

Response to Anonymous Referee #2 Comments: Insuring the green economy against natural hazards – charting research frontiers in vulnerability assessment

Note: Line numbers refer to the original manuscript. Line numbers from the revised manuscript (without tracked changes) are provided in brackets.

R2.1. The study provides a comprehensive overview of the vulnerability of green economy assets to natural hazards, identifying key gaps in the literature and proposing a structured taxonomy for future research. The methodology is well-defined, and the use of a systematic literature review to construct a vulnerability matrix is robust. However, there are areas where the paper could be improved to enhance its clarity, depth, and utility.

Author Response: *We thank the reviewer for their positive feedback on the paper, and for summarising areas for improvement. Please find our response to your points for improvement below.*

R2.2. The introduction effectively sets the context for the study. However, it could benefit from a clearer explanation of the significance of the green economy in the context of climate change and insurance (lines 24-35). Including more recent statistics or projections could provide a stronger foundation.

Author Response: *Thank you for your comment. We have addressed this in our response to Anonymous Reviewer #1 (R1.6).*

R2.3. While the paper identifies gaps in the literature (lines 50-55), it would be useful to elaborate on why these gaps exist. Are they due to the novelty of the technologies, lack of historical data, or other reasons? This could help guide future research more effectively.

Author Response: *Thank you for highlighting this point. We have highlighted the reasons for the lack of literature when we discussing specific assets and hazards. For example, where there is a lack of studies for pyroclastic flows and lahars impacting terrestrial engineered assets, due to the practice of avoiding construction in volcanic areas (see our response to Anonymous Reviewer #1 (R1.5)).*

However, in response to this comment, amendments were made to lines 156 - 157 (now lines 174 - 177, Section 2.2, Step 2: Literature review), mentioning low exposure history as a reason for literature gaps:

“In the latter case, the vulnerability assessment is made based on the authors’ judgement and experience. It was observed by the authors that assets with a low exposure history, including relatively new technologies/constructions, generally lacked an academic literature base. Here, the vulnerability of similar asset types were considered”.

Please also review our response to R2.7, which shows a lack of literature for mechanical components of the nacelle, due to modelling complexities.

To emphasise the key reasons why these gaps exist in published literature, we have made amendments to the conclusion lines 422 – 425 (now lines 486 - 491, Section 4, Conclusion). It now reads:

“The limited exposure data for complex green economy assets, as seen in the insurance sector; the insufficient alignment of published vulnerability assessments with design standards and insurance needs; and the increasing intensity of hazards due to climate change, have all contributed to the difficulty in establishing credible vulnerability ratings through existing research. This paper highlights the critical need for a representative green economy asset-hazard taxonomy, which is essential for guiding researchers in developing quantitative vulnerability assessments that are relevant to the insurance industry.”

R2.4. The proposed taxonomy is central to the study (lines 75-120). It would be beneficial to provide more justification for the selection of specific assets and hazards. For instance, why were certain assets or hazards prioritized over others? This could help readers understand the choices made and the potential limitations.

Author Response: *Thank you for suggestion. With regards to asset inclusion criteria, we have addressed this in our response to Anonymous Reviewer #1 (R1.7). In line with the amendments made for asset inclusion, changes have been made to lines 124 – 126 (now lines 132 – 137, Section 2.1.2, Defining hazards), to clarify the hazard inclusion criteria:*

“A new, operational hazard taxonomy for the insurance sector is therefore proposed herein, that is based on the existing hazard taxonomy by UNDRR and ISC (2020), with the addition of hazard process duration in hazard descriptions. Similar to the approach used for green assets (Section 2.1.1), hazards were prioritised and consolidated through author discussions. This process ensured that the selected hazards were the most relevant for the chosen assets, and practical for use at an operational level within the insurance industry.”

R2.5. The systematic review process is well-outlined (lines 130-155). However, providing more detail on the search strategy, databases used, and inclusion/exclusion criteria could enhance transparency and replicability.

Author Response: *Thank you for your suggestion. We have added more details on search strategy, databases used and inclusion/ exclusion criteria after sentence ending line 136 (new lines 147 – 152, Section 2.2, Step 2: Literature review):*

“A combination of asset and hazard names from the developed green economy taxonomy, alongside the terms ‘fragility’ and ‘vulnerability’, were searched within easily accessible, web-based literature databases (e.g. Google Scholar). Where literature results were found to be insufficient to give a representative vulnerability rating, alternative keywords were used, before reference lists of relevant published literature were hand searched. All literature found were included in the assessment, and were only excluded when a potential or definitive report or discussion of effect, damage, vulnerability, or loss of function was not present.”

An example was added to lines 147 – 149 (now lines 165 – 167, Section 2.2, Step 2: Literature review) to clarify the meaning of ‘broad internet search’:

“If the literature sources were not accessible, a broad internet search (e.g. via Google) was conducted to identify news reports or blogs that could provide examples of catastrophic failures of a particular asset due to a given hazard (Tier 5).”

R2.6. The presentation of the vulnerability matrix (lines 190-210) is comprehensive. However, it might be helpful to include a few illustrative examples or case studies to demonstrate how the matrix

can be applied in real-world scenarios. This could make the findings more tangible for practitioners.

Author Response: *Thank you for your comment. The presented matrix provides qualitative vulnerability ratings at each intersection, that are intended to be used alongside the literature heat map to identify research gaps in existing published literature. These ratings need to be transformed into a quantitative metric in order to be practically applicable by the insurance sector, for example through the macroseismic method used by Lagomarsino and Giovinazzi (2006). Ideally these qualitative ratings must be validated with the independent development of quantitative fragility/vulnerability functions, as mentioned in our response to comment R2.9. The second sentence starting on line 170 (now line 190) has been removed from section 2.3 (Step 3: Vulnerability assessment) to avoid confusion regarding the practical applicability of the vulnerability matrix.*

R2.7. The literature heat map (lines 220-250) is a valuable addition. However, it could be enhanced by a more detailed discussion of the trends observed. For instance, why are certain asset-hazard intersections more researched than others? Are there specific barriers to research in certain areas?

Author Response: *Thank you for your insightful feedback. In response to your recommendation, we have expanded the discussion on the trends observed in the literature heat map and included a new reference to EPRI (2021). The following details have been added before the sentence on line 249 (new lines 279 – 284, Section 3, Results):*

“As expected, natural assets and established engineered assets, which are predominant in the green economy, show a greater availability of quantitative literature. Despite this, the complexity of certain assets and the associated hazard processes can present significant barriers to research, even when a quantitative literature base exists. For example, structural components of wind turbines, such as the tower, have more fragility functions, because wind and seismic loads can be directly associated with the structure’s limit states. In contrast, mechanical components within the nacelle, such as the gearbox, have limited literature on the composition of their multiple subcomponents, and how these experience indirect loading (EPRI, 2021).”

R2.8. The discussion provides a good overview of the key findings (lines 285-390). However, it could benefit from a more detailed analysis of the implications for different stakeholders, such as policymakers, insurers, and researchers. What specific actions should they take based on these findings?

Author Response: *Thank you for your recommendation. We have addressed through the following amendments. A summary is presented in a new paragraph added before line 427 (new lines 493 – 494, Section 4.1, Future work):*

“In this section, recommendations for research and insurance industry practitioners are made, with the intention that outputs from these stakeholders will guide policymakers in changing codes of practice for the protection of green economy assets.”

Actions to be taken by the for the insurance sector based on key findings is addressed in our response to Anonymous Reviewer #1 (R1.7). Please also see our response to R2.10, which elaborates on the implications of having more practically-applicable, quantitative vulnerability models (which this study found a lack of) for the insurance sector.

The implications of key findings for researchers is also addressed through our response to Anonymous Review #1 (R1.2) .

- R2.9. While the paper outlines future research needs (lines 380-400), it could be more specific. For example, identifying specific technologies or methodologies that could be used to address the identified gaps would be helpful.

Author Response: *Thank you for highlighting more specific research needs. We have provided more guidance on the approaches that can be taken to develop quantitative fragility/vulnerability functions, with a new reference to Ioannou et al. (2017). A new paragraph is now added after line 419 (new lines 474 – 480, Section 3.2, Research gaps), reading:*

“To address the identified gaps, quantitative fragility and vulnerability functions can be developed using empirical models, that rely on systematic observations of functional loss and its root causes, as well as a clear understanding of their link. When empirical data is limited, analytical methods may be employed as an alternative, provided numerical modelling is feasible. In cases where both empirical data and numerical modelling are unavailable, expert elicitation approaches can be used, as seen in the case of Ioannou et al. (2017), which quantified the vulnerability of reinforced concrete buildings to various fire intensities. Depending on data availability, a hybrid approach that combines empirical, analytical, and expert-based methods may also be utilised.”

- R2.10. The conclusion effectively summarizes the main findings (lines 420-430). However, it could be strengthened by reiterating the practical implications and the urgency of addressing the identified research gaps in light of climate change and increasing natural hazards.

Author Response: *Thank you for your comment. We have addressed this in our response to Anonymous Reviewer #1 (R1.2), where we added a discussion on short-term research needs. Three further sentences have also been added in a new paragraph inserted before line 427 (new lines 495 to 498, Section 4.1, Future work), highlight the importance and urgency of addressing research gaps:*

“For the insurance sector specifically, practically-applicable, quantitative vulnerability models are needed to reduce uncertainty in pricing insurance premiums. More broadly, such models will improve the industry’s internal risk monitoring efforts, and help confidently achieve regulatory requirements. In turn, this will help de-risk investment in the growing green economy and improve its resilience to natural hazards.”

References

EPRI: Wind Turbine Gearbox Reliability Assessment: Value of Increased Reliability and Reduced Operations and Maintenance Costs, <https://www.epri.com/research/products/000000003002021422> (last access: 1 August 2024), 2021.

Ioannou, I., Aspinall, W., Rush, D., Bisby, L., and Rossetto, T.: Expert judgment-based fragility assessment of reinforced concrete buildings exposed to fire, *Reliab Eng Syst Saf*, 167, 105–127, <https://doi.org/10.1016/j.res.2017.05.011>, 2017.

Lagomarsino, S. and Giovinazzi, S.: Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings, *Bulletin of Earthquake Engineering*, 4, 415–443, <https://doi.org/10.1007/s10518-006-9024-z>, 2006.

UNDRR and ISC: Hazard definition and classification review (Technical Report), <https://www.undrr.org/publication/hazard-definition-and-classification-review-technical-report> (last access: 4 August 2023), 2020.