

ICE Calculator 2.0: Quantifying the Cost of Power Outages

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ABSTRACT

The Interruption Cost Estimate (ICE) Calculator is a publicly accessible tool used to estimate the economic costs electricity customers incur due to power interruptions. Originally developed over 15 years ago using survey data from 1989 to 2012, the need to update the tool has increased as electricity usage patterns and technologies have evolved. To address this, Berkeley Lab and Resource Innovations launched the ICE 2.0 Initiative in 2021, a nationwide effort to update the tool's underlying data and enhance its analytical capabilities. In Phase 1 of the project, updated surveys were administered to over 3,000 residential and nearly 4,000 non-residential customers across sponsoring utilities. New methodological features include the use of a novel willingness-to-pay technique for residential customers. Analysis of pooled results produced updated customer damage functions (CDFs), which serve as the tool's analytic engines. These include a generalized linear model (GLM) for residential customers and a two-part model (Probit and GLM) for non-residential customers. ICE 2.0 significantly advances the tool by incorporating improved regional representation, standardized survey methods, and robust sampling, enabling more accurate assessments of the economic impacts of electric grid reliability and resilience investments.¹

Introduction

The Interruption Cost Estimate (ICE) Calculator is a publicly available, online tool designed to estimate the economic costs electricity customers experience due to power interruptions. Developed over 15 years ago for the U.S. Department of Energy by Lawrence Berkeley National Laboratory (Berkeley Lab) and Freeman, Sullivan & Co., the ICE Calculator has become a routinely used resource for utility planners and decision makers seeking to quantify the economic benefits of grid reliability and resilience investments.

In 2021, Berkeley Lab and Resource Innovations, Inc. initiated the ICE 2.0 Initiative, a national, multi-client study aimed at updating the ICE Calculator's data and enhancing its analytical capabilities. This initiative involves partnering with sponsoring utilities to administer identical, modernized interruption cost surveys to representative samples of their customers. The results from these coordinated surveys are pooled across utilities and used to refresh the ICE Calculator's underlying customer damage functions (CDFs), the models that translate survey data into economic cost estimates.

The ICE 2.0 Initiative is being implemented in phases. Each phase consists of survey administration to customers of sponsoring utilities, followed by updates to the ICE Calculator based on pooled survey analysis. Phase 1, the focus of this report, was sponsored by eight major utilities: American Electric Power, Commonwealth Edison, Dominion Energy, Duke Energy, DTE Electric, Exelon, National Grid, and Puget Sound Energy. In total, this phase included 11 survey activities across 24 electricity distribution territories, primarily in the Eastern and Midwestern U.S., with one in the Pacific Northwest.

ICE 2.0 was designed to address two important needs. First, as electric utilities consider significant investments in reliability and resilience, it is essential that estimates of economic benefits reflect current customer behaviors, technologies, and expectations. The original ICE Calculator relied on data collected

¹ For additional information regarding the ICE Calculator, please visit icecalculator.com.

from 1989 to 2012, during which time electricity usage patterns have evolved considerably, particularly with trends such as remote work and increased automation. Second, to support decisions across the country, the ICE Calculator must capture geographic diversity. The original version was based largely on data from utilities on the West Coast and in the Southeast. The ICE 2.0 surveys improve national representation and employ consistent survey instruments and sampling methods across participating utilities.

Methodology

Valuation Methods

To estimate the economic impacts of power interruptions on electricity customers, the ICE 2.0 Initiative employs two distinct valuation methods: (1) a willingness-to-pay (WTP) approach for residential customers, and (2) a direct cost measurement approach for non-residential customers. These methods are tailored to the nature of losses experienced by each customer segment. Residential customers often incur intangible losses, such as inconvenience or discomfort, which are not easily quantified through direct cost methods. In contrast, non-residential customers are more likely to experience tangible, monetizable losses related to business operations, making them better suited for direct estimation techniques.

The WTP approach used for residential customers is grounded in contingent valuation methodology. Rather than asking customers to assign a direct monetary value to the interruption itself, the survey asks how much they would be willing to pay for a hypothetical backup service that could prevent the interruption from occurring. This technique is particularly useful in capturing intangible costs, such as lost comfort or productivity. The ICE 2.0 surveys implement a specific version of contingent valuation known as the one-and-one-half-bound dichotomous choice (OHDC) method (Cooper, Hanemann, and Signorello 2002). In this framework, respondents are presented with a hypothetical backup service priced within a given price range and are asked a series of yes/no questions to determine the highest amount they would pay. Compared to open-ended valuation, this closed-ended format minimizes the risk of underreporting and increases statistical reliability.

For non-residential customers, the ICE 2.0 Initiative applies a direct cost measurement approach, reflecting the more tangible and structured nature of business-related losses during power interruptions. Respondents are asked to estimate itemized costs associated with an outage scenario, including lost production value, restart labor and material costs, damage to equipment or materials, and any fuel or generator operation expenses. These are offset by any interruption-related savings, such as avoided wages or unused raw materials. Only incremental losses, those above and beyond normal operating costs, are included. Additionally, if a business can recover production later, that value is subtracted from the loss estimate to avoid overstatement. To simplify the survey experience, respondents complete a full cost breakdown only once (for a base scenario) and then estimate changes relative to this baseline for subsequent scenarios. This hybrid approach ensures accurate data collection without overburdening participants.

Survey Design and Sampling

The study was designed to collect sufficient survey responses to support both utility-level and aggregated analyses of interruption costs for the ICE Calculator. Target response counts were set at 250 for residential customers, 250 for small and medium non-residential (SMNR) customers, and 67 for large non-residential (LNR) customers, per utility study. These targets were chosen to ensure adequate statistical power to estimate interruption cost distributions not only for each individual utility but also for the combined dataset used to update the CDFs in the ICE Calculator.

Three survey instruments were developed to reflect the differing characteristics and energy use profiles of customer segments. For this study, SMNR customers had average annual demand below 200 kW, and LNR customers above 200 kW. Each survey began with questions about the respondent’s demographic (residential) or firmographic (non-residential) characteristics, past experiences with outages, and existing resilience measures such as backup generation. Following the introductory section, respondents were presented with a series of power interruption scenarios. Each participant was randomly assigned three of four possible durations, momentary (up to 5 minutes), 2 hours, 8 hours, and 24 hours. It should be noted that the general focus of the ICE Calculator is for interruptions less than 24 hours in length.

For each selected duration, respondents first answered questions about a base scenario defined as an unexpected outage occurring on a summer weekday at a random onset time (9 AM, 2 PM, or 7 PM). To measure how customer valuations change under different outage conditions, pivot scenarios were then presented. Each residential and SMNR respondent was shown one pivot, while LNR respondents received two. Pivots altered a single characteristic of the base scenario: either the customer received advance warning, the season changed to winter, or the day of the week changed to a weekend. This design was used to isolate the effect of specific contextual factors on interruption cost estimates.

The sampling methodology followed a stratified design. Each utility’s customer population was divided into three segments (residential, SMNR, and LNR), and each segment was further stratified by average annual electricity demand (kW). Samples were drawn from each stratum in proportion to total segment usage to ensure representation across the full range of customer sizes. Stratification was essential due to the highly skewed distribution of electricity use; high-usage customers are few in number but account for a large share of potential economic losses during outages. A simple random sample would likely underrepresent this critical group.

Table 1 displays the total number of responses collected per utility after the data were cleaned for outliers, illogical responses, and invalid answers.

Table 1. Phase 1 ICE Calculator Validated Residential and Non-residential Responses by Utility

Utility	Residential Responses	Non-residential responses
AEP East	314	342
AEP West	263	301
ComEd	259	369
Duke Energy Carolinas	270	404
Duke Energy Florida	267	367
Duke Energy Midwest	280	384
DTE Electric	271	351
Dominion Energy	281	288
Exelon	270	294
National Grid	275	350
PSE	276	424
Total	3,026	3,874

Residential Customer Damage Function

The estimation of interruption costs for residential customers followed a multi-step modeling process grounded in the OHDC framework. In this framework, respondents are presented with hypothetical outage scenarios and asked whether they would be willing to pay a specified amount to avoid the interruption. Each yes/no response was translated into a lower-bound WTP estimate by dividing the

bid price by the probability density of receiving that particular bid (Watanabe 2010). These individual-level WTP estimates were then aggregated by interruption duration, forming the basis for modeling the relationship between outage duration and average interruption cost. To ensure that cost estimates increased monotonically with duration, multiple functional forms were tested. The natural logarithm of duration and its square provided the best fit, producing a continuous cost function valid for durations from momentary to up to 24 hours.

The modeling process continued with the development of a CDF for residential interruption costs using a Poisson Quasi-Maximum Likelihood Estimator (QMLE). This estimator was chosen for its ability to provide consistent and strictly positive cost estimates, appropriate for the nature of WTP data. A Least Absolute Shrinkage and Selection Operator (LASSO) regression was first used to identify a subset of relevant explanatory variables while minimizing overfitting. Candidate models based on LASSO output were then evaluated using 100-fold cross-validation to simulate how the model would function within the ICE Calculator. While predictive accuracy was prioritized, some categorical variables not selected by LASSO, such as for low-income households, were included in the final model to ensure the ICE Calculator could be used to evaluate cost impacts on key population segments. The final residential CDF estimates the mean WTP based on average input values (e.g., percentage of customers with backup generation), aligning with how the ICE Calculator is intended to function in practical applications. Table 2 presents the variables included in the Phase I Residential ICE Calculator model.

Table 2. Residential Model Variables

Continuous Variables
<ul style="list-style-type: none"> • Interruption duration (in minutes) • Annual electricity usage (in kWh)
Categorical Variables
Season <ul style="list-style-type: none"> • Summer • Winter Ownership of Backup Generation <ul style="list-style-type: none"> • Yes • No Work from Home Status <ul style="list-style-type: none"> • Yes • No Total Household Income <ul style="list-style-type: none"> • Under \$50,000 per year • \$50,000-\$100,000 per year • \$100,000-\$150,000 per year • Over \$150,000 per year

Non-Residential Customer Damage Function

The estimation of interruption costs for non-residential customers followed a three-step process to develop a CDF capable of estimating interruption costs across a wide range of customer types and outage durations. The first step involved developing a continuous cost curve that interpolated between point estimates from the survey for momentary, 2-hour, 8-hour, and 24-hour interruptions. This step paralleled the approach used for residential customers and ensured that the CDF could estimate costs for any outage duration up to 24 hours. The second step addressed the skewed nature of the survey data by

applying a two-part modeling approach. This approach accounted for the fact that while many non-residential respondents reported positive interruption costs, a significant share reported zero cost. These results reflect the wide variation in how interruptions affect businesses of different types, some may suffer no losses from a short outage, while others may face significant costs due to production halts or system restarts. The two-part approach separately models the probability of reporting a non-zero cost (via a probit model) and the magnitude of the cost conditional on it being non-zero (via a generalized linear model, or GLM). This structure is well-suited to datasets with mixed zero and non-zero outcomes and supports more accurate prediction of mean costs across the population.

Variable selection for the non-residential model followed a similar process to that used in the residential methodology. LASSO regression was first applied to reduce the number of candidate explanatory variables from an initial set of more than 30. The resulting candidate models were then evaluated using 10-fold cross-validation, which provided an out-of-sample assessment of predictive accuracy through repeated testing on withheld data. Model selection emphasized parsimony to avoid overfitting and ensure usability in the ICE Calculator. While some variables were excluded based on statistical performance, others were retained to ensure the model remained representative of important customer segments and practical for end users to apply in diverse service territories. Table 3 displays the Phase I non-residential variables included in the ICE Calculator.

Table 3. Non-Residential Model Variables

Continuous Variables
<ul style="list-style-type: none"> • Interruption duration (in minutes) • Annual electricity usage (in kWh)
Categorical Variables
Advance Warning of Outage <ul style="list-style-type: none"> • Yes • No
Day of Week (Probit Only) <ul style="list-style-type: none"> • Weekday • Weekend
Industry (GLM Model Only) <ul style="list-style-type: none"> • Health Care and Social Assistance • Manufacturing • All Other Industries

Results

Residential Results

Table 4 displays the residential results from the Phase I ICE 2.0 Calculator update. These results were produced by using the average characteristics from the full set of residential customer survey responses, which were used as inputs into the model. Besides showing the cost per customer for each interruption, Table 4 also displays three other cost metrics. The cost per kW is the event cost divided by average customer demand. The cost per unserved kWh is the event cost divided by the expected amount of unserved kWh during the interruption. Lastly, the cost per Customer Per Minute (CMI) interrupted is the average event cost divided by the number of minutes in the interruption.

Table 4. Phase I Residential Interruption Costs (2023\$)

Duration of Power Interruption Event	Cost per Event	Cost per kW	Cost per Unserved kWh	Cost per CMI
Momentary	\$1.80	\$1.50	\$18.03	\$0.36
2 Hours	\$10.49	\$8.62	\$4.31	\$0.09
8 Hours	\$25.55	\$21.21	\$2.65	\$0.05
24 Hours	\$54.52	\$44.76	\$1.86	\$0.04

Figures 1 through 5 present how the residential results vary by the variables included in the CDF. The figures show how the results change based on annual usage, season, income level, backup generation, and work from home status.

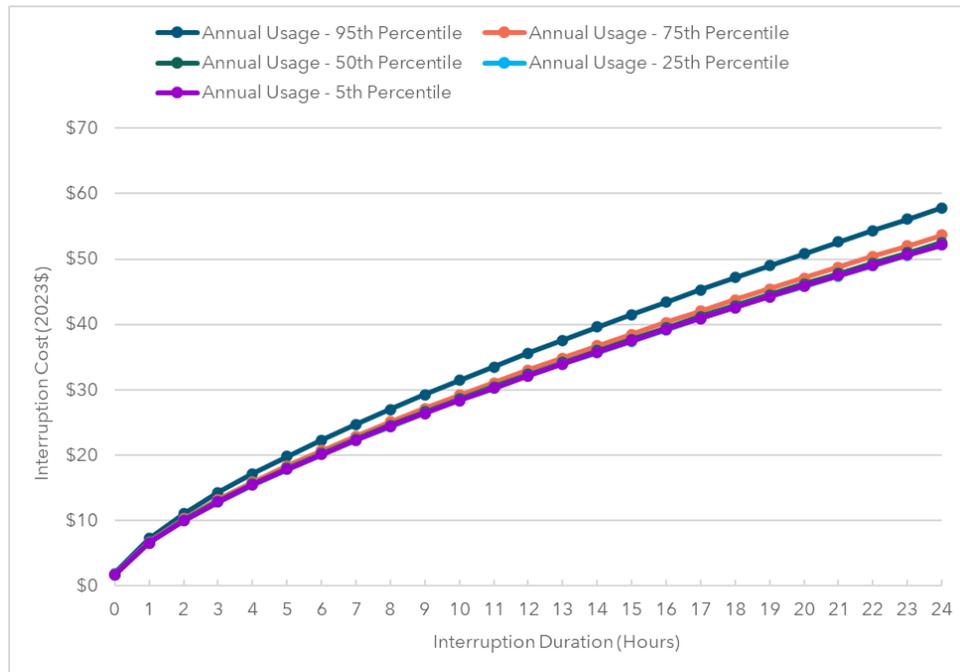


Figure 1. Residential Interruption Cost by Usage.

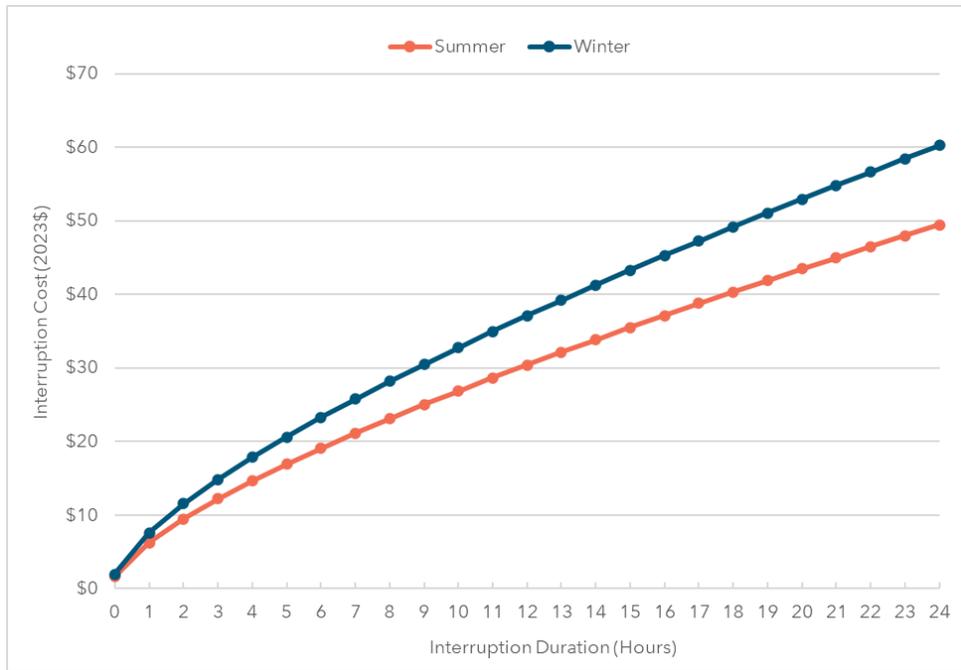


Figure 2. Residential Interruption Cost by Season.

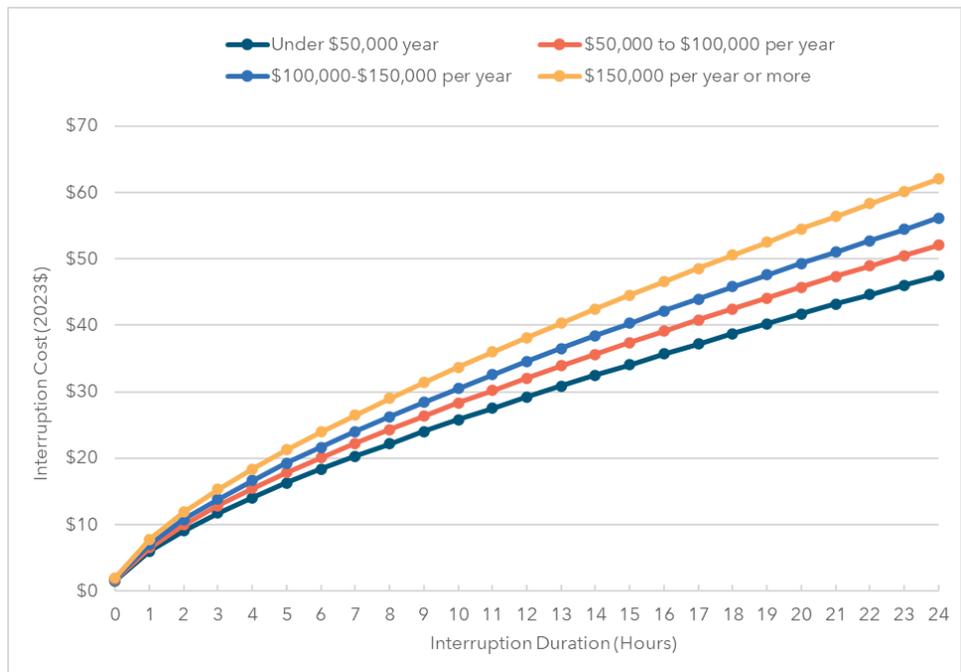


Figure 3. Residential Interruption Cost by Income Category.

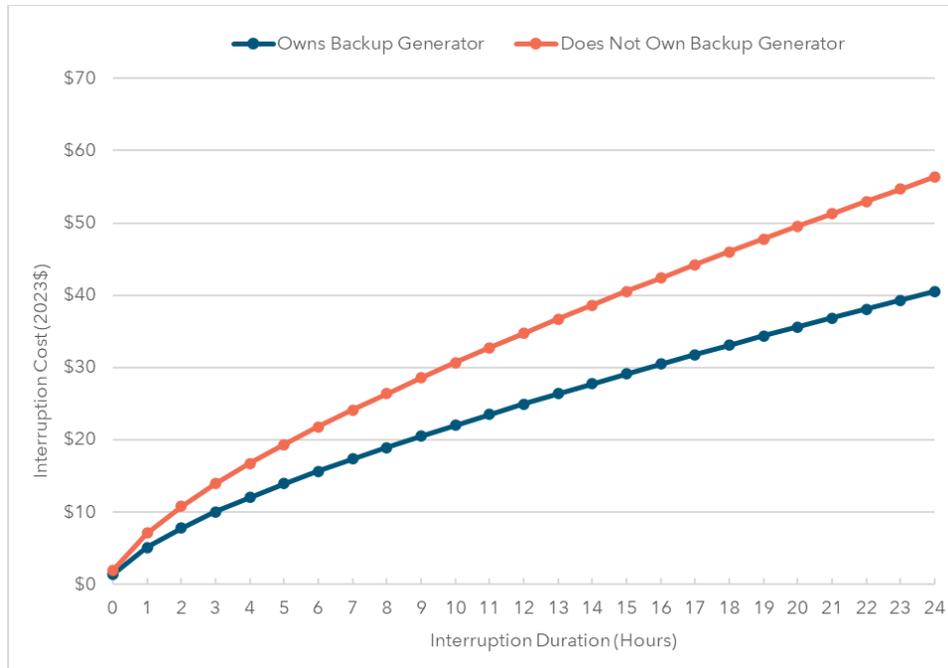


Figure 4. Residential Interruption Cost by Backup Generator Ownership.

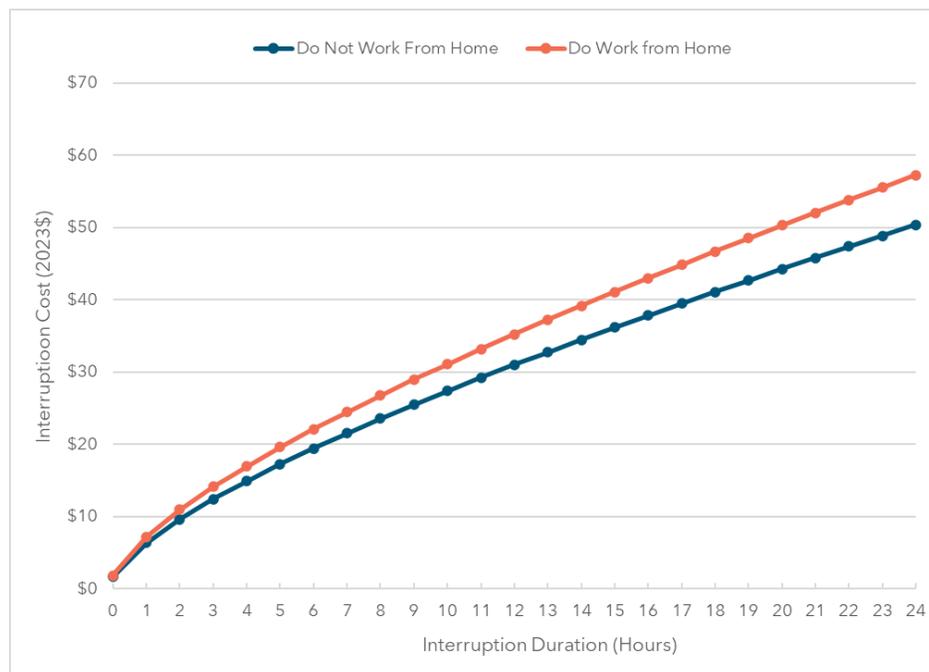


Figure 5. Residential Interruption Cost by Work from Home Status.

Non-Residential Results

Table 5 presents the non-residential results from the updated Phase I ICE 2.0 Calculator. These results were generated by applying the average characteristics derived from the complete set of non-residential customer survey responses, which served as inputs for the model. In addition to showing the cost per customer for each interruption, Table 5 also the cost per kW, the cost per unserved kWh, and cost per CMI.

Table 5. Phase I Non-Residential Interruption Costs (2023\$)

Duration of Power Interruption Event	Cost per Event	Cost per kW	Cost per Unserved kWh	Cost per CMI
Momentary	\$609	\$43	\$521	\$122
2 Hours	\$2,839	\$202	\$101	\$24
8 Hours	\$6,172	\$440	\$55	\$13
24 Hours	\$12,646	\$902	\$38	\$9

Figures 6 through 10 present how the non-residential results vary by the variables included in the CDF. The figures show how the results change based on annual usage, day of the week, industry type, and advanced warning of the outage.

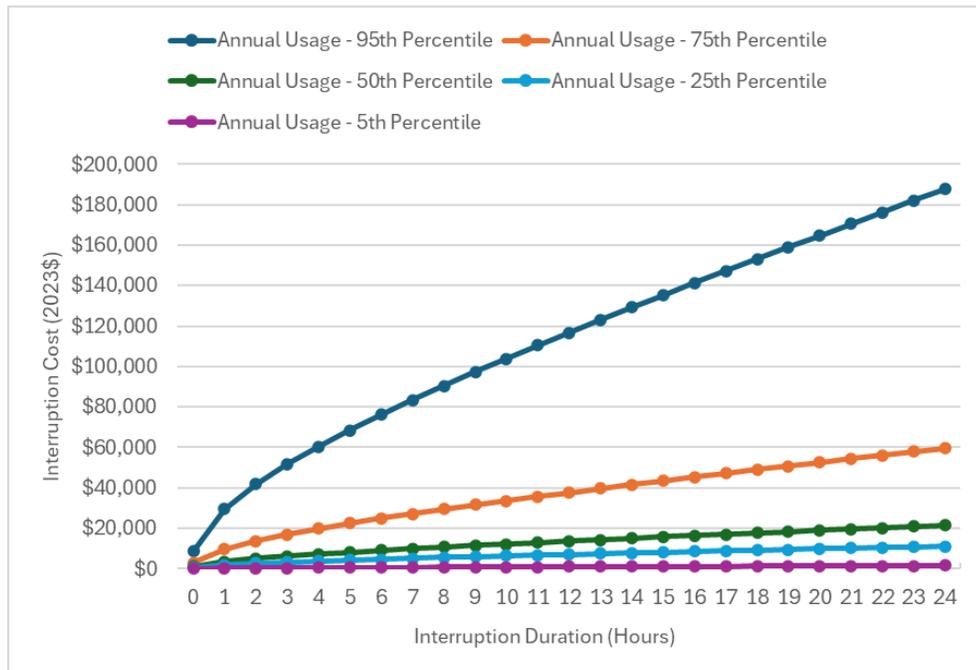


Figure 6. Non-Residential Interruption Cost by Usage.

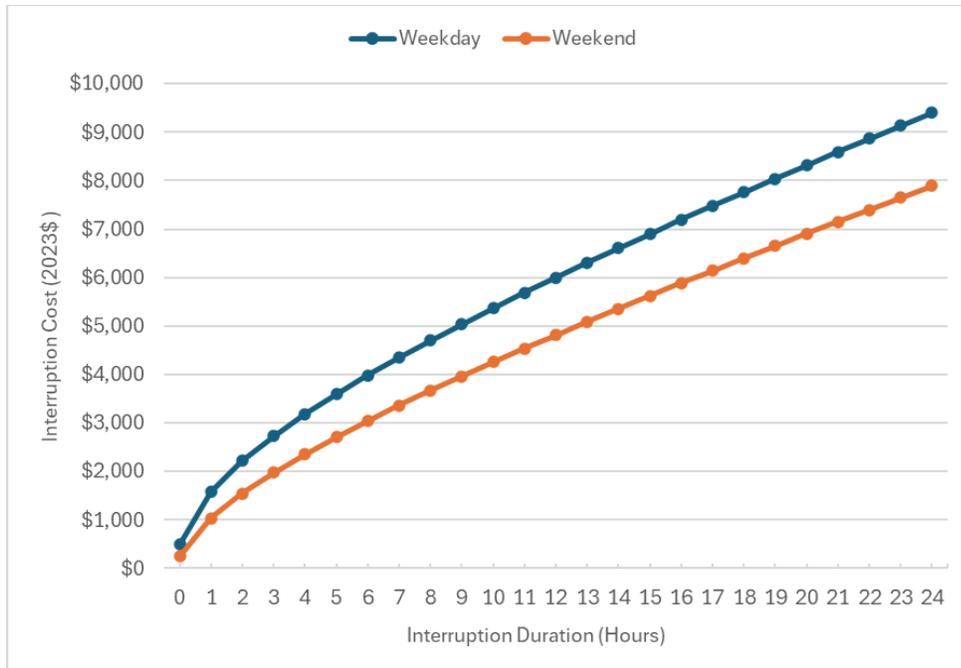


Figure 7. Non-Residential Interruption Cost by Day of the Week.

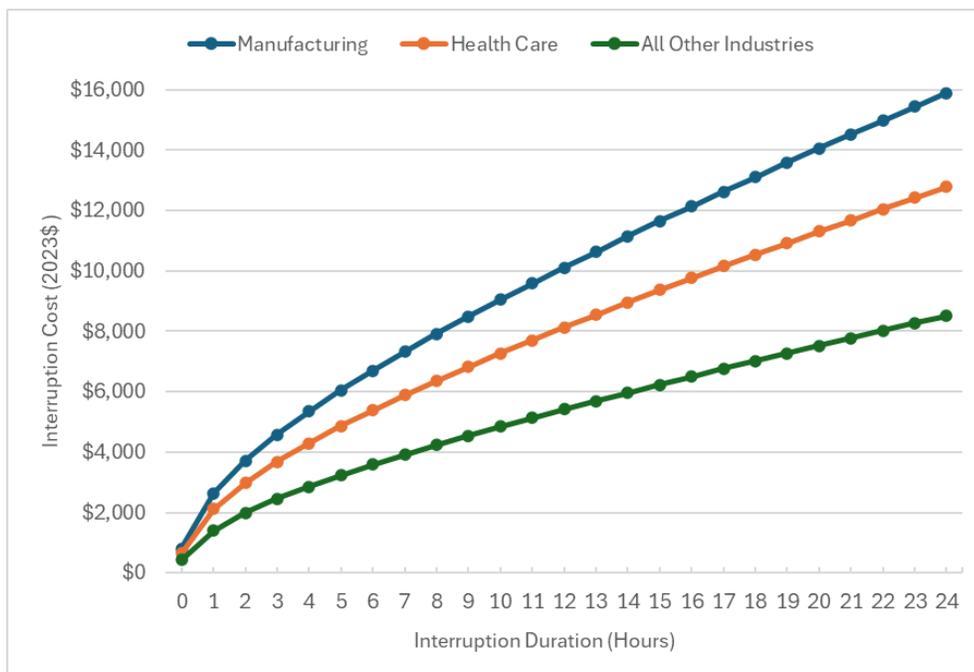


Figure 8. Non-Residential Interruption Cost by Industry.

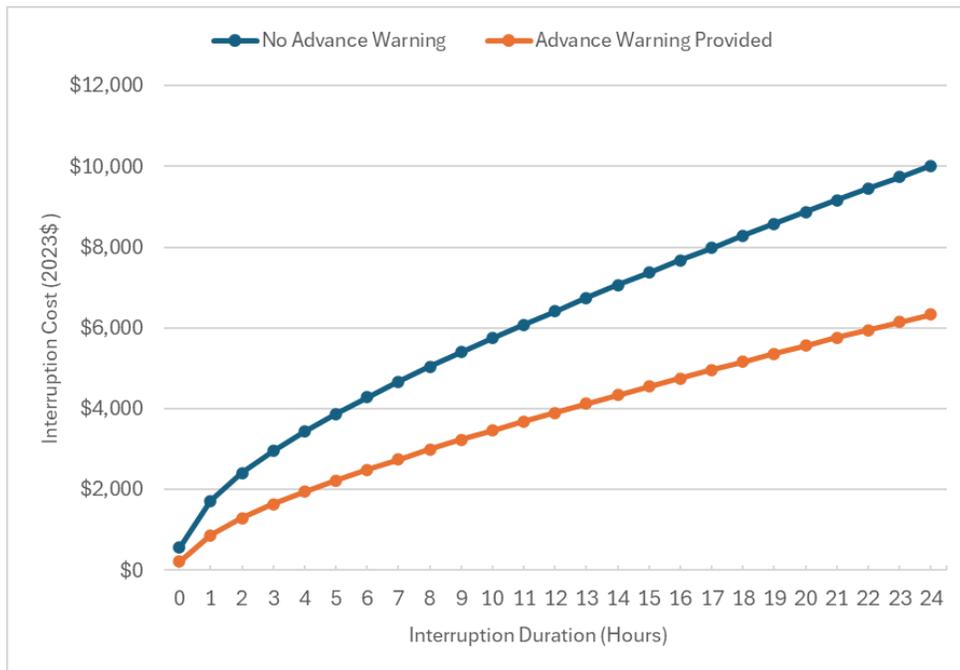


Figure 9. Non-Residential Interruption Cost by Advance Warning of the Outage.

Conclusions

The ICE Calculator is a widely used tool that helps utilities evaluate and prioritize grid reliability and resilience investments by estimating the economic costs customers experience during power interruptions. The tool translates avoided interruptions into measurable customer and economic benefits. By quantifying these costs, utilities can apply value-based reliability planning. Recent updates to the ICE Calculator ensure that its estimates more accurately reflect the real financial impacts of interruptions on households and businesses. This provides utilities and policymakers with robust, data-driven insights to guide investment decisions and better account for the social and economic value of reliability and resilience.

In Phase 1, surveys were conducted with statistically representative samples across 24 service territories, supported by eight sponsoring utilities. These results informed the development of updated CDFs that were integrated into the ICE Calculator in early 2025, alongside enhancements to its online interface. Future phases will expand geographic coverage and sample size, enabling improved modeling and the inclusion of additional variables, ultimately increasing the tool’s accuracy and regional relevance.

References

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- Watanabe, M. 2010. “Nonparametric estimation of mean willingness to pay from discrete response valuation data.” *American Journal of Agricultural Economics*, 92(4), 1114-1135.