

# Authors' Response to Reviewer Comments

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Gräfe et al.

**Manuscript:** Gräfe et al., *Review and quantification of major risks in wind farm development and operation*, Wind Energy Science Discussions

## Reviewer 1

### General comments

Thank you to the editorial team and the authors for the opportunity to review. These comments and questions are presented for consideration. Overall, the report covers an important topic and presents interesting interview results that add valuable perspective. Specific sections of the manuscript seem to be well written while others read overly verbose, which makes certain sections difficult to follow. Streamlining the narrative and improving transitions between sections could help enhance clarity and readability. The writing style occasionally feels formulaic, and a careful editorial review to ensure consistency in tone and flow may strengthen the overall presentation.

While the findings generally align with expected outcomes, the discussion could more clearly emphasize actionable recommendations for industry stakeholders, particularly regarding strategies to reduce risks and system costs. The paper would also benefit from incorporating more quantifiable comparisons where possible, e.g., if a particular risk management was implemented it could reduce system LCOE by 15%. In several sections, it was challenging to identify which factors had the largest influence on key economic metrics such as NPV or LCOE, getting lost in what seemed like distracting text to core discussion topics that could be more concisely written. The conclusion of the paper may benefit from a more synthesized perspective of the work. Perhaps by pulling together a summary table of results highlighting the highest priority risks, the relative impact of those risks, and the major drivers the offshore wind industry could invest in would help readers quickly understand the most consequential results and improve the practical usefulness of the study.

**Response:** We thank the reviewer for the constructive feedback. We have undertaken a comprehensive revision:

- **Verbosity and formulaic writing:** All six subsections of Section 4 were systematically compressed, removing redundant or overly detailed content while preserving all arguments, citations, and figures.
- **Synthesis table:** Added a synthesis table in the Discussion (§ 5.2), a merged table synthesizing economic signatures, moderate-scenario results ( $\Delta$ NPV, P10–P90, P(NPV<0)), and industry levers across all risk categories, including the combined-risk experiment result.
- **Combined-risk experiment:** Added § 5.1, demonstrating that individually moderate risks compound into super-additive tail risk when activated simultaneously.
- **Quantifiable comparisons:** The synthesis table and combined experiment directly answer the reviewer's request for cross-category comparison of economic impacts.

- **Conclusion rewrite:** Concise conclusion added (§ 7), framing the study as a review with illustrative case studies that demonstrates the necessity of integrated treatment and maps the remaining gaps.

## Specific comments

### R1-L11

Define ‘asymmetric downside risk’ and ‘long-tailed loss distributions’ in the Abstract section.

**Response:** We replaced the technical jargon in the abstract with plain language: “*some primarily shift mean outcomes, while others produce losses that are skewed toward worst-case outcomes, with rare but severe events dominating the overall risk profile.*” Language has been revised throughout the paper.

### R1-L39

Is the construction of the wind plant included in the ‘development’ phase?

**Response:** Construction and commissioning is treated as a distinct phase in our framework. The revised manuscript includes a lifecycle phase diagram that defines six phases: (1) Development & financing, (2) Construction & commissioning, (3) Operation, (4) Late-life assessment, (5) Lifetime extension, and (6) End-of-life. This figure clarifies the phase boundaries and is referenced consistently throughout the paper.

### R1-L42

What is a ‘tool chain?’

**Response:** We added a definition on first use: “*i.e. a sequence of coupled computational models that together translate technical assumptions into economic performance metrics.*”

### R1-L50

Is the ‘maintenance performance’ defining the efficiency of the maintenance activities or the performance of the wind plant?

**Response:** We clarified the wording. The phrase “maintenance performance” was replaced with “maintenance outcomes” to make clear that this refers to the results of O&M process execution (availability, downtime, cost), not the technical performance of the turbine itself.

### R1-L52

It may be worth including a graphic defining the phases of a wind project. The descriptions of the phases seem to be changing throughout the paper.

**Response:** We added a lifecycle phase diagram ( that defines six phases and conducted a consistency audit across the manuscript. Phase terminology is now consistent throughout the paper.

### R1-L58

If not defined later in the manuscript, it would be nice to include some high-level stats on the structured survey, e.g., approximately how many experts, etc.

**Response:** We added the key survey statistics (approximately 100 respondents, industry and academic experts) to the introduction where the methodology is first mentioned.

#### R1-L65

Would benefit the definition of ‘sector challenge.’ Is this specific to the wind sector?

**Response:** We added a concise definition on first use in the methodology: “*We use this term to denote industry-wide risk themes that are not specific to a single project, site, or technology.*”

#### R1-L93

The ‘constant power output’ does not consider time-series wind resource?

**Response:** Correct. This is a deliberate simplification: by using a fixed capacity factor rather than a time-series wind resource, the study isolates economic risk drivers from wind-resource variability, which is not the focus of the present work. WINPACT supports time-series wind input, but this capability is not exercised here in order to keep the scenario comparisons focused on the risk categories under investigation.

#### R1-L99

‘Access constraints’ are defined by events such as high winds or harsh seas?

**Response:** We added a parenthetical definition on first use: “*access constraints (i.e. weather-driven inability to dispatch vessels and crews, such as due to excessive wave heights or wind speeds).*”

#### R1-L104

Is this impacting the OPEX costs or affecting the finance assumptions of the project?

**Response:** The OPEX module exclusively affects operational expenditure (labor, logistics, vessels, spare parts) and availability-driven production losses. It does not modify financing assumptions. Financing conditions (WACC, cost of capital) are treated separately in the supply chain and financing risk assessment (Section 4.1).

#### R1-L108

Should the performance degradation theoretically start once the project is operating instead of at the end of the design life?

**Response:** The end-of-life module applies *additional* degradation modifiers for the extension period beyond the original design envelope, representing accelerated ageing effects. We clarified this in the module description. The Authors agree that a link between operating time, load conditions, degradation, and the occurrence of failure should be established in future work.

#### R1-L261

Assuming the OPEX, energy, and other variables in the LCOE equation are being held constant for this assessment. May be worth explaining these assumptions in a bit more detail.

**Response:** We added an explicit statement: “*All other parameters, including OPEX, annual energy production, and project lifetime, are held at baseline values, so that the resulting LCOE variation is attributable solely to supply chain and financing risk.*”

**R1-L438**

Did the approach consider failures beyond the wind turbine, e.g., substructure or cables?

**Response:** The reliability and O&M assessment is limited to turbine-level components (drive-train, blades, electrical systems, etc.). Substructure and cable system failures are not included in the current model. We have added an explicit acknowledgment of this scope limitation. Extending the framework to include balance-of-plant reliability is identified as a direction for future work.

**R1-L588**

Was it intentional to keep NPV and remove LCOE from Figure 8?

**Response:** An LCOE panel has been added to Figure 8, showing the LCOE distributions alongside the existing NPV and CAPEX panels.

**R1-L742**

Is it worth showing the impacts on LCOE in Figure 10. How much impact does the OPEX lever have?

**Response:** An LCOE panel has been added to Figure 10, showing the OPEX lever's impact on LCOE. Note that distribution shape has slightly changed compared to the original figure as an inconsistency between reported and simulated parameters was fixed.

**R1-L745**

Is there significance to the shaded areas in Figure 11 as compared to box and whiskers?

**Response:** The shaded areas are kernel density estimates (violin plots), which show the full shape of the simulated distribution rather than only summary statistics. We clarified this in the figure captions.

**R1-L879**

Is there a cost associated with implementation of O&M best practices?

**Response:** Thank you for pointing this out. Implementation costs for advanced O&M practices (e.g. CMS investment, training, advanced access platforms) have not been included in the I3 and I4 scenarios. As a fixed additional cost, their inclusion would shift the absolute values of the NPV distributions without changing the shape or spread of the results. If implementation costs are themselves a substantial source of uncertainty, they would be worth including as a probabilistic parameter in future analyses.

**R1-L1008**

These are the types of identified conclusions that make sense and placing emphasis on what might be possible to lower costs or increase performance would strengthen the outcome of the study.

**Response:** We added a synthesis table to the Discussion that ranks all six risk categories by economic signature, reports case-study magnitudes from the moderate-scenario experiments. The combined-risk experiment (§ 5.1) provides a quantification of how risks interact. Section 6 identifies integration gaps and research priorities. The conclusion (§ 7) has been rewritten to synthesize these elements.

**R1-L1032**

‘Overall’ appears to be used a couple of times in the Conclusion but in different context.

**Response:** The conclusion has been entirely rewritten as a concise three-paragraph synthesis (§ 7). The repetition no longer occurs.

**Technical corrections****R1-TC-L104**

Typo, ‘into to’ change to ‘into.’

**Response:** Corrected.

**R1-TC-L130**

Is ‘Risk’ capitalized intentionally? Should ‘section’ be capitalized?

**Response:** “Risk” decapitalized; “section” changed to “Section” with non-breaking space per journal style.

**R1-TC-L166**

Looks like part of the chart label got cut off on the right-hand side.

**Response:** The figure has been regenerated with the chart label fully visible. Additionally, the former Figures 1 and 2 have been merged into a single figure.

**R1-TC-L977**

This paragraph reads repetitious of the one prior.

**Response:** The duplicate paragraph was removed from the Discussion section.

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## Reviewer 2

### General comments

I think that manuscript covers a very important topic. Following comments are for the purpose to improve it. Overall, the manuscript presents a huge amount of data and at moments it can be overwhelming for a reader. While some sections of the manuscript seem to be better written than others, I believe that the manuscript would benefit from major technical revision (specific comment to follow) and would improve readability. At moments, it is very hard to follow the story due to “heavy language” (things can be simplified and written in a much better way) and way too many inconsistencies (with sections missing subsections or having an extra subtitles) and typos (missing parentheses, capital letters where there should not be one, abbreviations without introduction/explanation).

The work synthesized previous findings while offering some additional info. Still, as the authors stated themselves, this work still offers “fragmented risk treatment and provides a structured starting point for developing integrated,” but doesn’t offer any better picture of “integrated” risk, and conclusion is lacking better guidance of how to reach this “integrated” tools. I had a hard time to identify for each section which factors had the largest influence on key metrics, so once again, I do believe that the manuscript needs a major overhaul. Also, I’m not sure that all data used in this work can be equally applied across the ocean; I’m not sure we are looking at the same risk when we are talking about on- or off-shore wind farms at “all stages of life” depending if it is located in the USA or Europe.

**Response:** We thank the reviewer for the detailed feedback. We have undertaken a major revision addressing each of these concerns.

Regarding the applicability across onshore and offshore contexts: we acknowledge that on- and offshore wind farms face partly different risk profiles, particularly regarding maintenance logistics, access constraints, and foundation/substructure integrity. The survey did not distinguish between onshore and offshore respondents, while the quantitative case study is focused on an offshore wind farm. The risk categorization itself (supply chain, through-life decisions, curtailment, reliability, O&M processes, upscaling) is applicable to both onshore and offshore projects, but the relative importance and specific manifestation of individual risks will differ. We have added a note in the methodology clarifying this scope.

- **Heavy language and verbosity:** All six § 4 subsections were systematically compressed.
- **Inconsistencies in subsection structure:** All § 4 subsections now follow a uniform Review + Impact assessment template. Informal bold subheadings in § 4.3 were removed and folded into running prose.
- **Typos and abbreviations:** A comprehensive cleanup pass defined all abbreviations on first use and fixed line-level errors.
- **Integrated risk treatment:** Section 6 “Toward integrated risk treatment” identifies eight integration deficits (three interface gaps between coupled sub-models and five injection gaps between external drivers and the model chain). A combined-risk experiment (§ 5.1) provides empirical evidence that individually moderate risks produce super-additive tail outcomes when activated simultaneously.
- **Conclusion guidance:** The conclusion (§ 7) has been rewritten as a concise synthesis.

### Specific comments

#### R2-Abbreviations

All abbreviations in the text need to be explained when used for the first time.

**Response:** Corrected.

#### **R2-L93**

It would be very useful to have a graphical representation/diagram of WINPACT flow.

**Response:** An architecture diagram was created and placed as Figure 1 in Section 2.1, showing inputs, modules, outputs, and module interconnections.

#### **R2-L134**

“For each risk category, multiple scenarios are developed based on literature, available data, and the judgment of the authors” – I think some additional info on how the authors made those decisions.

**Response:** Each impact assessment subsection (§ 4.1 through § 4.5) provides a detailed justification of its scenario parameters, including the data sources, published benchmarks, and expert judgment underlying each choice. For example, § 4.1 derives stochastic commodity parameters from BLS price indices using fitted Merton jump-diffusion models; § 4.4 grounds its CV targets in specific fleet datasets.

#### **R2-L136**

It would be nice to know a bit more about “common baseline scenario is defined.”

**Response:** We expanded the baseline description in the methodology to include the key specifications: 34 turbines, 748 MW installed capacity, based on the 22 MW IEA reference turbine, with deterministic assumptions for all cost, production, and financial parameters and no stochastic variation.

#### **R2-L139**

Is there a difference in risk identification and categorization between USA and Europe?  
Would it be useful to know if there is a difference in survey results?

**Response:** This is a relevant question. Regional differences in risk perception certainly exist, particularly regarding regulatory frameworks, grid infrastructure maturity, and supply-chain localization. However, the risk categorization in this study is intentionally designed to cover wind energy systems in general rather than to capture region-specific risk profiles. A regional re-cut of the survey data has not been performed, as the sample sizes per region would not support statistically robust conclusions. We have added a note in the methodology acknowledging that regional differentiation of risk perceptions is a relevant direction for future work.

#### **R2-L225**

Every subsection should have a Review and Impact Assessment subsection. Please be consistent.

**Response:** All six § 4 subsections now follow a uniform Review + Impact assessment template.

#### **R2-L274**

“We obtain long-term price indices for these commodities from the U.S. Bureau of Labor Statistics” – is there the same data available for the EU and would the authors expect to see any difference?

**Response:** Steel and copper are globally traded commodities, so the U.S. BLS price indices serve as proxies for global market dynamics. Although price levels and short-term fluctuations differ between markets (US, Europe, Asia), the long-term trends in commodity supply, demand shocks, and jump behavior that drive the stochastic parameters in our Merton model are reflected in any major market index. We have clarified this in the text and note that a comparison with EU-sourced indices (e.g. Eurostat producer price series) would be a useful sensitivity check in future work.

**R2-L341**

Missing parentheses for “Carroll et al. (2016); Donnelly et al. (2024); Dinwoodie et al. (2013).”

**Response:** Corrected in several instances.

**R2-L401**

“Dependent on boundary conditions.” What are those boundary conditions?

**Response:** This text has been removed entirely.

**R2-L474**

“Transmission constraints” – Is this a subsection?

**Response:** The informal bold subheadings in § 4.3 (“Transmission constraints,” “Market-driven curtailment,” “Curtailment – Wildlife Constraints”) were removed. The entire review is now flat under § 4.3.1 Review with no sub-structure.

**R2-L977-982**

These sections are duplicated.

**Response:** The duplicate paragraph was removed from the Discussion section.

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