

A Method to Estimate the Economy-wide Consequences of Widespread, Long Duration Electric Power Interruptions

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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 develops and pilots a new approach to estimate the economic impacts of widespread, long duration (WLD) power interruptions, where survey results are scaled up to the broader regional economy, and used to drive a computational general equilibrium (CGE) simulation of the effects of power interruptions and attendant customer responses. This paper provides a novel perspective to assess the economic consequence of WLD, and has important policy implications for investments in power system resilience. However, the paper requires further revision. The specific comments are listed as follows:

1. Although two sources of power interruptions' economic losses are identified, they may overlap with each other. For example, according to the normal market equilibrium adjustment, the shortage of electricity would induce the substitution effect, increasing the consumption or input for other energy resources, such as petroleum and gas. In other words, the cost of fuel for generator can be viewed as part of this effect. Whether it is redundant to include this kind of items in the disequilibrium impact should be reconsidered.
2. Using total household expenditure to measure economic cost for household is not enough. The impact of social welfare including Equivalent Variation (EV) and Compensate Variation (CV) should be supplemented.
3. The WLD that occurs in different seasons has obviously different economic costs. Though you mentioned "split 50-50 between summer or winter events", you have better elaborate the seasonal effect on costs in detail.
4. There may be some typos in the manuscript (e.g., line 157, the number of figs; line 393, number of micro-regions)

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

The manuscript proposes a methodology to estimate the economy-wide monetary costs of widespread and long-duration (WLD) power outages. This study improves upon prior work to consider long-duration outages and resilience costs, moving beyond prior understanding of short-duration outage costs. This work is of significance to the field of power system resilience and will help to quantify the economic consequences of WLD power outages and justify investments in resilience. This reviewer believes that the paper is of great technical merit and that the methodology is sound and reproducible. Please find specific comments and questions below:

1. In the introduction, the authors mention both the economic and social costs of WLD interruptions. However, this paper pertains to monetary and economic costs, while social costs that cannot be measured in the economy are seemingly outside the scope of the paper (e.g., health issues related to losing power). It would be helpful for readers to know that other "costs" due to WLD interruptions exist that cannot be measured using these methods.
2. It is not clear in section 1 how the methodology in this work differs from Baik et al. 2021, since that paper is cited in the approach outlined on line 96. Fig. S1 does explain the differences, but the introduction could benefit from clarifying how the methods differ.
3. The analysis of evacuation is of particular interest. Is any thought given to residents who may not be able to evacuate

(e.g., due to lack of access to a vehicle or public transportation or not being able to afford a hotel)?

5. The direct cost questions in the survey are an interesting alternative to willingness-to-pay (WTP) questions, since prior work has discussed that WTP favors wealthy respondents. It would be of interest to many other researchers in this field if the authors described why they chose not to use WTP and instead asked about specific direct costs.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have made significant revisions in response to the comments provided by the reviewers in the first round. The authors have successfully addressed all the concerns raised, including:

- 1.Overlap of Economic Losses: The authors have clarified the potential overlap between equilibrium and disequilibrium economic losses, adding a discussion on bottom-up/top-down misalignment, which alleviates previous concerns regarding undercounting and double counting.
- 2.Inclusion of Social Welfare Impacts: They have incorporated measures of Equivalent Variation (EV) and Compensate Variation (CV) in the analysis, providing a more comprehensive view of the economic impacts.
- 3.Seasonal Effects: The authors have acknowledged the limitations regarding seasonal variations in economic costs and have added a caveat discussing the need for future research to develop season-specific models.
- 4.Non-Monetary Costs: The manuscript now includes a discussion on non-monetary costs associated with power interruptions, addressing the concerns about health issues and other social impacts.
- 5.Methodological Clarifications: The authors have clarified how their methodology differs from previous work, enhancing the understanding of their approach.
- 6.Equity Concerns Related to Evacuation: The authors have added a discussion on the challenges faced by residents who may not be able to evacuate, highlighting equity issues and the need for planning.
- 7.Rationale for Direct Cost Questions: The authors have provided a clear rationale for using direct cost questions instead of willingness-to-pay (WTP) questions, which adds depth to their methodological choices.

Given these comprehensive revisions and the authors' efforts to address all reviewer comments, I believe the manuscript is now suitable for publication. I recommend accepting the paper for publication in its current form.

(Remarks on code availability)

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Reviewer #2

(Remarks to the Author)

The authors have sufficiently addressed all of my previous comments and concerns in their revised manuscript.

(Remarks on code availability)

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Reviewer	Comment	Authors' Response
1	This paper develops and pilots a new approach to estimate the economic impacts of widespread, long duration (WLD) power interruptions, where survey results are scaled up to the broader regional economy, and used to drive a computational general equilibrium (CGE) simulation of the effects of power interruptions and attendant customer responses. This paper provides a novel perspective to assess the economic consequence of WLD, and has important policy implications for investments in power system resilience.	Thank you for taking the time to review our manuscript. We appreciate the compliment as well as the constructive suggestions
1	Although two sources of power interruptions' economic losses are identified, they may overlap with each other. For example, according to the normal market equilibrium adjustment, the shortage of electricity would induce the substitution effect, increasing the consumption or input for other energy resources, such as petroleum and gas. In other words, the cost of fuel for generator can be viewed as part of this effect. Whether it is redundant to include this kind of items in the disequilibrium impact should be reconsidered	We thank the reviewer for pushing us to consider this interesting and important point. We have picked up the example provided and run with it, adding a paragraph in the discussion section on bottom-up/top-down misalignment (undercounting and double counting) beginning on line 265. Unfortunately, in the present analysis not much can be done to address these issues. Progress on this front will require development of methods to downscale simulated changes in prices and demand by aggregate sectors/household groupings to heterogeneous survey responses, followed by recomputation of the disequilibrium expenditure shocks imposed on the model. One can envision the magnitudes of the shocks going up or down as a result of such adjustments, depending on methodological details of downscaling that weight the price or quantity effects more heavily. Addressing this complexity is a study in its own right, and is well beyond the scope of the present paper.
1	Using total household expenditure to measure economic cost for household is not enough. The impact of social welfare including Equivalent Variation (EV) and Compensate Variation (CV) should be supplemented.	Done. Fig. 4 has been updated. The two measures closely track the change in real expenditure, with CV (squares) > delta real expenditure (bar) > EV (diamonds) as expected for a price increase (Willig, AER 1976), telling a consistent story.
1	The WLD that occurs in different seasons has obviously different economic costs. Though you mentioned "split 50-50 between summer or winter events", you have better elaborate the seasonal effect on costs in detail.	The reviewer is correct in that the intuition suggests different economic costs depending on the season. However, the calibration data available for the CGE model does not distinguish economic activity by season, which would then require generous assumptions to manually apportion economic activity for the winter and summer seasons. Furthermore, our internal analysis suggested that there were no significant differences in the choice of strategic response by customers as a function of the season in which the interruption occurred. Finally, splitting the analysis by season would have halved the sample for each, creating numerous challenges to find enough sample for our disaggregations by household income and geographic location. A seasonally-explicit model was left for future development given the data challenges implied to correctly identify seasonal variations in economic activity, strategies, and costs. We added the following text in the caveats section of the paper: " In this work, we aggregated survey responses across seasons due to limitations in temporal disaggregation of economic activity data, as well as relatively similar strategic response from customers. Further work is needed to produce credible season-specific models."
1	There may be some typos in the manuscript (e.g., line 157, the number of figs; line 393, number of micro-regions)	Good catch. We corrected the typos by correctly counting the number of micro-regions and correcting the figure numbering in selected locations of the manuscript. We also reviewed the manuscript for additional typos.

- 2 The manuscript proposes a methodology to estimate the economy-wide monetary costs of widespread and long-duration (WLD) power outages. This study improves upon prior work to consider long-duration outages and resilience costs, moving beyond prior understanding of short-duration outage costs. This work is of significance to the field of power system resilience and will help to quantify the economic consequences of WLD power outages and justify investments in resilience. This reviewer believes that the paper is of great technical merit and that the methodology is sound and reproducible.
- 2 In the introduction, the authors mention both the economic and social costs of WLD interruptions. However, this paper pertains to monetary and economic costs, while social costs that cannot be measured in the economy are seemingly outside the scope of the paper (e.g., health issues related to losing power). It would be helpful for readers to know that other "costs" due to WLD interruptions exist that cannot be measured using these methods.
- 2 It is not clear in section 1 how the methodology in this work differs from Baik et al. 2021, since that paper is cited in the approach outlined on line 96. Fig. S1 does explain the differences, but the introduction could benefit from clarifying how the methods differ.
- 2 The analysis of evacuation is of particular interest. Is any thought given to residents who may not be able to evacuate (e.g., due to lack of access to a vehicle or public transportation or not being able to afford a hotel)?
- Thank you for reviewing our manuscript. We appreciate the thoughtful and constructive suggestions that you have provided.
- This is another good point. We have included the following paragraph to provide a bit more detail: "Note also that the estimates presented above only represent market values, and hence do not include the significant amount of benefits to customers from their relocation decisions. These include, but are not limited to avoiding adverse health and inconvenience impacts and risk to local/state/national security from WLD interruptions. In many cases, it is difficult to assign a defensible monetary number to the value of avoiding morbidity, mortality, and security impacts. Furthermore, our approach did not account for the potential capital and operations and maintenance (O&M) costs to ComEd's electricity infrastructure from the precipitating event(s) that led to the WLD interruptions."
- Thanks for pointing this out. Indeed, Baik et al. (2021) serves as the methodological foundation for this study. We have revised the sentence on page 2 to better reflect this connection. The original sentence stated: "We address this gap by developing a state-of-the-art three-step hybrid resilience valuation approach that integrates customer interruption surveys and CGE modeling (Baik et al. 2021 – see Figure S1)." The revised sentence now reads: "As outlined in our earlier paper (Baik et al. 2021), we developed a state-of-the-art methodology to integrate customer interruption surveys with CGE modeling. This approach can be summarized in the following three steps (see Fig. S1)."
- Thank you for your interest in this important issue. We appreciate your focus on this specific point. We have a companion paper that delves deeper into customer resilience tactics for long-duration outages. This paper explores the factors influencing these choices and analyzes the economic costs associated with them.
- In line with your question, relocation is indeed the most common strategy, and its dominance increases with outage duration (as can be seen from Figure S5). However, it's also the most expensive option, potentially leading to an equity issue. Additionally, our data (though not included here but included in the companion paper) shows a significantly lower generator ownership rate in low-income groups compared to others. This disparity could exacerbate health and equity concerns during long outages. Furthermore, evacuation during outages could become chaotic without advanced planning, given the increased traffic volume exceeding regular commutes. We've also discussed how to address these potential issues while reducing the community impacts of widespread and long-duration power interruptions.
- We believe our companion paper, currently under review, will offer valuable insights into the economic and strategic aspects of customer behavior. Together, these papers will provide a comprehensive picture of customer responses to long-duration power interruptions.

The direct cost questions in the survey are an interesting alternative to willingness-to-pay (WTP) questions, since prior work has discussed that WTP favors wealthy respondents. It would be of interest to many other researchers in this field if the authors described why they chose not to use WTP and instead asked about specific direct costs.

Thank you for your insightful comment regarding the use of direct cost questions instead of WTP questions. We appreciate you raising this point. Our decision to employ direct cost questions stemmed from the study's central focus on a hybrid method. In this approach, the survey serves as a primary source of data for the CGE model. As outlined in section S.3.1, the model necessitates sub-cost information related to power outages. Ultimately, these costs can be summed up to represent the economic costs of power interruptions and compared with WTP estimates.

We plan to conduct follow-up studies using the willingness-to-pay method and converting the estimates into value of lost load customer-damage functions in the partner utility's service territory. This will allow us to compare the two approaches and explore the differences in greater detail.