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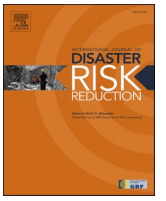
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The short-term response of residential customers to long-duration power interruptions

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A B S T R A C T

Increases in the frequency, intensity, and duration of extreme weather events will translate into the potential for widespread, long duration power interruptions with substantial social and economic impacts. This paper fills a gap by using specifically designed surveys to understand the strategic response of residential customers to 1-, 3-, and 14-day interruptions. We find that relocation is 5-10 times more expensive than staying home, but that up to 85% of customers relocate with a 14-day interruption. The economic consequences of these decisions are highly unequal – with lower income customers spending substantial portions of their monthly income to mitigate interruption impacts – and are equivalent to $5 to $25 billion in our case study in the state of Illinois in the United States. We discuss the drivers for the relocation decision, including the fact that customers that own backup generation are significantly less likely to relocate and estimate the impacts on transportation infrastructure due to this relocation. These results can be used by utilities, regulators, planners, and other decision makers to understand the multifaceted nature of mitigation options for resilience enhancements within and outside the power system.

1. Introduction

Modern society heavily relies on electric power for nearly all facets of individual, household, commercial, industrial, and governmental activities. This reliance highlights the collective vulnerability to power disruptions,[1] making them a pivotal concern within electric utility planning. Most power outages originate at the distribution system, last a few seconds to a few hours, and affect localized parts of utility service territories. In contrast, widespread, and long-duration (WLD) power interruptions typically last days, weeks, or longer, and affect entire service territories or larger areas. They are less frequent than brief, localized interruptions but occur more frequently than is commonly perceived [1]. WLD power interruptions can have significant economic and social impacts, affecting not only utilities and electricity customers directly but also regional economies more broadly. Their growing risk, due to factors including the increasing frequency of extreme weather events, is becoming a significant issue for electricity policy and planning in the United States and beyond.

Traditionally, electricity reliability studies for generation, transmission, and distribution system planning have been rooted in engineering criteria. As increased attention is focused on WLD interruptions, technical research has broadened to examine larger-scale infrastructure deployment, addressing questions about the types of utility-scale and distributed technologies, grid enhancements, and other investments necessary to reduce vulnerabilities. Extensive surveys have been conducted to understand the economic impact of short, localized power outages. This research, focusing on customer experiences, helps guide investment decisions aimed at improving reliability [2]. Studies estimate the total cost of interruptions by combining two approaches: (1) residential customer

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[1] In this paper, we use the terms power disruption, interruption, and outage interchangeably—this terminology indicates a complete loss of power for some amount of time.

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willingness-to-pay to avoid disruptions, and (2) non-residential customer estimates of interruption-related costs and savings from using alternative power sources. There is a small, but growing amount of literature on the economics of WLD interruptions, primarily using computational regional economic modeling, which can estimate both direct and indirect costs of these disruptions[2] [3].

At the same time, in the study of power interruptions as in energy analysis more generally, considerations of equity are becoming increasingly important. Researchers are studying the disparate impacts of power interruptions on vulnerable and less-advantaged customers, which are of growing concern to decision-makers,[3] as is the importance of understanding how policies and measures to mitigate these impacts should account for heterogenous socio-demographic and economic circumstances.

A central theme in economic and other social science research on WLD power interruptions is the importance of *resilience* – the capacity of electricity users to adapt to power interruptions in ways that mitigate their impacts – for example, by using back-up generators in homes and businesses. Customers can develop short-term adaptations that do not include durable goods and long-term adaptations that include durable goods. For residential customers, these durable goods may include acquiring diesel generators, battery storage, or retrofitting their homes to add more insulation. This paper focuses on the short-term response of customers that consume non-durable goods - if any - as a resilience strategy to mitigate WLD interruptions.

This paper addresses the following research questions:

- How do the duration of interruptions, their season, the urban/rural condition of customers, and their household income influence the decision to relocate during long-duration interruptions?
- What are the economic costs of different strategic responses to long-duration interruptions and what are the equity considerations of these responses?
- What interventions can planners, policymakers, and regulators implement to mitigate the impacts of power interruptions equitably and effectively?

Our research on disproportionate impacts during power interruptions reveals actionable interventions for planners, policymakers, and regulators to proactively address these disparities in the context of WLD interruptions. By examining how customers navigate interruptions within the existing infrastructure, we have identified key insights to inform immediate, equitable, and effective interventions that bolster resilience. These interventions can directly address the specific needs of vulnerable communities while strengthening the entire system.

The paper is organized as follows. The next section provides a literature review and summary of how our work relates to and contributes to the knowledge base on resilience to WLD power interruptions. Section 3 summarizes our survey approach, including sampling strategy and the key questions posed to respondents. Section 4 then presents a summary of the reported overall resilience strategies, a statistical analysis of the determinants of the decision whether to relocate during an interruption, and analyzes the details of customer resilience costs, including the differences among income groups. The paper concludes with a summary of our main findings, their key implications, and suggestions for further work.

2. Literature review

From a technological point-of-view, “resilience” refers to the electricity system's capacity to withstand disruptive events without interrupting service to customers, or to recover expeditiously when interruptions occur [4]. In this paper, we focus on the complementary topic of *human* resilience in the face of WLD power interruptions: How electricity customers adaptively respond to the loss of electricity services in ways that mitigate its impact on their households.

Work on, or related to, residential resilience to WLD power interruptions takes several forms. A very basic issue is the deployment of back-up electricity sources. Hill [5] revealed that 15% of U.S. homes possess portable or standby generators, with a 45% increase in generator sales in 2012, a year with over 120 major outage events. Thompson and Pescaroli [6] analyzed generator sales nationwide and identified underlying trends influencing changes in consumer preference for electricity resilience. Their findings suggest a surge in backup generator adoption across the U.S., indicating a growing private demand for energy resilience driven by perceived risks and diminishing tolerance for power disruptions. In a related study, Dominianni et al. [7] examined power outage preparedness (having a three-day drinking water supply, non-perishable food, and a working flashlight) and concern among New York City residents, and found that 58% were prepared.

A number of surveys related to specific events have been conducted, generally dividing into those in which respondents experienced power interruptions and those in which respondents were presented with hypothetical interruptions. The former include *ex-post* studies of the impacts of hurricanes and other extreme weather events and one on the effects of utility power shut-offs to reduce wildfire risks. Chakalian et al. [8,9] studied Floridians who had experienced power outages during Hurricane Irma in 2017. They found that 45% of respondents had used a back-up generator, and that about 20% had evacuated. Abi Ghanem et al. [10] found that customers in the U.K experiencing power interruptions during winter storms significantly shaped subsequent resilience. Helsloot and Beerens [11] found that about 40% of residents in the Netherlands attempted to adapt by seeking emergency power sources during an

[2] “Direct” costs for residences are also in terms of avoided microeconomic welfare losses, while those for businesses are in terms of the value of lost production; “indirect” costs are upstream- or downstream production losses that propagate through an impacted regional economy.

[3] These include public entities such as state urban planners, local governments, emergency response agencies, and state energy officials, as well as private actors such as electric utilities and vendors of backup generation.

extended power interruption in 2007. Mildenberger et al. [12] found that experiencing public safety power shutoffs[4] in Northern California increased respondents' intentions to purchase generators and home battery systems.

There have also been several studies using statistical or other modeling or simulation methods. Abbou et al. [13] developed mixed-logit models predicting individual adaptation probabilities for electricity and water interruptions in Los Angeles, California, emphasizing the role of individual characteristics and outage duration. Their findings highlighted the influence of factors such as medical device usage on adaptation choices. Gangwal et al. [14] applied this approach to outages caused by winter storms in New York, North Carolina, and Texas. Dulam et al. [15] applied the "Household Adaptations to Service Interruptions (HASI)" theoretical typology to study adaptation attributes in the context of outages. Mahdavian et al. [16] simulated a hypothetical blackout to examine societal responses, finding that expressed intentions to evacuate increased with outage duration. Nejat et al. [17] used logistic regression and principal component analysis to analyze the effects of Winter Storm Uri in Texas in 2021, and found that power outages caused by the storm disproportionately affected vulnerable populations. Reilly et al. [18] examined tradeoffs between individual and collective actions to strengthen power system resilience, using an agent-based model to study the interactions affecting a community's likelihood of power loss during repeated hurricanes.

A subset of these studies considered equity aspects. Dominianni et al. [7] found that levels of preparedness and awareness of power outage notification programs were low among vulnerable respondents, defined as older adults (65 years or older), and respondents with household members who require assistance with daily activities or depend on electric medical devices. Abbou et al.'s [13] findings included Hispanic and Caucasian respondents being 10 percentage points less likely than Asian respondents to move to a friend's or relative's home during an outage, and that higher-income respondents, in general, were more likely to move. Chakalian et al. [8,9] observed enhanced resilience in households with higher incomes and fewer vulnerabilities in post-Hurricane Irma Florida, where Caucasian respondents were more likely to utilize generators. Challenges with accessing food and water were noted in households with young children. Nejat et al. [17] found that the prevalence of power outages in Texas following Winter Storm Uri in 2021 was higher in neighborhoods with, among other characteristics, more multi-family and less owner-occupied housing, and more residents living in poverty and without health insurance. Table 1, below, contains a summary of these studies.

There have been numerous studies of evacuations or relocations caused by natural disasters, particularly hurricanes, with some of these examining transportation impacts. For example, Staes et al. [19] found disparate impacts on Florida roadways of the evacuation for Hurricane Irma in 2017, with most interstate highways remaining congested, others underutilized, and roadways that were usually underutilized being severely impacted by congestion and bottlenecking. However, there is very little work on those related specifically to power outages. Abbou et al. (2021) found that persons with higher income were more likely to move (to a relative's dwelling, hotel, or out-of-town) in the event of a power outage. Dugan et al. [20] created a "social vulnerability index" to analyze the effects of power outages that included evacuation, with "evacuation vulnerability" meaning being subject to obstacles in complying with mandatory evacuation orders. Scheele et al [21] used an agent-based model to analyze residents' decisions regarding evacuation following a hypothetical volcanic eruption in New Zealand, including the particular influence of loss of electrical service. These studies, however, did not examine large-scale transportation infrastructure implications of evacuations.

The research described in this paper makes several contributions. First, in contrast to the work discussed above, we combine granular data on consumers' resilience strategies with information on the economic costs of these strategies, drawing upon a novel customer survey of residential electricity customers of Commonwealth Edison (ComEd) - a large investor-owned utility (IOU) in the Midwest U.S. Second, as noted above, previous research on the economics of both short- and long residential power interruptions has been based on the concepts of stated or revealed preference. These approaches estimate the value customers place on electricity reliability, whereas the approach used in this study measures reported household expenditures and losses associated with responding to actual interruption events. The two approaches therefore capture related but distinct dimensions of interruption impacts. Our survey focused on direct and indirect customer costs incurred during outages, including expenditures, lost time, and spoiled goods, to provide insight into the practical mechanisms underlying household responses to power interruptions. To improve response reliability, the survey included structured cost categories, bounded recall questions tied to specific outage events, and consistency checks across related responses. However, the results remain subject to common self-reported survey limitations, including recall bias, omission of unobserved costs, and potential over- or under-estimation of interruption-related impacts. Third, we integrate this information with data on key dimensions of equity and vulnerability - household income and dependence on electrical medical equipment - to identify possible differences in these actions across a heterogeneous customer population. Fourth, one important possible resilience action is to voluntarily leave the area of residence during a long-duration power disruption. Mass evacuation for any reason may put significant burdens on a regional transportation system. This possible consequence of power interruptions specifically has also received little attention in the research literature, which our paper contributes to. This paper presents a statistical analysis of the determinants of customers' decisions of whether or not to evacuate, examines the costs associated with doing so, and assesses the role of customer-owned backup generation in this decision.

3. Methods and data

We analyze survey data obtained from ComEd's residential electricity customers to understand how customers react to hypothetical WLD power interruptions. This survey provided valuable insights into individual behaviors and mitigation strategies and included data

[4] Deliberate interruptions in power by the Pacific Gas & Electric utility to reduce the risk of wildfires caused by electricity infrastructure.

Table 1
Studies on resilience to power interruptions: Preparedness and/or behavior.

Study	Event type or other	Location	*Ex-post* or hypothetical	Data/methods	Equity aspects considered
Abbou et al. [13]	Electricity and water service interruptions – 1-, 3-, 7-, or 30-day duration	Los Angeles County, California	Both	Stated- and revealed-preference survey; mixed logit modeling	Income, race, employment status, education, electricity-dependent medical equipment
Chakalian et al. [8,9]	Hurricane Irma, 2017	Highland and Orange Counties, Florida	*Ex-post*	Survey/interview	Income, race/ethnicity, employment status, access to food/water/medical care
	Winter storm, 2022		Both	Stated- and revealed-preference survey; mixed logit modeling; typology framework	
Dulam et al. [15]		New York state and North Carolina			Income, race, employment status, education, electricity-dependent medical equipment
Dominianni et al. [7]	Preparedness study	New York City	Hypothetical	Random sample telephone survey	Income, race/ethnicity, dependence on electric medical equipment
Gangwal et al. [14]	General outages; winter storms	California, New York, North Carolina, Texas	Both[a]	Stated- and revealed-preference survey; mixed logit modeling	Income, race, employment status, education, electricity-dependent medical equipment
Abi Ghanem et al. [10]	United Kingdom 2014 winter storms	North and West Wales, U. K.	*Ex-post*	Interviews with residents who had experienced power interruptions of more than 12 h	None specified
Helsloot and Beerens [11]	2007 three-day winter power outage caused by accidental damage to power lines	The Netherlands	*Ex-post*	Interviews with affected residents	None specified
Hill [5]	Back-up generation ownership survey	U. S. National	N/A	Industry market survey	None specified
Mahdavian et al. [16]	3-day blackout	France and Germany	Hypothetical	In-person scenario role-playing workshop	Effects on elderly participants
Mildenberger et al. [12]	2019 Public-safety power shutoffs	Northern California	*Ex-post*	Mail-to-web survey of affected customers	Income, employment status, educational attainment, non-English-at-home

[a] 29% of respondents reported having lost power during Superstorm Sandy in 2012.

on customer preparedness (e.g., backup generators), preferred responses to outages, and the direct costs incurred or savings realized during these events. The survey instrument is available in the supplementary information.

We designed a survey instrument based on prior methodological work integrating customer interruption cost (CIC) survey and computable general equilibrium (CGE) modeling for estimating the impacts of widespread and long-duration power interruptions [2]. We adapted the instrument to reflect ComEd's service territory and the specific WLD power interruption scenarios evaluated in this study and implemented it using the Qualtrics survey platform. The residential survey targeted a stratified sample of ComEd customers developed using information from ComEd's customer database. The sampling approach was designed to achieve representation across rural, suburban, and urban service areas. The research team developed the recruitment sample using information from ComEd's customer database and conducted recruitment outreach through postal mail and email. Prior to the main survey launch, a two-week pre-test was conducted from March 3–16, 2022 with 330 customers to evaluate the clarity of interruption scenarios and survey questions and to assess whether the recruitment strategy could achieve the anticipated response rates. Responses from the pre-test were not included in the final analytical dataset.

The main survey was administered online over a nine-week period from April 20–June 21, 2022 to the remaining recruited sample. The survey targeted approximately 200 completed responses from each geographic area. These targets were initially informed by Cochran's sample size formula and were subsequently adjusted based on project timeline and resource constraints. Respondents received a $5 incentive upon completion. Respondents who did not complete all required components of the survey were excluded from the analysis. Missing responses occurred primarily in a small number of critical sections, including resilience strategy selection and key cost reporting modules. These items were treated as required fields for inclusion because they are necessary for constructing consistent resilience and cost measures. The final residential analytical sample includes 814 valid responses out of 829 completed

Table 2
Sample design and response summary by geographic area.

Area	Population count	Sample size	Target number of responses	Responses received	Response rate	Valid response
Rural	235,269	2110	200	266	13%	258
Suburban	1,219,878	2110	200	354	17%	350
Urban	2,075,837	2110	200	209	10%	206
Total	**3,530,984**	**6330**	**600**	**829**	**13%**	**814**

residential surveys. Table 2, below, summarizes the population, sample, and responses received for the residential survey.

We reviewed all survey responses for completeness, internal consistency, and potential outliers prior to analysis. Most cost and savings estimates were collected using open-ended direct-response questions. We applied structured data cleaning procedures to address inconsistencies, including identification of implausible values, correction of likely unit misreporting, and harmonization of reported cost components across respondents. Where feasible, missing cost components were infilled using related survey responses and intermediate calculations. The survey design incorporated bounded interruption scenarios and structured cost categories to improve comparability across respondents.

The survey introduced respondents to three hypothetical scenarios representing varying durations of power interruption induced by extreme weather events, spanning from more typical occurrences to the most extreme event that the utility could anticipate: 24 h, three days, and two weeks. These durations were defined in coordination with ComEd to reflect representative operational planning scenarios, including a short-duration event associated with routine restoration conditions, a mid-duration event reflecting more sustained outage conditions, and a long-duration event representing an extreme but plausible system-wide disruption. Half of the respondents were exposed to summer events, and the other half to winter events. Each scenario described a complete power disruption affecting a 20-mile radius around the customer's residences, starting suddenly and without warning. Within a few hours of the outage, respondents would receive notification from the utility regarding the estimated restoration time (24 h, three days, or two weeks), which would remain unchanged. For each of the three WLD power interruption scenarios, residential survey participants were given one of three possible resilience strategy choices:

1. Stay home and do activities that do not require electricity
2. Stay home and operate backup power systems that had been previously purchased
3. Temporarily move to a location that has power (outside the impacted area in a 20-mile radius)

Following their chosen mitigation strategies, respondents estimated the associated costs incurred. As noted above, unlike typical customer interruption cost surveys of residential customers that ask about their willingness-to-pay for hypothetical backup services, our survey focused on expenditures incurred due to the simulated interruptions. This included expenses for food spoilage, lost income, meals, lodging, transportation, and fuel/generator rental for those utilizing backup power.

In addition to exploring mitigation strategies and power interruption costs, respondents provided valuable information to evaluate the impact of power disruptions on their households. This information encompassed their ability to operate heating systems during outages, the type of residence they inhabited, the composition of their households (e.g., the number of occupants), and their annual household income.

4. Results

In this section, we examine the responses to mitigating the impacts of 1-, 3-, and 14-day power interruptions. Section 4.1 focuses on how people's strategies for coping with these disruptions change depending on the outage duration, and what factors influence their decisions about relocating during an outage. Section 4.2 examines the financial burden that these coping strategies place on customers. Finally, Section 4.3 examine the impacts of relocation decisions on transportation infrastructure.

4.1. What determines customers' resilience responses to long duration interruptions?

Customer's responses to long-duration power interruptions are conditioned by their particular attributes – such as income, household occupants, rural/urban location, and type of residence – and attributes of the interruption itself – such as season and duration. In this section, we report outcomes from the survey, and then process these outcomes using a logistic regression model to identify the relative relevance of drivers for the relocation decision.

Survey results suggest that interruption duration is one of the most impactful attributes influencing customer resilience response. Fig. 1 depicts how customer behavior depends on outage durations. Customers expressing a preference for temporary relocation during shorter interruptions consistently leaned towards maintaining that decision if durations were longer. Respondents who preferred staying at home and operating their backup generators during the one-day power interruption (105 responses) remained relatively consistent with longer-duration interruptions. Approximately 80% of these individuals chose to stay at home with backup generators even as the outage extended to three days (81 out of 105). Notably, half of the respondents with backup generators chose to remain at home throughout the longest outage duration (53 out of 105).

Conversely, respondents who initially favored staying at home without backup generators are more sensitive to interruption duration. Roughly half of the respondents chose to remain without backup generators during a one-day outage (439 out of 814), but 50% of these individuals shifted their strategy to temporary relocation when exposed to a three-day interruption (235 out of 439). Finally, another 67% of the remaining customers who had chosen to stay home with a three-day interruption chose to temporarily relocate for the longest duration (136 out of 202).

These findings align with existing research indicating that the intention to evacuate increases with the duration of power interruptions [16]. However, our results offer a more nuanced understanding, suggesting that such intentions vary at different rates based on individuals' preferred strategies for mitigating the impacts of prolonged power outages and their ownership of backup generators. This highlights the need for differentiated approaches to outage management, considering the diverse needs and preferences of consumers.

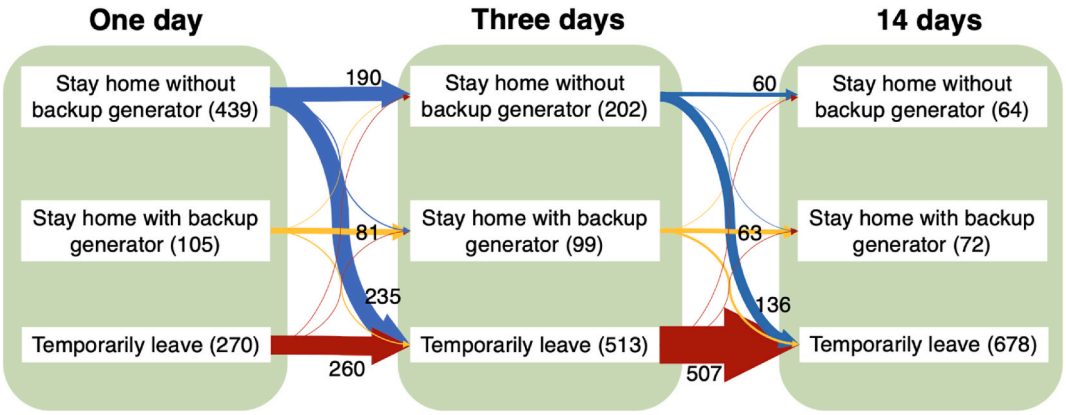


Fig. 1. Sankey diagram depicting the evolution of respondents' behavior in mitigating the impacts of prolonged power interruptions across varying durations. The thickness of an arrow reflects the number of respondents transitioning between strategies, and the numbers next to the arrows represent the major transitions of respondents between strategies as the power interruption lengthens.

We implement a logistic model to investigate the significance of other variables as determinants of a resilience strategy. The dependent variable in the logistic model indicates whether customers relocate during a specific timeframe, while the independent variables encompass factor variables (such as weather scenario, income levels, household income relative to the federal poverty line, geographical regions, and ownership of backup generators or critical medical devices) and continuous variables (including household member count, lost income, spoiled food value due to power interruptions, and duration of power interruptions). The basic model is shown in Equation (1) below. We also explore alternative models by incorporating additional potentially relevant variables that may be correlated with variables they substitute, but contribute to a better understanding of the relocation response. Table 3 details the specific variables used in both the base and alternative models and Table 4 reports descriptive statistics for these variables. We calculate the Variance Inflation Factor (VIF) to test for multicollinearity in the covariates. We find that the Generalized VIF for covariates in the base model and all the alternative models is below 1.4 and generally close to 1, which suggest very little correlation between covariates.

$$logit(p(x)) = Weather + Household\ income\ level + Residence\ type + Region + Number\ of\ household\ members + Ownership\ of\ critical\ medical\ devices + Ownership\ of\ backup\ generators \quad (1)$$

Table 3
Explanatory variables for the regression analysis.

Variable	Description	Included in the base or alternative model?
Weather	Dummy variable captures the weather conditions during the power interruption scenarios, summer (reference level) and winter	All models
Household income level	Categorical variable categorizes participants' annual household income level as above $100k (reference level), between $50 to $100k, and below $50k.	Base model, Alt 2, Alt 3
Vulnerability	Dummy variable categorizing participants with household income exceeding the federal poverty line (reference level) and below the federal poverty line	Alt 1
Residence type	Categorical variable identifies participants' residence type as single-family home (reference level), duplex, townhouse, apartment, and others.	All models
Region	Categorical variable identifies participants' geographical area as urban (reference level), suburban, or rural	All models
Number of household members	Number of residents living in the participants' households. Ranging from 1 to 12	All models
Ownership of critical medical devices	Dummy variable indicating participants who do not own critical medical devices (reference level) and others with at least one critical medical device.	All models
Ownership of backup generators	Dummy variable indicating participants who do not own backup generators (reference level) and others with at least one backup generator.	All models
Duration of power interruption	Duration of given power interruption. 1, 3, and 14.	All models
Value of spoiled food	Expected amount of monetary loss due to food spoilage during the one-, three-, and 14-day outages divided by 1000 (continuous). Ranging from 0 to 7.5.	Alt 3, Alt 4
Lost income	Expected amount of monetary loss due to lost income during the one-, three-, and 14-day outages divided by 1000 (continuous). Ranging from 0 to 30.84.	Alt 4

Table 4
Descriptive statistics for variables used in the regression analysis.

Duration of power interruption	Severe summer thunderstorm			Ice storm		
	1 Day N = 399[a]	3 Days N = 399[a]	14 Days N = 399[a]	1 Day N = 415[a]	3 Days N = 415[a]	14 Days N = 415[a]
Number of household members	2.61 (1.45)	2.61 (1.45)	2.61 (1.45)	2.44 (1.31)	2.44 (1.31)	2.44 (1.31)
Missing	4	4	4	4	4	4
Value of spoiled food	0.23 (0.42)	0.46 (0.56)	0.49 (0.52)	0.19 (0.35)	0.42 (0.49)	0.50 (0.64)
Missing	51	52	40	54	47	32
Lost income	0.08 (0.32)	0.21 (0.58)	0.65 (1.99)	0.09 (0.38)	0.17 (0.60)	0.58 (2.20)
Decision to relocate	121 (30%)	231 (58%)	321 (80%)	149 (36%)	282 (68%)	357 (86%)
Household income						
Above 100k	122 (31%)	122 (31%)	122 (31%)	130 (31%)	130 (31%)	130 (31%)
Under 50k	90 (23%)	90 (23%)	90 (23%)	82 (20%)	82 (20%)	82 (20%)
$50-100k	106 (27%)	106 (27%)	106 (27%)	106 (26%)	106 (26%)	106 (26%)
Refuse	81 (20%)	81 (20%)	81 (20%)	97 (23%)	97 (23%)	97 (23%)
Residence type						
SFH	283 (71%)	283 (71%)	283 (71%)	294 (71%)	294 (71%)	294 (71%)
Duplex	20 (5.0%)	20 (5.0%)	20 (5.0%)	7 (1.7%)	7 (1.7%)	7 (1.7%)
Townhouse	19 (4.8%)	19 (4.8%)	19 (4.8%)	34 (8.2%)	34 (8.2%)	34 (8.2%)
Apartment	43 (11%)	43 (11%)	43 (11%)	48 (12%)	48 (12%)	48 (12%)
Other	34 (8.5%)	34 (8.5%)	34 (8.5%)	32 (7.7%)	32 (7.7%)	32 (7.7%)
Region						
urban	98 (25%)	98 (25%)	98 (25%)	108 (26%)	108 (26%)	108 (26%)
suburban	175 (44%)	175 (44%)	175 (44%)	175 (42%)	175 (42%)	175 (42%)
rural	126 (32%)	126 (32%)	126 (32%)	132 (32%)	132 (32%)	132 (32%)
Ownership of critical medical devices	71 (18%)	71 (18%)	71 (18%)	86 (21%)	86 (21%)	86 (21%)
Ownership of backup generators	46 (12%)	46 (12%)	46 (12%)	51 (12%)	51 (12%)	51 (12%)

[a] Mean (SD); n (%).

Base model results and alternate models reveal that individuals' odds of relocating during extended power interruptions are higher for winter events compared to summer events (Table 5). This may reflect that Illinois customers believe that power interruptions occurring in the winter are more hazardous than the summer conditions and therefore prefer to relocate more during the former. Household income is not statistically significant in the base model, but it is in the alternative specifications. Results suggest that poor customers are more likely to relocate than wealthier customers. This particular result is surprising given the economic costs associated with relocation, which we will describe in the next section, and stands in contrast with results from recent studies (e.g. Ref. [13]). A possible explanation for this difference is that Abbou et al. based its study in Los Angeles, whose climate is milder than that of Illinois. Poor customers that tend to have deficient dwellings may not want to endure interruptions in Illinois compared to those that might occur in milder Los Angeles weather.

In the base model - as well as all the other model specifications - rural customers are consistently less likely to relocate compared to their urban counterparts - a statistically significant result. Rural customers may be naturally more prepared to endure weather events, but may also reflect that they consider it less practical to relocate given that they live far from other population centers and that road access may be more severely compromised after storms compared to urban customers.

Housing type does not appear to be a statistically significant covariate in the base model, but the addition of monetary covariates in other specifications makes apartment buildings statistically significant. Results in alternate specifications suggest that customers who live in apartment buildings have higher odds of relocation compared to customers who live in single-family homes. This may reflect that living conditions in multi-family buildings may deteriorate faster than in other types of dwellings, in particular if elevators are not working and accessing higher floors is challenging. In turn, the number of household members is significantly correlated with the odds of relocating, with every household member increasing the odds of relocating by about a factor of 0.12.[5] This result may reflect the fact that families, which typically have several household members, are more likely to relocate compared to single individuals.

The models test for the correlation of owning two specific assets: critical medical devices and backup generators. Findings show that users of critical medical devices that are powered by electricity are very likely to relocate. Indeed, the odds of relocating increase by a factor of 0.7 when owning these devices. In contrast, households that own generators are significantly more likely not to relocate and stay at their house, which is expected given that their backup source can provide at least some basic services. These two results are consistent across model specifications.

The duration of a power interruption is positively correlated with the odds of relocating. When controlling for all other variables, each additional day an interruption lasts increases the odds of relocation for the residential customer by a factor of about 0.17-0.18. This result is not surprising based on the results earlier in this section (e.g. see Fig. 1). We reiterate that in our survey, customers had perfect information on the duration of the interruption at its onset. The odds of relocating when a shorter interruption lengthens for unforeseen reasons are not captured in this analysis.

[5] Note that our responses have adequate sample size for households up to size 6. The impact of additional household members above 6 may not be captured well in these results.

Table 5
Logistic regression results for relocation decisions among respondents with annual household income information.

	Dependent variable: Relocation (1: Yes, 0: No)				
	Base model (Base)	Base with vulnerability status (Alt 1)	Base with spoiled food value (Alt 2)	Base with spoiled food value and lost income (Alt 3)	Base without income from all respondents (Alt 4)
Weather (Winter)	0.28** (0.11)	0.27** (0.11)	0.26*** (0.12)	0.26*** (0.12)	0.43*** (0.10)
Household income level (Under $50k)	0.24 (0.15)		0.28** (0.16)	0.28** (0.16)	
Household income level ($50-100k)	−0.023 (0.13)		0.001 (0.14)	0.002 (0.14)	
Vulnerable (household income below the federal poverty line)		−0.25 (0.18)			
Residence type (Duplex)	0.19 (0.29)	0.21 (0.28)	0.035 (0.30)	0.034 (0.30)	0.13 (0.27)
Residence type (Townhouse)	−0.35 (0.23)	−0.33 (0.23)	−0.34 (0.30)	−0.34 (0.30)	−0.39** (0.20)
Residence type (Apartment)	0.29 (0.19)	0.44** (0.18)	0.32* (0.20)	0.33* (0.20)	0.36** (0.16)
Residence type (Other)	0.31 (0.21)	0.34 (0.21)	0.14 (0.22)	0.14 (0.22)	0.34* (0.18)
Region (Suburban)	0.022 (0.14)	−0.001 (0.14)	0.037 (0.15)	0.037 (0.15)	0.076 (0.12)
Region (Rural)	−0.38** (0.15)	−0.35** (0.15)	−0.31* (0.16)	−0.31* (0.16)	−0.35*** (0.13)
No. Household members	0.12*** (0.04)	0.12*** (0.04)	0.073 (0.05)	0.075 (0.05)	0.11*** (0.04)
Ownership of critical medical devices	0.74*** (0.14)	0.76*** (0.14)	0.64*** (0.15)	0.64*** (0.15)	0.69*** (0.13)
Ownership of backup generators	−1.89*** (0.20)	−1.95*** (0.20)	0.52 (0.36)	0.52 (0.36)	−2.01*** (0.17)
Duration of power interruption	0.18*** (0.01)	0.18*** (0.01)	0.20*** (0.01)	0.20*** (0.02)	0.18*** (0.01)
Value of spoiled food			0.65*** (0.17)	0.65*** (0.17)	
Lost income				−0.032 (0.06)	
Constant	−0.90*** (0.21)	−0.83*** (0.19)	−0.95*** (0.23)	−0.96*** (0.23)	−0.86*** (0.17)
Observations	1890	1890	1890	1890	2418
Log-likelihood	−1030.32	−1031.15	−869.22	−869.10	−1311.37
Akaike Inf. Crit.	2088.65	2088.29	1768.43	1770.19	2646.58

Note: * = significant at 10%, ** = significant at 5%, *** = significant at 1% | Standard errors in parentheses under coefficients.

The alternate specifications introduce a different way to represent income as well as two economic impacts (expected cost of spoiled food and expected income loss). Using a vulnerability index instead of household income brackets does not appear to influence the results and its coefficient is not statistically significant.

The cost-related covariates, however, do introduce changes, in particular the cost of spoiled food. Introducing the latter increases the odds of poor customers relocating compared to wealthier customers and moderately increases the odds of relocating for generation-owning customers. Interestingly, the odds of relocating are positively correlated with increased costs of spoiled food, which raises a question of causality. Customers may decide to relocate regardless of the expected cost of spoiled food; then, customers who relocate expect that all of their food will spoil, in contrast with customers who stay home may decrease their losses in spoiled food by consuming it before it goes bad. The regression results may very well be capturing this dynamic. It is also possible that the cost of spoiled food may be acting as a proxy for the overall economic costs of the interruption and customers' responses may reflect that larger expected economic costs substantially increase the odds of relocating. The causal relationship between the relocation decision and the expected economic costs of the interruption cannot be established with our survey and should be examined with survey instruments specifically designed for this purpose.

An unobservable variable that can explain a relocation decision are customer's traits such as risk aversion or past trauma from disasters. From the independent variables in the model, generator ownership may be endogenous if customers purchase generators due to these unobservable traits. We tested for the potential endogeneity of generator ownership using a Rivers-Vuong control function approach, which requires an instrumental variable. Our survey asked whether the respondent had endured an interruption of 24 h or longer, which is a suitable instrument to test for ownership of generators. Employing this 'Past 24-h power interruption' as an instrumental variable, the first-stage F-statistic (11.45) in the River-Vuong approach indicates sufficient instrument strength. We find that the residual term is not statistically significant ($p > 0.05$), failing to reject the null hypothesis of exogeneity.

The regression analysis highlights the role that key variables have in driving customers to relocate under long duration interruptions. The strategic response and its drivers inform the monetary impacts of these interruptions and the survey instrument was designed to capture the costs that relocating and non-relocating customers would incur due to their strategic response. The levels and distribution of these costs among income brackets provide important information to understand the economic impacts of long duration interruptions. The following subsection explores these results.

4.2. What are the economic costs of customers' strategic responses to long-duration power interruptions?

Table 6 below summarizes the cost categories associated with each risk-mitigation strategy employed during the long-duration power interruptions. For example, all customers may suffer income losses regardless of their resilience strategy. In contrast, only customers that have and operate backup generation may experience fuel related costs.

Based on their choice of resilience strategy, we asked residential customers about the costs they would incur during the three long-duration power interruptions. Note that these costs include monetary *expenditures* that directly come from the strategic response to the interruption, as well as *losses* that accrue due to the interruption itself. These costs were estimated at the household level, with the applicable cost categories varying according to the chosen resilience strategy.

The economic cost analysis distinguishes the decision to stay home for customers with and without generation because of the different cost structure between those customers. Fig. 2 illustrates the average power interruption costs breakdown by selected resilience strategy and duration of power interruptions. For the relocation strategy, respondents were asked to consider temporarily moving some or all household members to a location with electric service, including staying with family or friends, hotels, or emergency shelters outside the affected area. The survey intentionally treated these as a single relocation category and did not distinguish among accommodation types or the duration of relocation within the outage period. Consequently, the reported relocation costs represent average expected expenditures across a range of relocation scenarios envisioned by respondents. Power interruption costs tend to rise proportionally with outage duration for all three strategies. Relocation incurs the highest average cost across all three interruption durations and can be five times to an order of magnitude higher compared to the costs that customers that own generators incur. Staying home without a backup generator is typically the option with the second highest cost, typically double to five times higher than the respondents with generators. Respondents who chose staying home with backup generators had the lowest costs. However, it's important to note that these results are partially influenced by excluding the acquisition cost of backup generators for existing owners. This exclusion is due to both a lack of data on acquisition costs and the difficulty of allocating this cost to specific outages.

We analyzed responses by risk category and three income levels (Fig. 3) to understand the impact of income on cost changes across mitigation strategies. For simplicity, we focused on average costs for a 14-day outage. Not surprisingly, lost income increased with household income for all strategies. However, examining other expenses reveals a more nuanced story of how the financial burden of outages affect households. The "relocation" group's meal and lodging costs showed minimal variation across income brackets. However, other costs like spoiled food and lost income rose with income, highlighting the income gap's impact. For the "stay home with generator" group, wealthier respondents spend significantly more on meals and transportation during outages (averaging $495) compared to other groups (averaging $70-$73). Other groups reported very low costs in these categories, likely due to affordability constraints or a preference for alternative strategies.

The analysis of costs by income brackets shows that higher income households generally incur higher expenditure and losses due to interruptions. However, these households have higher income and the actual burden of these expenditures and losses may be less important compared to poorer households. To assess this burden, we calculated a relative financial burden ratio. This ratio is obtained by dividing the estimated economic loss incurred during the interruption as reported by the customer by the median monthly income within each income bracket. We used the originally reported ten income brackets (ranging from under $25k to above $250k) for the calculation and then aggregated them into the same three broader categories (low: under $50k, middle: $50k to $100k, high: above $100k) for easier visual representation (see Fig. 4).

Our analysis reveals a disparity in the relative financial burden experienced by households during power outages. Lower-income households consistently suffer a significantly higher proportion of monthly income loss compared to their higher-income counterparts. This disparity persists regardless of the chosen mitigation strategy, such as staying home or relocating. The most substantial impact occurs for customers that decide to relocate. In this group, the median share of monthly income lost during the 14-day outage substantially increases and becomes roughly equivalent to the entire monthly income of a low-income household, half their income for middle-income households, and a quarter for high income households. For the other two resilience strategies, the share of monthly

Table 6
Types of costs incurred during long-duration power interruptions by risk-mitigation strategies.

Risk-mitigation strategy	Cost categories						
	Spoiled food	Income losses	Meal with transportation	Generator fuel cost	Generator rental cost[a]	Relocation transportation	Meal and lodging
Stay home with backup generators		✓		✓	✓		
Stay home without backup generators	✓	✓	✓				
Temporarily relocate	✓	✓				✓	✓

[a] Before introducing the outage scenarios, respondents were asked about their backup generators, including the size and fuel type. This data then served as the basis for estimating fuel costs. However, there were some respondents who indicated that they did not have a generator, but opted for staying home with generators. For these respondents, we estimated rental costs as well as fuel costs based on market data.

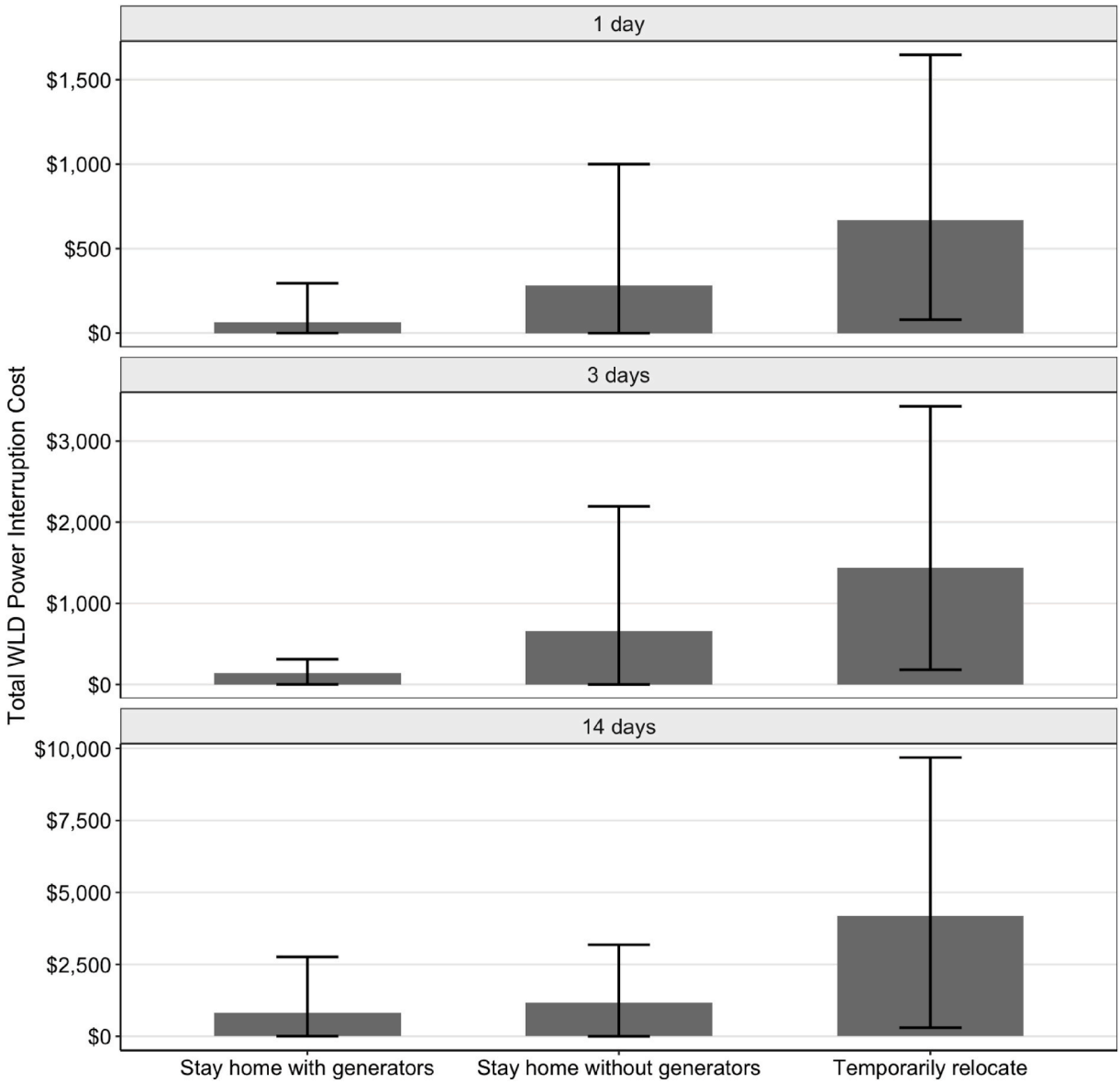


Fig. 2. Average total costs of 1-, 3-, and 14-day power interruptions by selected risk-mitigation strategy and duration of power interruption. Columns indicate the averages with error bars indicating the empirical 5th to 95th percentile ranges.

income that accrues due to staying at home - with and without generators - is still regressive. However, the absolute values are two to four times lower than the customers who relocate, and the differences across income brackets are less pronounced.[6]

In summary, the research findings show that relocation, as broadly defined in the survey, is the most expensive strategy on average, regardless of the duration of the power interruption, but it is also the most common strategy as the duration of the interruption increases. Consequently, the cumulative costs of power interruptions escalate significantly with duration. This phenomenon has profound equity implications, as poorer households might spend about four times as much income as wealthier households to cover relocation costs. In many cases, these relocation costs could place substantial financial strain on lower-income households and may

[6] We also performed two-sample Kolmogorov-Smirnov tests to ensure the observed differences between income groups are statistically significant. These tests compared both the power interruption costs and the percentage of monthly income lost across income brackets (see Tables A2 and A3). Daily interruption costs revealed statistically significant differences between many income-group combinations for the relocation group and some for the stay home without backup generator group. These findings initially suggest a lower impact on lower-income households. However, a more nuanced picture emerged when analyzing the percentage of income lost. This metric, reflecting the households' ability to pay and the higher value placed on electricity from lower income households, reveals the significantly higher impacts on low-income households.



Fig. 3. Average costs of 14-day power interruptions by selected risk-mitigation strategy and income level.

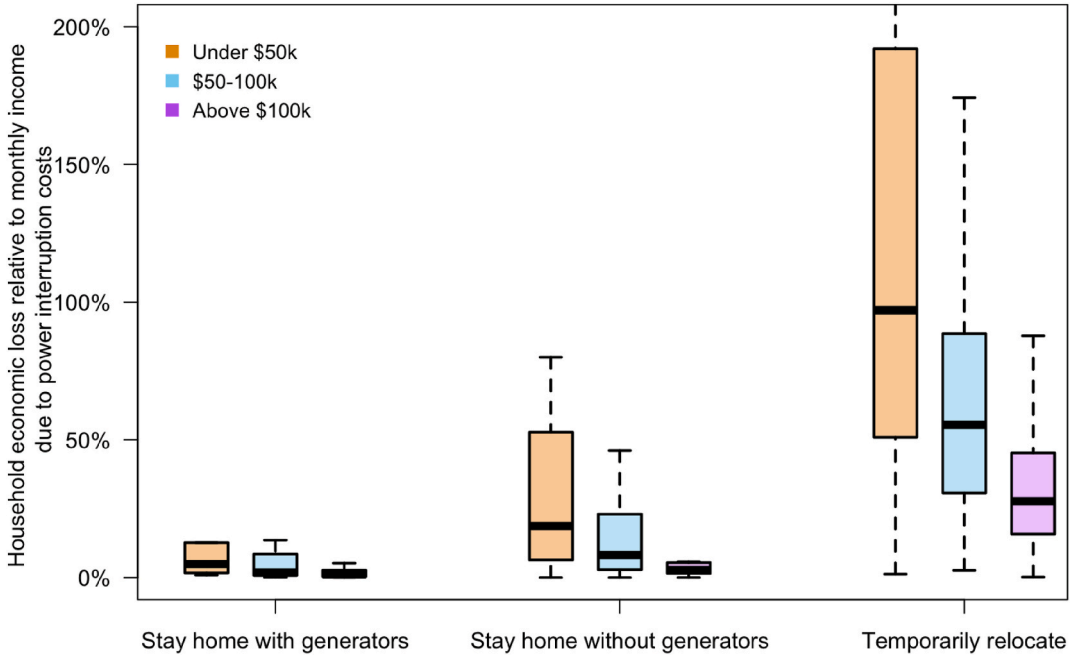


Fig. 4. Distributions of household economic loss relative to household income due to the 14-day-long power interruptions by reported household income level and selected risk-mitigation strategy.

require difficult trade-offs or reliance on financial resources beyond regular monthly income.

Sections 4.1 and 4.2 have reported the drivers of relocation, its financial impacts, and its distributional consequences. In some ways, relocation behaves like a luxury good, with its demand increasing more than proportionally to income. A more adequate interpretation is that customer responses reflect that with a very long duration interruption their only option is to leave their homes and relocate, and they will do that almost regardless of its costs because it might be a life-or-death decision.

The survey did not provide information on how other residents in DuPage (or surrounding) counties might react to the interruption. However, we presume that customer decisions to relocate are, up to a point, made independent of what other customers would decide, because in practical terms a given household has limited opportunity or means to query more than a relatively small number of others. The caveat is that during the course of an interruption, publicly-available information may be provided on road conditions. In any case, in the following subsection we investigate what is one potential implication of the large-scale evacuation implied in customer responses.

4.3. An example of community-level impacts of relocation decisions

Our survey focused only on customer expectations and intentions, not on the impact of the respondents' aggregated anticipated resilience behavior. Given the relatively high rates of relocation especially in the longer interruption durations, we estimate how local and regional transportation infrastructure would be affected by population relocation as implied by the survey responses. This analysis could assist city planners and emergency responders with anticipating problems that may arise due the potential large-scale evacuation implicit in customers' responses.

We select one area in the ComEd service territory - DuPage County Illinois, immediately west of Chicago – as an example for this analysis. DuPage County is the second largest in Illinois and has publicly-available data for this analysis. Extrapolating from the survey results suggests that 45% of the resident population in DuPage County would relocate out of the county during a 1-day power interruption, and up to 80% during a 3-day interruption. Assuming that neighboring counties and areas are not affected by the interruption, we suppose that these persons would go as far as these neighboring counties or further.

We use demographic, employment, and commuting information from the U.S. Census Bureau [22], the Chicago Metropolitan Agency for Planning [23] and the Illinois Department of Employment Security [24] to put these survey outcomes in context (see Table 6). We assume that during the interruption:

1. All workers who normally commute out-of-county by driving alone would be among those relocating, along with the rest of their households;
2. There is at most one such worker per household;
3. All workers who normally commute into the county would cease doing so.

Because our survey did not ask customers about the exact timing of their planned relocations, we also assume that, for a 3-day interruption, customers who relocate would attempt to leave on the first day.

Table 7 shows about 85% out-going commuters drive alone. Under Assumptions 1 and 2, the potential transportation impact of an interruption depends substantially on its duration, as shown in Table 8. A 1-day interruption would result in a relatively small number of additional persons leaving the county, by whatever mode of transport. By contrast, in a 3-day interruption the number of persons attempting to relocate beyond those riding with a normal out-commuter comprises 35% of the DuPage population, a.

71% increase over the normal number of daily commuters.[7]

Based on the historical record, is reasonable to assume that a substantial proportion of the departing residents would attempt to drive. We note that a large number of segments in the county's arterial road system are classified as providing a "failing" level of service (in terms of average traffic speeds) during peak hours under current, normal traffic flows [25]. Our estimates thus highlight the importance of advance planning for extended power interruptions, including substantial engagement with the county residents regarding possible relocations or evacuations. Spread out over an entire day and managed by location (i.e., in terms of the relocation timing of different parts of the county, and departure route), this increased traffic load might be manageable. Otherwise, the 3-day power interruption scenario could result in intractable traffic conditions and potentially dangerous conditions for customers that are evacuating during or right after an extreme weather event.

It is instructive to compare these estimates to several in the literature. Dulam et al. [15] found that in a stated preference survey, up to 48% of respondents would consider relocating during 1-day outage, and up to 65% during a 7-day. However, their corresponding revealed preference estimates were only 5-6%, suggesting that the actual experience of power outages – and possibly relocation or attempted relocation during same – reduces the propensity to relocate. It might be the case that the implications of this discrepancy for actual relocation behavior in the future would therefore depend on the proportion of residents in a given area who have previously experienced long-duration outages.[8]

[7] The Census Bureau data do not indicate the fraction of households in which more than one person commutes out-of-county on a daily basis.

[8] Although not addressing power outages *per se*, Bhowmik et al. [26] estimated that the evacuation rate in Florida during 2017's Hurricane Irma was just under 35% over 9 days. *Ceteris paribus*, this might also indicate that our 3-day stated preference evacuation figure could be an overestimate.

Table 7
DuPage County statistics (Census Bureau and 2023 DuPage County "Community Data Snapshot".

County population	Resident workforce	Live-work in county	Commute from elsewhere	Commute to out-of-county (as % of county population)	Est. out-commuters driving alone	Avg. household size	% households with at least 1 vehicle
921,217	461,643	274,956	279,442	186,687 (20.3%)	157,551	2.63	96%

Table 8
Power interruption-induced changes in daily outgoing travel from DuPage County.

Power interruption duration	Total number relocating out- of- county (as % of resident population)	Relocators in normal drive-alone, out-commuter households	Additional relocators (as % of resident population)
1 day	417,959 (45%)	414,358	3601 (0.4%)
3 days	733,561 (80%)	414,358	319,203 (35%)

5. Discussion, conclusions, and further work

Recent large-scale disasters have underscored the imperative to proactively address risks to critical infrastructure, particularly in energy systems and interdependent networks. Utilities and regulators express a keen interest in "resilience investments" and preventive measures, with studies assessing their costs and benefits. These investments, however, should not be developed in a vacuum. Customers affected by these extreme weather events take action to protect themselves, their families, and property and understanding these actions is critical to design effective hazard mitigation and resilience enhancing interventions. In addition, resilience investments affect customers and may influence their decisions on how to respond to extreme weather events.

Existing studies have shed light on trends in generator ownership, community behaviors, and growing private demand for energy resilience. However, most of these studies are based on case studies developed for specific weather events, which makes their findings relatively unique to the circumstances of that event. We address this issue by leveraging decades of experience in designing surveys to capture the value of lost load for electric utility customers. The survey instrument designed for this work provides a structured way to inquire about customer behavioral responses and their economic impact using duration and season controls to make results more generalizable. Our work fills a crucial gap in the knowledge base on how customers respond to long duration interruptions of varying lengths under different conditions.

We offer several relevant findings in this paper. First, robust results of our logit analysis are that the likelihood of relocation (1) increases with power interruption duration, winter season, urban residence, number of persons in household, and ownership of a medical device; and (2) decreases with the presence of backup generation. It is possible that the relocation decision is influenced by the economic costs of relocation or the losses endured by not relocating, but we are not able to establish causality with our data.

Second, we find that consumers' expenditures and losses increase with duration, regardless of which strategy (stay home with or with backup generation, or relocate). Moreover, costs as a proportion of income are higher for lower-income households for all mitigation strategies. In particular, the median share of monthly income accrued by interruption costs exceeds 100% for low income customers for a 14-day interruption. This means that customers are willing to spend all of their income to mitigate the impacts of such a long duration interruption, and in many cases potentially incur in debt or use up savings to do so. Among the strategies, relocation is the highest-cost and staying home without backup generation is the second highest-cost option. Income losses are a sizable portion of interruption costs for customers that stay at home, with or without backup generators.

Third, our survey respondents were told to assume that power would be interrupted everywhere within a twenty-mile radius of their residence, but provided information only about their own circumstances. Aggregating these responses may reveal the impact of these individual responses. Indeed, an analysis of one county in the ComEd service territory suggests that, based on existing commuting patterns, the aggregate transportation impacts of a 3-day power interruption could be substantial in terms of congestion on streets, roads, and highways. Our analysis suggests about a 70% increase with respect to regular peak hour traffic.Our finding that the likelihood of relocation increases with outage duration is consistent with the results of Gangwal et al.'s [14] and Dulam et al.'s [15] stated preference survey. Similarly, both of those studies found, as we did, that the use of backup generation decreases relocation likelihood. Our finding that relocation likelihood increases with medical device ownership is consistent with Gangwal et al.'s results for California but not for North Carolina.

Our findings have several key implications for decision-makers. First, our results in general highlight the importance of policies and measures to prevent widespread, long-duration power interruptions from occurring in the first place. Recall that outages to the power system can be mitigated or prevented, and how frequently those outages translate to customer interruptions can be mitigated as well. Such interventions can yield large benefits in terms of both avoiding customer economic costs and other impacts and preventing potentially significant problems with non-energy public infrastructure. Moreover, when they do occur, measures to reduce their scope and duration - i.e., to achieve timely restoration of power to affected areas - are also important, given how much costs escalate as the disruption length increases.

Second, the economic costs of long duration interruptions vary widely across customers, but they add up to a sizable amount. We calculate the share of households in our survey that adopt each resilience strategy (Fig. 1) and apply this proportionally to calculate the number of households in ComEd's service territory that would adopt each strategy, based on a total of 3,727,675 households. We then

multiply this by the 14-day interruption cost per household, using the 25th percentile as a low bound and the 90th percentile as an upper bound (see Fig. 2) These simplified statewide extrapolations of our results suggest that a 14-day interruption could produce $5 to $25 billion in economic costs to residential customers alone. Regulators and city planners can use these values as a starting point to conduct cost-benefit analyses of customer-, community-, and grid-level resilience investments. Furthermore, both system-wide prevention and customer-level resilience can reduce sizable equity disparities in the impacts of severe power disruptions and the costs of customers' response strategies. These pertain both to differences in these costs as a function of income and to the particular vulnerability of households using electricity-dependent medical equipment. Policymakers might consider providing financial assistance to low-income households when long duration interruptions occur, both to limit the economic strain of their short-term resilience response as well as enabling these lower income customers to afford the resilience response that they consider appropriate to protect their family and property.

Third, our results show the challenges of improving resilience for residential customers due to the widespread nature of long duration interruption impacts. In other words, electric service interruption impacts can be mitigated with actions that are outside of the power sector. For example, results show that loss of income can be a relatively large loss for customers during the shorter interruptions examined in this work. It follows that income loss insurance against these types of events may – mitigate the economic impact, but it is not clear that the local utility would be the best supplier of such insurance products. Similarly, results show that customers in apartment buildings are more likely to relocate compared to customers in other housing situations. Understanding the reasons for this likelihood may require involving city planners, developers, and other non-utility stakeholders. These two examples highlight the relevance of economy-wide analysis of the impacts of long-duration interruptions and analysis of efficient mitigation strategies.

Fourth, because even with utility actions and public policy long duration interruptions may not be prevented with absolute confidence, our findings show that increasing deployment of residential power supply (photovoltaic panels, storage systems, or fuel-based generators) can serve as, in effect, a valuable insurance policy to reduce or eliminate customer costs and other impacts. Furthermore, our results show that, if decision-makers conclude that preventing massive relocation after interruptions is a necessary strategy to keep the population safe, ownership of backup generation is a strong predictor to reduce the likelihood of relocation.

Finally, our modeling for a single county in Illinois suggest that relocation decisions may put undue strain on transportation infrastructure, to the point where many customers may not be actually able to meet their resilience needs. It follows that advance planning to efficiently manage relocations or evacuations could reduce the risks of significant impacts on transportation infrastructure in the event of severe power interruptions caused by power interruptions.

This study has several limitations. First, like other stated preference surveys, our results are subject to uncertainty associated with evaluating hypothetical scenarios. Respondents may have limited experience with WLD power interruptions, which may affect their ability to estimate costs and express expected responses. To reduce these challenges, the survey presented detailed and realistic outage scenarios, decomposed interruption impacts into individual cost categories, and included preparatory questions and exercises before cost estimation (Arrow et al., 1993). Nevertheless, respondents may interpret aspects of the scenarios differently or have difficulty articulating their expected costs and resilience decisions (Shaikh et al., 2007; Cameron et al., 2002). Second, the survey assumes that customers know the interruption duration when selecting a resilience strategy. In practice, restoration times are uncertain, and customer responses may evolve as the interruption unfolds, which is not captured in the survey. Third, our instrumental variable based on having experienced an WLD interruption before could be improved by asking more information about changes in decisions or preferences that the experience had on the respondent, as prior studies show that familiarity and experience can influence stated preference responses (Johnson et al., 1990; McFadden, 1994). Fourth, although the survey provided respondents with information about road conditions, fuel availability, and weather conditions when considering relocation, individual interpretations of these factors may vary. Relocation decisions may also be influenced by localized factors, such as historical traffic patterns, government mandates, and the decisions of others, which are not captured in the survey. Finally, relocation was intentionally defined as a broad strategy encompassing stays with family or friends, hotels, and emergency shelters. The survey did not distinguish among relocation destinations or collect information on the duration of relocation within the outage period. As a result, the reported relocation costs represent average expected expenditures across a heterogeneous set of relocation scenarios. Future surveys could distinguish among relocation destinations and durations to better characterize the sources of relocation costs and improve estimates of their distribution across households.

This work contributes to utilities' and other decision-makers' assessments of potential policies and measures to address such topics using cost-benefit methods. As described in Larsen et al. [3], survey information of the type discussed in this paper can be used to calibrate computable general equilibrium models of regional economies. As mentioned in the Introduction, these are used to comprehensively assess the economic impacts of widespread, long-duration power interruptions. In addition to this type of analysis, there are several avenues for further research expanding upon what we have described. Refinements to the survey design could provide deeper insight into customers' decision-making on responding to power interruptions, including the causal relationship between costs and relocation decisions. Finally, a better understanding of the reasons for relocation of residential customers will shed light on effective policies to equitably address resilience challenges.

CRediT authorship contribution statement

Juan Pablo Carvallo: Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sunhee Baik:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Alan H. Sanstad:** Writing – original draft, Software, Methodology, Investigation, Formal analysis,

Conceptualization. **Peter H. Larsen:** Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Statements & declarations

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All authors contributed to the study conception and design. Data collection, curation, and preparation was performed by Sunhee Baik. Methodology and data analysis was performed by Juan Pablo Carvallo, Alan Sanstad, and Sunhee Baik. Visualization was performed by Sunhee Baik. The first draft of the paper was written by Juan Pablo Carvallo, Alan Sanstad, and Sunhee Baik, and reviewed by Peter Larsen. Funding was acquired by Peter Larsen and Juan Pablo Carvallo. All authors contributed, read, and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2026.106487.

Data availability

The data that has been used is confidential.

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