaluating GEI's feasibility and economic viability. Below, we provide a detailed response, structured into **two points.**

First, we would like to explain **the reasons for simplifying certain techno-economic aspects.** Our core objective is to explore the practical pathway towards net-zero emissions (NZE) through a globally interconnected solar-wind system, providing geographic and temporal details of solar-wind plant deployment, storage capacity allocation, and transmission configuration. To isolate and focus on the key issues of global interconnection optimization, we simplified the competition with fossil generation, Power-to-X (PtX) technologies, and demand-side responses. Additionally, our scenario is benchmarked against the solar-wind penetration targets proposed by the International Energy Agency, which are considered prerequisites for achieving NZE. While fossil generation and other factors may influence specific deployments, they do not alter the renewables-dominated NZE future. Therefore, these simplifications do not affect the overarching conclusions of this study.

In the revised manuscript, we have **included an explanation in the *Multi-objective problem definition* subsection** of the revised *Methods* section as follows: "…It is emphasized that our optimization framework assumes a high penetration of solar and wind energy as a central goal under the premise of a global commitment to decarbonization. While competition from fossil-fueled generation with CCUS, PtX technologies, and demand-side responses may influence the specific configuration of global interconnections, they do not change the overarching conclusion of a renewable energy-dominated NZE future. Therefore, simplifying these factors does not affect the main outputs of the optimization framework. Instead, this simplification allows us to focus on isolating and addressing the key issues associated with optimizing global interconnections." (Lines 597-604). We have also **highlighted the primary focus of this study** in the revised *Introduction* section as follows: "To address the existing geographic and temporal gaps[4,7,32,33], we integrate high-resolution spatial (500-meter) and temporal (hourly) data to comprehensively evaluate the global potential of solar and wind energy regarding their exploitability, accessibility, and interconnectability. We develop a multi-objective optimization framework to identify cost-effective and resource-efficient interconnection strategies that balance investment costs, renewable energy penetration, and power curtailment. Here, we outline an optimized, phased pathway to establish a globally interconnected solar-wind power system, and provide valuable insights into the spatial distribution and deployment timeline of solar-wind power plants, the allocation of storage and transmission capacities, and potential benefits and risks of global interconnection. Our work advances a more nuanced understanding of global energy interconnection and offers a concrete pathway to realize this vision." (Lines 86-95).

Second, we discuss the important role of broader technologies in enhancing the feasibility of global interconnections. For example, demand-side responses such as load shifting and energy efficiency improvements could reduce reliance on storage systems. PtX technologies and large-scale storage solutions offer additional ways to address the intermittency of renewable energy. These options can serve as valuable complements to interconnection strategies. In the revised manuscript, we have **added these extended analyses** in the *Discussion* section as follows: "…These characteristics reinforce both the attractiveness and practical feasibility of global interconnection. In addition, we recognize the critical role of broader technological options in shaping its feasibility. Fossil generation with carbon capture, utilization, and storage (CCUS), Power-to-X (PtX) technologies, and demand-side solutions such as dynamic load management and energy efficiency improvements, provide essential flexibility to accommodate the intermittency of renewable energy. This increased flexibility broadens the range of pathways for achieving multi-objective optimization

(Fig. 2e). The synergy between global interconnection and these complementary options has the potential to further reduce infrastructure requirements and investment costs, unlocking additional benefits in the transition to a renewable energy-dominated future." (Lines 409-417). We have also **highlighted this point as a key direction for future research** in the *Limitations* subsection of the revised *Methods* section as follows: "…Third, our optimization framework does not explicitly model the competition between global interconnections and fossil fuel generation, storage, or PtX technologies, nor does it incorporate demand-side responses. These aspects are critical for a holistic evaluation of global interconnection strategies, and their inclusion in future studies could provide deeper insights into the techno-economic trade-offs and feasibility of global interconnections." (Lines 809-813).

Comments #4

Also, the details of the grid requirements are not taken into account (e.g. becomes the world one large load balancing area or are these interconnections only for specific bottlenecks).

Response: Thank you for your insightful comments. In this revision, we have made significant updates to address your concerns. Below, we provide a detailed response, structured into **two points.**

First, our baseline scenario assumes a phased approach to global interconnection, with interconnections initially addressing regional bottlenecks and then the world gradually becoming one large load-balancing area. This approach accounts for the varying levels of interconnectivity and grid development in different regions. For instance, in highly interconnected regions like Europe, the main task of interconnection is to address specific bottlenecks. Conversely, in less developed regions, such as Africa, interconnections must address both internal load balancing and regional power exchange. In the revised manuscript, we have **clarified this phased approach in the *Development scenarios* subsection** of the *Methods* section as follows: "…Therefore, our baseline scenario assumes a phased approach to global energy interconnections, with interconnections initially designed to address regional bottlenecks and then gradually transitioning to a unified global load-balancing framework. Specifically, we envision a transition from S-A in the 2030s to S-C in the 2040s, culminating in S-G by the 2050s…" (Lines 730-734). Additionally, we have emphasized the regional disparities toward global interconnection in the **revised *Discussion* section** as follows: "…Investment allocation should also account for regional disparities in interconnection and grid development. For example, in Europe, the primary focus is on resolving specific bottlenecks to optimize power sharing and reduce curtailments[30]. Conversely, less connected regions, such as parts of Africa and Central Asia, face the dual challenge of enhancing cross-regional interconnections while simultaneously improving internal load balancing to stabilize their grids. Accelerating the interconnection process is strongly recommended, as higher interconnection levels reduce the grid's reliance on energy storage (Figs. 2c) and maximize the advantages of prioritizing transmission infrastructure over large-scale storage solutions (Fig. 3a)." (Lines 427-434).

Second, we have made efforts to incorporate details of grid requirements into the refined model, including existing infrastructure, baseload generation and flexible power sources, as well as transmission losses. More details are presented in the following:

1) Existing infrastructure: Current wind, solar, storage, and transmission capacities (see **Table R6** for details) were incorporated into the optimization model as initial constraints. This is clarified in the revised *Multi-objective problem definition* subsection of the *Methods* section as follows: "…The decision variables—$\mathbf{I}_s$, $\mathbf{I}_w$, $\mathbf{P}_s$, $\mathbf{V}_s$, and $\mathbf{P}_t$—are subject to their current states (Supplementary Table S4) to ensure that the optimized future configuration keeps compatible with ongoing or planned efforts. Specifically, the designed capacities for solar, wind, or storage in each regional grid should exceed existing installed capacities, and the transmission power for each connection should surpass the current capacity." (Lines 578-583).

2) Baseload and flexible sources: The electricity dispatch model incorporates baseload generation (e.g., nuclear, geothermal) and flexible power sources (e.g., hydropower, CCUS-based systems) with time-varying shares to reflect future grid dynamics (see **Table R7** for details). This adjustment is detailed in the revised *Trans-regional electricity dispatch* subsection of the *Methods* section as follows: "…We categorize power generation units into four types: baseload generation (including nuclear, geothermal, and unabated fossil fuels), real-time solar-wind generation, stored solar-wind generation, and other flexible units (such as hydropower, hydrogen-based, and fossil fuels with CCUS). During electricity dispatch, baseload generation is always prioritized, followed by solar and wind generation (to maximize their penetration), with any remaining gap filled by flexible units. Referring to the IEA's NZE scenario (Supplementary Table S1), we set the share of baseload generation to decline gradually from 36% in the 2030s to 11% in the 2040s and further to 9% by the 2050s… Conversely, when a grid's solar-wind generation is insufficient to meet demand, the shortage is first compensated by surplus from interconnected grids, then by stored solar-wind generation, and finally, if needed, by other flexible reserves." (Lines 621-633).

3) Transmission losses: Transmission losses are modeled as a proportion of power transmitted over each transmission line, increasing as a function of distance. A loss matrix (see **Fig. R14** for details) is incorporated into the transregional dispatch model and a path-finding algorithm is applied to select the most cost-effective transmission routes. These adjustments are described in the revised *Trans-regional electricity dispatch* subsection of the *Methods* section as follows: "... As a result, transmission losses are calculated at 5% per 1,000 kilometers on land and 3% per 1,000 kilometers at sea. The centroid of each regional grid is used to calculate the average distances between grids, forming the transmission loss matrix shown in Supplementary Fig. S4c. When surplus power exists in any one grid, a path-finding algorithm identifies all potential transmission routes based on the network topology (Supplementary Fig. S4b), where each grid acts as a node...Transmission losses for each route are calculated as the sum of losses from all sub-connections, and the least costly routes are prioritized for electricity transmission…" (Lines 642-653).

Third, we acknowledge the importance of further detailed analyses of grid requirements, including balancing mechanisms, frequency regulation, and the coordination of regional and global grids. These aspects will enable a deeper understanding of how GEI can transition from resolving specific bottlenecks to functioning as a unified global load balancing system. In the ***Limitations* section** of the revised *Methods* section, we explicitly note: "…Fifth, future research should integrate detailed grid requirements, including balancing mechanisms, frequency regulation, and regional coordination, to fully evaluate the operational feasibility of transitioning from regional bottleneck resolution to a unified global load-balancing system…" (Lines 816-818).

We hope these revisions address your concerns and meet with your approval. Once again, thank you for your valuable feedback, which has significantly contributed to improving the quality of our manuscript.

Dear Reviewers,

We greatly appreciate your insights and constructive feedback on our manuscript titled "**Globally Interconnected Solar-wind System Addresses Future Electricity Demands**". We have carefully considered each comment and have made corresponding revisions to the manuscript. Below, we provide a point-by-point response to each comment. Changes to the manuscript text are highlighted in red in the revised document, and our responses to the comments are noted in blue below for clarity. Please note that the line numbers refer to the version with accepted revisions (no revision marks) that was uploaded into the system.

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

General Comment

The paper is much improved. The authors made a noticeable and serious effort to address my comments as best as possible within the boundaries of their model and purpose of the paper. I especially commend the new resilience section, scenario elaboration, and the added workflow chart. The latter will aid greatly in appealing to a larger audience, even though it is not in the main text itself. The many clarifications throughout add up as well. Despite understandable limitations, there is clear value in what the paper does.

Response: We sincerely appreciate your positive feedback and recognition of our efforts to improve the manuscript. Your previous constructive comments greatly contributed to refining our work, and we are pleased that the revisions have enhanced the clarity and broader relevance of the study.

Comments #1

While I consider the paper ok as is, I would also not mind a clearer statement of the paper's objective in the introduction. The abstract reads "we demonstrate the potential of a globally interconnected solar-wind system to address future electricity demands." Something this explicit is missing in the introduction. It would just be about adding a sentence that sums it up: This paper aims to / shows …". The current one at lines 86-88 just does not quite do it.

Response: Thank you for your valuable suggestion. We have revised these lines to explicitly state the study's objective, ensuring better alignment with the abstract. The revised sentences now state "To address the existing geographic and temporal gaps[4,7,32,33], this study investigates the feasibility and benefits of a globally interconnected solar-wind system in addressing future electricity demands. We integrate high-resolution spatial (500-meter) and temporal (hourly) data to comprehensively evaluate the global potential of solar and wind energy regarding their exploitability, accessibility, and interconnectability." (Lines 92-96).

Comments #2

I would also simply replace the wording of 'equitable energy access' with that of energy availability, to avoid the connotations usually associated with the term access in energy access and equity literature, which the paper does not quite cover.

Response: Thank you for your careful consideration of terminology. We agree that "energy availability" is a more appropriate term in this context to avoid unintended connotations related to energy access and equity. We have replaced "equitable energy access" with "energy availability" throughout the manuscript.

Comments #3

If possible, a few final words by the authors that sum up the core findings in the text (like in the abstract) and then interpret them for science and society/policy, would also be appreciated. The discussion sticks very close to the model, but it is left to the reader to interpret the broader implications of the findings. None of these three comments need delay the review process, but they would be a welcome addition.

Response: Thank you for your insightful suggestions. In this revision, we have added a short summary of the core findings to the final paragraph of the **Discussion** section. Additionally, we have explicitly interpreted the broader scientific and policy implications of these findings. The added paragraph reads: "In summary, our findings underscore the substantial potential of a globally interconnected solar-wind system to enhance energy availability and grid stability on a global scale. By leveraging the spatiotemporal complementarity of renewable resources, such a system can bolster electricity supply resilience and reduce dependence on fossil fuels. Our results contribute to the ongoing discourse on large-scale renewable energy integration by quantifying the interconnectable potential of solar and wind resources and identifying optimal pathways for trans-regional power exchange. From a policy perspective, these findings highlight the critical role of international collaboration and strategic infrastructure investment in accelerating the transition toward a low-carbon, resilient energy future." (Lines 432-439).

Reviewer #2 (Remarks to the Author):

Comments #1

I commend the authors for significantly enhancing the technical rigor of their analysis. The inclusion of stress tests, which simulate the system's performance under challenging conditions like extreme weather events and geopolitical tensions, demonstrates a commendable effort to consider real-world vulnerabilities and uncertainties. This approach effectively captures the stochastic nature of renewable energy resources and the potential for disruptions in a globally interconnected grid. Furthermore, the incorporation of regional cost variations for solar and wind deployment, accounting for factors such as levelized cost of energy (LCOE) differentials, adds a layer of nuance and accuracy to the data analysis, reflecting the complexities of global energy markets.

Response: Thank you for your encouraging feedback. The incorporation of stress tests and regional cost variations was aimed at providing a more realistic and refined assessment of system resilience and economic feasibility. We appreciate your recognition of these additions and are pleased that they enhance the depth and applicability of our analysis.

Comments #2

The improved documentation of baseload and flexible power sources, particularly the integration with the IEA's Net Zero Emissions (NZE) scenario, strengthens the study's applicability to real-world energy transition pathways.

Response: Thank you for your positive feedback. We appreciate your recognition of our revisions and their contribution to strengthening the study's applicability.

Comments #3

Furthermore, the comprehensive description of computational methods for trans-regional interconnections, including explicit descriptions of the algorithms and parameters used, enhances the reproducibility of the study. The clear presentation of assumptions and limitations, along with the inclusion of sensitivity analyses exploring the impact of key parameters, strengthens the robustness of the findings and allows for a more nuanced interpretation of the results within the context of the study's scope.

Response: Thank you for your positive feedback. We appreciate your recognition of the enhanced reproducibility of our methodology and the improved robustness of our findings.

Reviewer #3 (Remarks to the Author):

General Comment

The authors have revised the paper in response to the review comments in a truly impressive fashion. The manuscript is now much clearer about the goal and limitations of the work and where it contributes beyond the existing literature. The stronger focus on the modeling work really shows the added value much stronger than the earlier version of the paper.

While reading the text, I had three main comments that eventually were addressed later in the text or in the Methods section, but that would be good to address earlier on:

Response: Thank you for your encouraging feedback. We appreciate your recognition of the improvements in clarity, modeling focus, and contribution beyond the existing literature. Regarding your suggestion to clarify certain aspects earlier in the manuscript, we recognize the importance of guiding the reader more effectively. We have carefully considered these comments and made adjustments where appropriate. Please see below for a detailed response.

Comments #1

The first few pages only discuss solar and wind, but do not mention hydro at all, even though this is also widely considered a major contributor to non-biomass renewable energy and flexible technology that is complementary with intermittent renewables. Also, the main paper barely mentions that the model evaluates solar and wind in the context of the full power system, leaving the question to be answered in the Methods section. Around Line 624, the four generation categories are described, but it remains unclear whether the technologies mentioned in these categories are resolved in the model or whether these four categories are treated a aggregate characteristic power generation options.

Response: Thank you for your insightful comments. To address these concerns, we have made the following **three clarifications** in the manuscript.

First, we have introduced hydropower earlier in the Introduction, recognizing it as a major non-biomass renewable energy source and a flexible technology that complements wind and solar generation. The revised text in the first and second paragraphs of the section Introduction states: "…Stakeholders have explored myriad avenues for a sustainable energy transition, relying primarily on the expansive deployment of PV and wind plants[6-8]. While **hydropower** remains a key non-biomass renewable energy source, its large-scale expansion is constrained by geographic and environmental factors. Consequently, it is often regarded as a flexible resource that complements the variability of wind and solar power[6] (Lines 43-47) …Currently, regional power systems incorporating intermittent energy sources are heavily reliant on energy storage systems and **flexible generation sources, such as hydropower**, for peak shaving and load leveling amidst generation-demand mismatches[11]…" (Lines 51-53).

Second, we have explicitly stated in the final paragraph of the Introduction and the first paragraph of the "Optimal Configuration and Pathway" section that our study evaluates solar and wind integration within **the context of a full power system**, ensuring this is clear to readers from the outset. The revised text in the Introduction now reads: "…Here, we outline an optimized, phased pathway for integrating solar and wind energy into a globally interconnected and **fully coordinated power system**…" (Lines 98-99). Similarly, the "Optimal Configuration and Pathway" section now states: "…To address these complexities, we design a comprehensive multi-objective optimization framework to identify the optimal global interconnection pathway **within the context of a full**

power system (see Methods). Central to this framework is a simplified trans-regional electricity dispatch model (Supplementary Fig. S5), which enables an hourly analysis of electricity generation, transmission, storage, consumption, and curtailment while **accounting for interactions with other generation sources, including baseload and flexible technologies**…" (Lines 164-169).

Third, in the Methods section, we have explicitly stated that **baseload generation and flexible units are treated as aggregate categories rather than individually modeled.** The flexible units are collectively represented as a dispatchable reserve to balance residual load fluctuations after solar and wind generation and interregional exchanges are accounted for. Meanwhile, solar and wind generation are explicitly modeled with high-resolution temporal and spatial variations. The revised Methods section clarifies these aspects: "We categorize power generation units into four types: baseload generation, real-time solar-wind generation, stored solar-wind generation, and other flexible units. Baseload generation (including nuclear, geothermal, and unabated fossil fuels) and flexible units (including hydropower, hydrogen-based sources, and fossil fuels with CCUS) are **treated as aggregate categories rather than individually modeled**. (Lines 587-591) …In our model, solar and wind generation are explicitly modeled with high-resolution temporal and spatial variations, whereas **flexible units are collectively represented as a dispatchable reserve** used to balance residual load fluctuations after solar and wind generation and trans-regional exchanges have been accounted for. Referring to the IEA's NZE scenario (Supplementary Table S1), we set the share of baseload generation to decline gradually from 36% in the 2030s to 11% in the 2040s and further to 9% by the 2050s." (Lines 599-604).

Comments #2

Line 203 introduces transcontinental corridors across northern America-Eurasia and southern America-Africa, which raises the question about capacity of such backbone interconnections. I found the answer in Figure 2, but would help to clarify such information in the text.

Response: Thank you for your suggestion. In this revision, we have explicitly stated the maximum transmission capacities of key transcontinental corridors to enhance clarity. The revised text now reads: "…Establishing transcontinental corridors across northern America–Eurasia and southern America–Africa will be paramount, followed by routes like western Asia–northern Africa, southern Asia–southeastern Asia, and central Asia–eastern Asia. The maximum transmission power along these key corridors varies significantly and exhibit directionality (Fig. 2d). The Northern America–Eastern Europe corridor should support up to 6.8 TW eastward and 6.0 TW westward, while the Southern America–Western and Middle Africa corridor should reach 10.5 TW eastward and 8.0 TW westward. These capacities are optimized to balance solar-wind generation and demand across interconnected regions and facilitate efficient transcontinental electricity exchange..." (Lines 200-207).

Comments #3

The GEIDCO proposed plan for global energy interconnection does not rely on HVDC cables as discussed in this paper but rather of Ultra-HVDC cables, which have lower losses (but probably higher investment costs) than the ones described around Line 640. It might be worth exploring the GEI plans in more detail and update some of the assumptions.

Response: Thank you for your insightful comments. We acknowledge that the Global Energy Interconnection (GEI) concept proposed by GEIDCO primarily relies on Ultra-High Voltage Direct

Current (UHVDC) rather than conventional HVDC. To address this concern, **we investigated the impact of transmission losses on capacity requirements** based on the optimized spatial layout (Fig. 2 in the main text). Using the original loss assumptions (5% per 1,000 kilometers on land and 3% per 1,000 kilometers at sea) as the baseline, we introduced additional scenarios where losses were reduced to 80%, 60%, 40%, 20%, and 0% of the baseline values. We recorded the hourly transmission power of each interconnection corridor and compared the maximum capacities across scenarios. The results (Fig. R1a) indicate that reducing transmission losses leads to lower capacity requirements, with variations across different transmission corridors. Importantly, a comparison between Fig. 2d and Fig. R1b shows that the regional distribution of transmission capacity remains largely unchanged, demonstrating the robustness of our analysis.

In the revised manuscript, **we have incorporated these analyses** and made the following modifications:

First, in the Methods section, we have clarified the differences between HVDC and UHVDC and explained how assuming HVDC in this study influences the analytical results. The revised text reads: "In this study, we adopt HVDC as the primary long-distance transmission technology on land due to its current feasibility and widespread global deployment. This approach differs from the GEI concept proposed by GEIDCO, which primarily relies on UHVDC technology. UHVDC offers lower transmission losses[65] but likely entails higher investment costs compared to HVDC. Future transition from HVDC to UHVDC is expected to reduce overall capacity requirements and improve transmission efficiency. Nevertheless, under the premise of fair technology sharing, the fundamental spatial layout and regional distribution patterns under global interconnection are unlikely to change significantly (Supplementary Fig. S8)." (Lines 624-631).

Second, in the main text, we have added an explanation regarding the impact of reduced transmission losses on capacity requirements: "…Future advancements in transmission technology, including the transition from high-voltage direct current (HVDC) to UHVDC as proposed by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO), could reduce the capacity requirements for transregional transmission (Supplementary Fig. S8a). Nevertheless, under a globally interconnected system with equitable technology sharing, the general spatial distribution and interconnection patterns are expected to remain largely unchanged (Fig. 2d and Supplementary Fig. S8b)." (Lines 210-215).

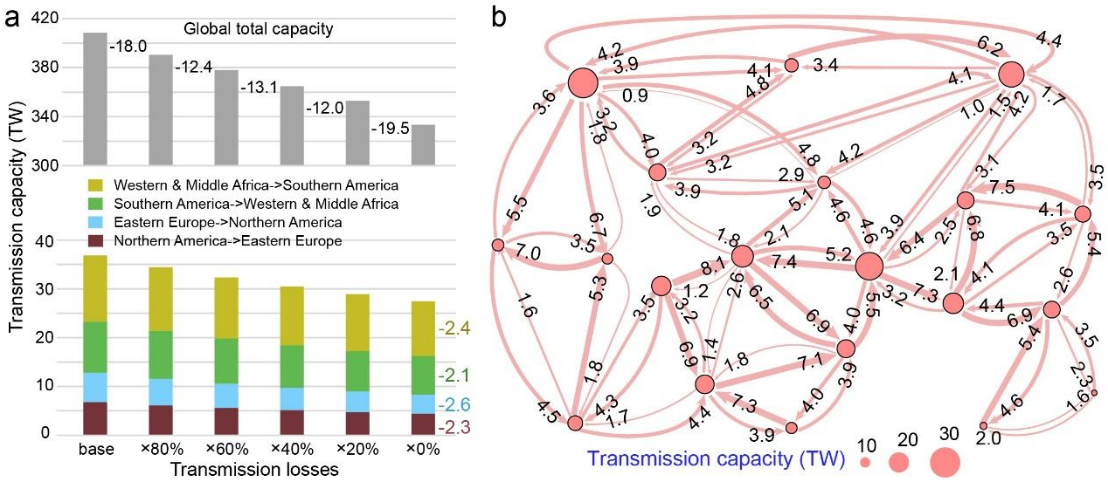

Fig. R1 (also appears as Fig. S8 in the revised SI). Impact of transmission loss reduction on capacity requirements and regional distribution. a, Global and corridor-specific transmission capacity changes under scenarios where transmission losses are reduced to 80%, 60%, 40%, 20%, and 0% of the baseline values. Lower transmission losses lead to reduced capacity requirements, with variations across different corridors. **b,** Regional distribution of transmission capacity when transmission losses are reduced to 0%. A comparison with Fig. 2d reveals that changes in transmission losses do not fundamentally alter the regional allocation patterns of transmission capacity.

We hope these revisions address your concerns and meet with your approval. Once again, thank you for your valuable feedback, which has significantly contributed to improving the quality of our manuscript.